International Journal of Research and Review
[Indexed, Peer-Reviewed Journal]
Volume 13; Issue: 5; May 2026
Website: www.ijrrjournal.com
E-ISSN: 2349-9788; P-ISSN: 2454-2237

Review Paper

Biochar for Climate-Resilient Soil and Water Conservation: A Critical Review

Bontor L. Tobing[1], Fitryane Lihawa[2], Abdul Samad Hiola[3], Asda Rauf[4], Wahyuni K. Baderan[5]

[1,3]Doctoral Program in Environmental Science, Universitas Negeri Gorontalo, Gorontalo, Indonesia.
[2,4,5]Postgraduate Program, Universitas Negeri Gorontalo, Gorontalo, Indonesia.

Corresponding Author: Fitryane Lihawa

DOI: https://doi.org/10.52403/ijrr.20260550

ABSTRACT

Biochar is increasingly positioned at the interface of renewable carbon management, sustainable agriculture, and land-degradation control. This critical review synthesizes evidence from global meta-analyses and recent mechanistic and field studies to evaluate how biochar contributes to runoff reduction, soil erosion control, and climate-resilient soil function. Yet its value for runoff and water-erosion mitigation remains highly context dependent because biochar properties interact with soil texture, rainfall regime, slope, vegetation cover, and time since application. The updated evidence indicates that biochar can reduce runoff and soil loss, but rarely as a stand-alone or universally scalable amendment. Instead, its most defensible function is as a soil sponge-stability-vegetation intervention that redistributes rainfall, strengthens aggregate and rill-flow resistance, and improves the biological cover needed for durable erosion control. Recent field and mechanistic studies refine the earlier meta-analytic conclusions by showing dose optima near low-to-moderate topsoil concentrations, larger responses in coarse and medium-textured soils, event-scale dependence under high-erosivity rainfall, and strong synergies with vegetation, mulch, and filter-strip systems. The same evidence also identifies risks that must be managed, including phosphorus percolation, fine-particle export, increased surface runoff in karst settings, high-rate detachment responses, salinity, polycyclic aromatic hydrocarbons, and aging under compaction. We therefore propose a precision framework that matches feedstock, pyrolysis conditions, particle size, rate, placement depth, co-amendments, and monitoring endpoints to dominant erosion pathways. Future progress requires multi-year field trials, standardized reporting, pathway-specific hydrological accounting, and integration with circular biomass and climate-resilient land-management strategies.

Keywords: biochar; soil erosion; runoff; sponge function; soil structure; vegetation cover; hydrological connectivity

INTRODUCTION

Accelerated soil erosion by water is no longer a local agronomic problem; it is a coupled challenge for food security, the carbon cycle, and water quality. Global analyses have projected large increases in water-driven soil erosion during the twenty-first century under plausible land-use and climate-change trajectories, and European projections similarly suggest future increases in soil loss without stronger conservation measures (Borrelli et al., 2017; Borrelli et al., 2020; Panagos et al., 2021). Recent erosion-risk studies reinforce the same message from regional perspectives: rainfall erosivity is projected to increase in key monsoon systems, land-use and soil-property changes can reconfigure erosion risk at basin scales, and tropical island landscapes remain highly sensitive to land-cover decisions (Guo et al., 2024; Li et al., 2024a; Liu et al., 2025; Liu et al., 2026; Wang et al., 2025). Against this background, soil conservation research has moved beyond single measures and toward interventions that can simultaneously improve water regulation, soil structure, vegetation establishment, nutrient retention, and carbon storage (Lal, 2010; Wu et al., 2020).

Biochar occupies a distinctive position in this transition because it is both a carbon-rich amendment and a material with strong physical and chemical effects on soil. Earlier biochar research established potential benefits for highly weathered tropical soils, soil physical properties, water retention, crop yield, and environmental remediation, but also emphasized that response size is contingent on feedstock, pyrolysis temperature, soil texture, baseline fertility, pH, and management (Barrow, 2012; Beesley et al., 2011; Blanco-Canqui, 2017; Glaser et al., 2002; Omondi et al., 2016; Razzaghi et al., 2020; Schmidt et al., 2021; Verheijen et al., 2014; Zhang et al., 2016). The soil conservation question is therefore not whether biochar is universally beneficial, but rather where, when, and how it modifies the coupled processes of runoff, detachment, transport, and deposition (Blanco-Canqui, 2019; Hseu et al., 2014; Peng et al., 2016; Smetanová et al., 2013).

The 2023 systematic global meta-analysis of biochar impacts on runoff and soil erosion by water marked an important shift by quantifying biochar effects on erosion and runoff rather than inferring them from hydrological or fertility proxies (Gholamahmadi et al., 2023). Its central findings were nuanced: biochar reduced runoff by 25% and erosion by 16% on average, erosion mitigation was much stronger in tropical than temperate latitudes, significant erosion reductions occurred mainly at 0.6-2.5% gravimetric topsoil concentrations, shallow incorporation was more effective than deeper mixing, and vegetated experiments showed more than twice the erosion reduction observed in bare-soil experiments (Gholamahmadi et al., 2023). These results implied that direct structural effects and indirect plant-mediated effects interact. They also exposed a limitation: the evidence base available to that meta-analysis contained relatively few long-term field studies, patchy reporting of biochar properties, and limited capacity to test interactions among climate, soil texture, rate, pyrolysis condition, application depth and vegetation cover (Gholamahmadi et al., 2023; Tufanaru et al., 2015; Weir et al., 2018).

Recent literature published after the 2023 synthesis changes the interpretive landscape. A new meta-analysis reports an overall 27.86% reduction in rainfall-induced soil erosion, an optimal dose range of 0.8-2%, stronger reductions in coarse-grained soils, and larger benefits in long-term field experiments than in short-term laboratory studies (Lu et al., 2024). Four-year field monitoring on the Loess Plateau reports average annual runoff reductions of 9-36% and annual soil-loss reductions of 43-79%, but shows that reductions vary among rainfall patterns and that high-intensity rainfall can weaken control effectiveness (Li et al., 2024b). Mediterranean vineyard studies now connect biochar-induced reductions in runoff, fine-earth loss, splash erosion, and coarse-fragment export with increases in infiltration, stored water, vegetation cover, and aboveground biomass under natural rainfall (Gholamahmadi et al., 2025a; Gholamahmadi et al., 2025b). These newer studies therefore support the earlier meta-analytic inference while moving the field from average effect sizes toward mechanistic and site-specific diagnosis.

This review builds on that progression by updating the science after the 2023 meta-analysis, identifying mechanistic convergence across hydrology, soil physics, plant productivity, and water-quality studies, and translating those mechanisms into a precision framework for biochar-based erosion control. The emphasis is not on promoting biochar as a generic amendment, but on defining the soil, climate, vegetation, and management conditions under which it can contribute to sustainable land restoration, climate resilience, and circular biomass use.

LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

The review is organized around a simple proposition: biochar influences erosion through three interacting domains. First, it can modify the soil sponge function, defined here as the soil's combined capacity to accept rainfall, store plant-available water, and release water without producing destructive overland flow. Second, it can modify soil structural resistance through aggregation, pore architecture, cohesion, crusting resistance, critical shear stress, and rill or interrill erodibility. Third, it can modify vegetation pathways by changing plant establishment, canopy interception, root reinforcement, litter input, and biological feedback (Blanco-Canqui, 2017; Gholamahmadi et al., 2023; Omondi et al., 2016; Razzaghi et al., 2020; Zanutel et al., 2024a). These domains are not independent. More infiltration can reduce runoff energy, stronger aggregates can reduce detachment for a given shear stress, and greater vegetation cover can reduce raindrop impact, slow flow, and enhance root-driven aggregation (Jeffery et al., 2017; Jongen et al., 2026; Smit et al., 2019).

The sponge-stability-vegetation framework also helps reconcile contradictory evidence. Biochar may reduce runoff but has a weaker effect on soil loss if detachment remains controlled by crusting, rill shear, or high-intensity rainfall. Conversely, it may reduce soil loss more than runoff when cohesion, aggregation, or surface cover reduces sediment availability while some runoff persists (Li et al., 2024b; Maisyarah et al., 2023; Rončák et al., 2023). In karst landscapes, improving subsurface pathways may reduce underground leakage or fissure-associated losses while unexpectedly increasing surface runoff and surface soil loss if pore connectivity and aggregate disruption alter water-routing efficiency (Yin et al., 2024; Zi et al., 2025). In compacted vineyards, biochar may initially limit machinery-induced increases in bulk density, but the benefit can decline after repeated traffic and 1 year of field management (De Francesco et al., 2025). The relevant question is therefore not only the sign of the average effect, but the process domain in which biochar acts and the pathway through which rainfall becomes runoff, infiltration, percolation, evaporation, or sediment transport.

A second organizing principle is that the biochar dose-response curve is rarely linear. The 2023 meta-analysis suggested an apparent erosion-control optimum around 0.6-2.5% in the topsoil, with no significant effect at lower or higher concentrations (Gholamahmadi et al., 2023). Lu et al. (2024) independently found an optimal 0.8-2% range in a newer meta-analysis, while several field and flume studies reveal that excessive rates can increase detachment capacity or alter hydrological connectivity in ways that do not improve erosion control (Li et al., 2025b; Li et al., 2025a; Conte et al., 2025; Gholamahmadi et al., 2023). This convergence is important because it suggests that biochar should be designed as a targeted soil-engineering amendment rather than applied solely to maximize carbon addition.

A third organizing principle is that biochar performance depends on complementary management. Straw-biochar co-application reduced erosion from wildfire-degraded soils under extreme rainfall, mulch and biochar showed complementary hydrologic and phytotoxic responses in Mediterranean agricultural soils, and vegetation filter strips combined with biochar provided more stable nutrient-loss reductions under continuous rainfall than either measure alone (Canedo et al., 2025; Li et al., 2025c; Prats et al., 2021). A global mulching meta-analysis found much larger average reductions in runoff and soil loss than typically reported for biochar alone, implying that biochar may be most powerful when embedded in a conservation system that includes surface cover, vegetation, and runoff filtering (Fan et al., 2023; Vahidi et al., 2025). Thus, the emerging literature favors integrated design over stand-alone amendment.

MATERIALS & METHODS

1. Review design

This article was developed as a critical narrative review rather than a new meta-analysis or systematic review. The objective was to synthesize and interpret evidence on how biochar affects runoff, soil erosion, hydrological partitioning, soil structure, vegetation feedback, and environmental trade-offs. The review was organized around the soil sponge-stability-vegetation framework introduced in this paper. Emphasis was placed on studies that reported direct erosion, runoff, infiltration, soil-water storage, aggregate stability, rill or interrill erodibility, vegetation cover, nutrient-loss pathways, or risk-related endpoints. Because several quantitative syntheses are already available, this article did not recalculate pooled effect sizes; instead, it used published meta-analytic results and recent mechanistic and field evidence to derive design rules and boundary conditions (Gholamahmadi et al., 2023; Lu et al., 2024).

2. Literature scope

The evidence base comprised peer-reviewed studies relevant to biochar-mediated soil and water conservation, with priority given to global meta-analyses, long-term or natural-rainfall field studies, rainfall-simulation experiments, flume studies, lysimeter studies, and recent reports through 2026 addressing soil physical properties, hydrological connectivity, vegetation response, nutrient transfer, ecotoxicity, and remediation. Foundational studies on biochar effects on soil physical and hydrological properties, carbon management, and land restoration were retained where they provided mechanistic context (Blanco-Canqui, 2017; Omondi et al., 2016; Razzaghi et al., 2020; Schmidt et al., 2021). Recent evidence was prioritized when it directly updated the 2023 baseline or addressed underrepresented issues such as aging, high-erosivity rainfall, karst flow pathways, compaction, co-application with mulch, or vegetation-mediated erosion control.

3. Synthesis approach

The synthesis followed a thematic and mechanism-oriented approach. Evidence was first grouped by dominant process: rainfall partitioning and sponge function, soil structure and erodibility, pore architecture and hydrological connectivity, vegetation and biological feedback, and chemical or ecotoxicological constraints. Findings were then compared across soil texture, climate, rainfall regime, biochar rate, placement, particle size, feedstock, study duration, and co-amendment. Greater interpretive weight was given to studies that linked process measurements with runoff or soil-loss outcomes, because such designs allow stronger causal interpretation than endpoint-only comparisons. The two summary tables were constructed to condense (i) the updated evidence base and mechanisms and (ii) practical application, safeguards, and reporting priorities. This approach allowed the review to identify convergent findings, contradictions, boundary conditions, and research priorities without introducing a new quantitative meta-analysis.

RESULTS OF LITERATURE SYNTHESIS

The first important update is that independent synthesis now broadly corroborates the 2023 effect-size direction while refining the conditions for success. Gholamahmadi et al. (2023) reported a 16% average erosion reduction and a 25% runoff reduction across 184 pairwise observations; Lu et al. (2024) reported a 27.86% soil-erosion reduction across 174 paired comparisons from 45 studies. The exact magnitudes differ due to data selection, response variables, and subgroup structure, but the direction is consistent: biochar often reduces water erosion, yet heterogeneity is high, so the practical recommendation cannot be an unconditional rate. Both syntheses identify an intermediate dose window, a stronger response in coarse or medium-textured soils, and the importance of study duration and field realism (Gholamahmadi et al., 2023; Lu et al., 2024). The newer synthesis strengthens confidence that biochar can be a legitimate soil conservation measure, while the combined evidence cautions against universal claims.

The second update is the rise of multi-year natural rainfall experiments. Laboratory rainfall simulations remain valuable because they control rainfall intensity, slope, and initial moisture, but they can miss antecedent soil moisture, seasonal vegetation dynamics, atmospheric-river events, crust recovery, aging, and cumulative traffic effects (Gholamahmadi et al., 2025a; Li et al., 2024b; Rončák et al., 2023; Zanutel et al., 2024b). Four-year Loess Plateau monitoring showed that biochar reduced annual runoff and soil loss, but its effectiveness depended on rainfall patterns: moderate and low rainfall events were more controllable than high-intensity, high-duration, high-erosivity events (Li et al., 2024b). Mediterranean vineyard box lysimeters monitored over a full hydrological cycle showed that biochar increased stored water during dry periods, reduced the runoff coefficient, and cut multiple erosion fractions, with atmospheric-river events highlighted as a reason why short simulations may bias inference (Gholamahmadi et al., 2025a). The methodological implication is clear: rainfall simulation remains necessary but insufficient.

The third update is a sharper mechanistic measurement. Earlier studies often measured runoff and sediment without enough information on aggregate stability, cohesion, pore structure, particle-size distribution, hydrophobicity, ash, pH, electrical conductivity, or vegetation cover. Recent studies increasingly quantify detachment capacity, rill erodibility, critical shear stress, mean weight diameter, total porosity, soil organic carbon, pore connectivity, structural connectivity, and hydrological connectivity (Bagarello et al., 2025; Conte et al., 2025; Li et al., 2025b; Li et al., 2025a; Zhao et al., 2025; Zanutel et al., 2024a). These endpoints are more diagnostic than runoff alone because they describe the soil's resistance to detachment under imposed hydraulic energy. For example, Zhao et al. (2025) identified total porosity, cohesion, mean weight diameter, and soil organic carbon as critical factors influencing detachment capacity and rill erodibility. Li et al. (2025b) found that mean weight diameter and cohesion dominated early after application, whereas total organic carbon became more important after three years. This temporal shift from physical aggregation to organic-carbon-mediated resistance is a promising hypothesis for long-term biochar function.

The fourth update is a stronger recognition of risk and trade-off. Some studies report that biochar can increase specific loss pathways or environmental risks. Maisyarah et al. (2023) found that nutrient loss from sloped biochar-amended soil followed the order percolation greater than surface runoff greater than soil erosion, and that the most effective high-temperature wood biochar treatment also raised concern about soluble phosphorus percolation. Xing et al. (2025) found that a 2% biochar concentration reduced ammonia nitrogen, total phosphorus, and erosion losses, but could increase export of particles smaller than 20 micrometers. Coelho et al. (2025) showed that feedstock and dose influence phytotoxicity and water ecotoxicity, with PAHs and salinity requiring pre-application screening. Chávez-García et al. (2023) reported broad improvements in tailings but also concerns about arsenic mobilization. Zi et al. (2025) observed reduced subsurface and underground fissure losses in karst while surface runoff and surface soil loss increased. These studies do not negate the conservation value of biochar; they define the safeguards required for responsible deployment.

The fifth update focuses on integrating biochar into plant and cropping-system resilience. The earlier meta-analysis inferred that vegetation cover was a key indirect mechanism because vegetated experiments reduced erosion more than bare-soil experiments (Gholamahmadi et al., 2023). Recent studies strengthen that inference. In Mediterranean vineyards, biochar increased vegetation cover and aboveground biomass while reducing runoff and erosion (Gholamahmadi et al., 2025b). In legume-rich pasture, biochar increased aboveground biomass by about 50% and shifted community structure toward legumes, likely through pH, potassium, and biological effects (Jongen et al., 2026). In acidic soils, a large meta-analysis found biochar increased soil pH and crop yield, with the strongest yield gains in tropical regions and strongly acidic soils (Zhang et al., 2025). In Malawi, rice-husk biochar improved growth and post-stress recovery of Hibiscus sabdariffa under water stress, and in the Andes, biochar-amended soils were framed as a water-saving strategy for quinoa production (Condori-Ataupillco et al., 2025; Mazibuko et al., 2025). Vegetation is therefore not a secondary outcome; it is part of the erosion-control mechanism.

Table 1. Updated evidence-based and mechanistic interpretation of biochar impacts on runoff, erosion, and soil sponge function.

Evidence strand	Context/design	Biochar or paired measure	Main hydrological/erosion outcomes	Mechanistic signal	Implication for the review	Ref.
Foundational global synthesis	Meta-analysis of runoff and water-erosion experiments	Biochar across climates, soils, rates and cover conditions	Runoff reduced by 25% and erosion by 16%; stronger erosion reduction in tropical settings; best response at intermediate topsoil concentration	Infiltration, structure and vegetation operate together	Defines the baseline and demonstrates the need for moderator-based recommendations	Gholamahmadi et al. (2023)
Recent meta-analysis	174 paired comparisons from 45 studies of rainfall-induced erosion	Biochar properties, soil properties and experimental conditions used as moderators	Overall erosion reduction of 27.86%; optimal range around 0.8-2%; stronger response in coarse-grained soils and long-term field studies	Dose, texture and duration govern response ratio	Corroborates the 2023 synthesis and narrows practical dose boundaries	Lu et al. (2024)
Natural rainfall field monitoring	Four years of runoff plots on the Loess Plateau	Apple-branch biochar at 0-7% in sloping farmland	Annual runoff reduced by 9-36% and annual soil loss by 43-79%, but effectiveness weakened during high-erosivity events	Rainfall pattern changes the runoff-soil loss relationship	Shows why multi-year natural rainfall is essential	Li et al. (2024b)
Mediterranean vineyard sponge function	18-month outdoor box lysimeters under natural rainfall	4% vineyard biochar in sandy loam vineyard soil	Runoff coefficient reduced by about 45%; fine-earth, coarse-fragment and splash erosion decreased; infiltration and stored water increased	Biochar strengthens soil sponge function and reduces multiple	Links full hydrological cycles with erosion response	Gholamahmadi et al. (2025a)

				erosion fractions		
Vegetated vineyard mechanism	Box lysimeters with biodiverse pasture mixture	Woody biochar in sandy loam vineyard soil	Runoff and fine-earth erosion decreased; infiltration, soil water content, vegetation cover and biomass increased	Plant cover and sponge function acted jointly	Supports vegetation-mediated erosion control	Gholamahmadi et al. (2025b)
Interrill erosion and aging	Fresh and century-old biochar in silt loam and sandy loam soils	1-2% fresh biochar and kiln-site old biochar	Old biochar increased time to runoff in sandy loam; 2% fresh biochar reduced final soil-loss rate	Aggregate resistance and soil type controlled response	Aging and soil texture must be separated in field design	Zanutel and Bielders (2023); Zanutel et al. (2024a)
Rill detachment modeling	Field-collected loess cores tested in flumes	Biochar rate and particle-size combinations	Biochar reduced detachment capacity and rill erodibility; larger particles performed better	Total porosity, cohesion, aggregate mean weight diameter and SOC predicted resistance	Links amendment design to rill-process equations	Zhao et al. (2025)
Karst flow partitioning	Three-year field monitoring in soil-mantled karst hillslopes	0, 1.36 and 2.72% biochar	Subsurface and underground losses decreased, but surface runoff and surface soil loss increased	Pore connectivity and aggregate disruption altered pathway routing	Karst systems require surface and subsurface accounting	Yin et al. (2024); Zi et al. (2025)
Biochar with mulch or filters	Rainfall simulations and riparian filter-strip experiments	Biochar plus straw mulch or vegetation filter strips	Mulch-containing treatments reduced runoff and interrill erosion; filter strips plus biochar stabilized nutrient reductions	Surface protection, adsorption and vegetation filtering interacted	Integrated conservation systems usually outperform bare biochar alone	Canedo et al. (2025); Li et al. (2025c); Prats et al. (2021)

Note: SOC = soil organic carbon; EC = electrical conductivity; PAHs = polycyclic aromatic hydrocarbons; CEC = cation exchange capacity. Rates are presented as reported in the cited literature.

1. Soil Sponge Function and Hydrological Partitioning

The term soil sponge function is useful because erosion begins with rainfall partitioning. If soil rapidly accepts rainfall, stores a larger fraction of water, and maintains infiltration during storms, both runoff volume and erosive power can decline. Biochar can support this pathway by reducing bulk density, increasing saturated water content, increasing macroporosity, altering pore-size distribution, and changing water-retention curves (Edeh et al., 2020; Omondi et al., 2016; Razzaghi et al., 2020; Zanutel et al., 2024a). The strongest recent evidence comes from studies that pair hydrological measurements with erosion outcomes. Gholamahmadi et al. (2025a) reported reduced runoff coefficients and erosion fractions, along with greater stored water and infiltration, in Mediterranean vineyard soil. Gholamahmadi et al. (2025b) similarly linked reduced runoff and fine-earth erosion with improved infiltration and soil water content in vegetated vineyard lysimeters. Dengxiao et al. (2024) showed that combining biochar with water-retaining agents increased water retention and drought resistance in Fluvisols. Si et al. (2025) extended the hydrological focus to rainwater redistribution, evaporation, and desiccation cracking in karst limestone soil. Collectively, these studies support the view of sponge function as a measurable mechanism rather than a metaphor.

However, the sponge function has two boundary conditions. First, extra infiltration is beneficial for erosion only if water is stored or transmitted without creating off-site nutrient or contaminant risks. Maisyarah et al. (2023) found that percolation accounted for the majority of soluble nutrient losses and warned that phosphorus movement through percolation must be considered even when runoff and erosion decrease. Second, infiltration pathways can be geomorphically specific. In karst, biochar may alter surface, subsurface, and underground fissure flow differently (Yin et al., 2024; Zi et al., 2025). A conservation treatment that reduces underground leakage may still be unacceptable if it increases surface detachment on soil-mantled hillslopes. Therefore, sponge-function evaluation should partition water into surface runoff, lateral subsurface flow, percolation, fissure flow, evapotranspiration, and storage rather than reporting runoff alone.

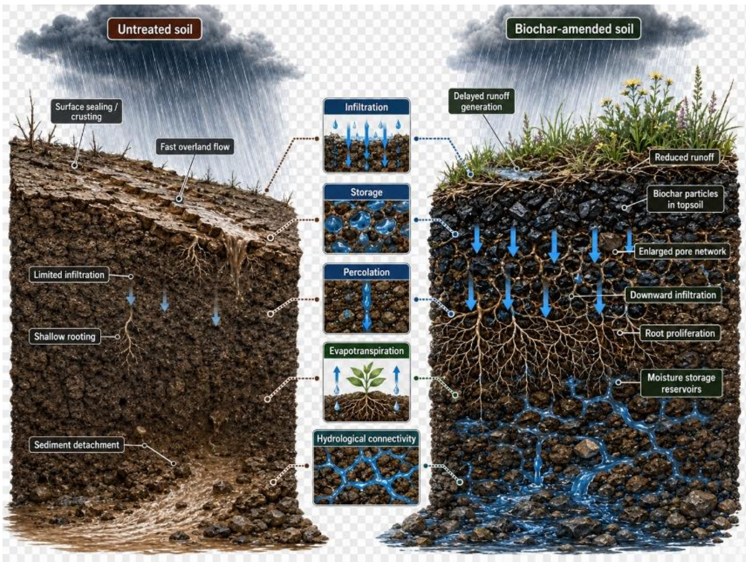

Figure 1. Biochar-induced reconfiguration of rainfall partitioning and soil sponge function.

2. Soil Structure, Aggregate Resistance and Erodibility

The most robust direct pathway is soil structural modification. Biochar can reduce bulk density and alter soil pore networks, but recent work suggests that its influence on physical properties often operates primarily through changes in soil structure rather than through biochar's internal porosity (Zanutel et al., 2024a). Fresh biochar in temperate silt loam and sandy loam decreased bulk density, increased saturated water content and increased macroporosity, whereas century-old biochar effects were mostly nonsignificant, possibly because of low contents or internal pore clogging (Zanutel et al., 2024a). Interrill experiments found that old biochar and 2% fresh biochar improved aggregate resistance to slaking in sandy loam, old biochar increased time to run off, and 2% fresh biochar reduced final soil loss rate (Zanutel & Bielders, 2023). Long-term kiln-site work then questioned whether century-old biochar consistently reduces interrill erodibility across cropland textures, underscoring the importance of soil type and biochar persistence (Zanutel et al., 2024b).

Rill and flume studies deepen this mechanistic view. Biochar affects detachment capacity, rill erodibility and critical shear stress through cohesion, mean weight diameter, soil organic carbon and aggregate stability (Li et al., 2025b; Li et al., 2025a; Zhao et al., 2025). The Loess Plateau studies are particularly important because loess soils are highly erodible and because the studies measured resistance under controlled flow rates and slopes. Zhao et al. (2025) found that larger biochar particles and higher rates significantly reduced detachment capacity and rill erodibility, with total porosity, cohesion, mean weight diameter and soil organic carbon as critical factors. Li et al. (2025b) showed that moderate rates after one to two years reduced detachment capacity, very high rates increased it, and after three years all treatments reduced detachment capacity relative to bare soil. Li et al. (2025a) linked rill erodibility and critical shear stress to cohesion, mean weight diameter and total organic carbon over three years. These findings argue for time-aware dose recommendations rather than one-time rate prescriptions.

3. Pore Architecture and Hydrological Connectivity

Pore architecture links sponge function with structural resistance. Nuclear magnetic resonance and hydrological measurements show that biochar can increase mesopores and micropores, influence structural connectivity, and affect functional connectivity differently depending on concentration (Bagarello et al., 2025; Conte et al., 2025). Bagarello et al. (2025) found that adding 5% biochar to rilled clay-loam soil increased the number of pores in key mesopore and micropore classes and generally improved the soil's ability to transmit water, although improvements were not always statistically significant for processes governed by larger pores. Conte et al. (2025) suggested that a target wood-biochar concentration of 5% mitigated rill erosion, improved structural connectivity, and did not appreciably modify functional connectivity; concentrations greater than 5% produced little additional change in pore distribution. These findings complement the meta-analytic observation that erosion control often peaks at intermediate rates (Gholamahmadi et al., 2023; Lu et al., 2024). Connectivity also explains why the same amendment can reduce one erosion pathway and intensify another. In karst, Zi et al. (2025) reported that biochar increased aggregate number, porosity, pore connectivity and tortuosity, reduced subsurface runoff and underground fissure flow, and sharply reduced subsurface and fissure-associated soil loss. Yet surface runoff and surface soil loss increased, probably because altered structure affected rainfall infiltration and transport efficiency and because native aggregate disruption increased surface detachment susceptibility (Zi et al., 2025). Yin et al. (2024) likewise framed karst biochar effects in terms of surface and underground runoff and soil loss rather than a single runoff endpoint. For precision management, the lesson is that hydrological connectivity must be interpreted in the landscape context. Enhanced connectivity can mean more storage and less erosive flow in one setting, but faster pathway activation in another.

4. Vegetation, Roots and Biological Feedback

Vegetation is the most plausible explanation for the difference between bare and vegetated responses observed in the 2023 meta-analysis. Vegetation reduces raindrop kinetic energy, increases surface roughness, improves root cohesion and supplies organic inputs that reinforce aggregation (Gholamahmadi et al., 2023; Smit et al., 2019). Biochar can amplify this pathway by increasing pH in acidic soils, improving potassium availability, retaining water and supporting microbial habitat (Jeffery et al., 2017; Jeffery et al., 2024; Jongen et al., 2026; Kammann & Graber, 2024; Zhang et al., 2025). The plant pathway is especially relevant where yield gaps, acidity, drought or nutrient constraints limit cover establishment. Tropical crop-yield responses to biochar were stronger than temperate responses in earlier syntheses, and a newer meta-analysis of acidic soils reports especially strong pH and yield effects in tropical regions and strongly acidic soils (Jeffery et al., 2017; Zhang et al., 2025).

Recent field evidence strengthens the root-cover hypothesis. Gholamahmadi et al. (2025b) found that biochar increased vegetation cover and aboveground biomass while reducing runoff and fine-earth erosion in Mediterranean vineyard soil. Jongen et al. (2026) found a strong boost in pasture productivity and legume biomass, with community composition shifts likely linked to pH and potassium availability. Zhao et al. (2024) combined ridge-furrow technology with biochar to enhance alfalfa yield and reduce erosion on sloping land, demonstrating that cropping architecture and amendments can be integrated. Mazibuko et al. (2025) reported improved growth and post-stress recovery in water-stressed hibiscus, while Condori-Ataupillco et al. (2025) framed biochar as a water-saving strategy for quinoa in low-rainfall Andean conditions. These findings indicate that erosion control should be assessed over plant growth cycles rather than only during rainfall events.

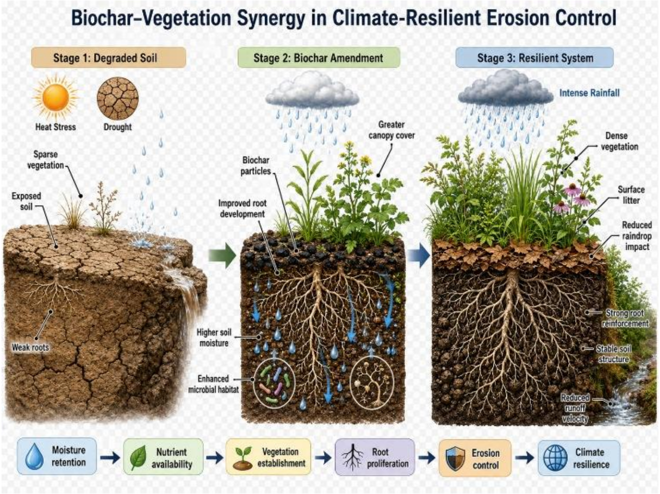

Figure 2. Biochar-vegetation synergy in climate-resilient erosion control.

5. Chemical Properties, Hydrophobicity and Ecotoxicity

Biochar chemistry can support or undermine erosion control. Alkalinity and ash can ameliorate acid soils and increase crop performance, but ash composition, soluble salts, pH, electrical conductivity and contaminants can alter aggregation, microbial activity, plant establishment, hydrophobicity and water quality (Coelho et al., 2025; Gholamahmadi et al., 2023; Mao et al., 2019; Prakongkep et al., 2013; Zornoza et al., 2016). The 2023 meta-analysis found stronger erosion reduction with biochar produced above 500 degrees C than with biochar produced at 300-500 degrees C, but also noted that temperature, ash, and feedstock interactions were difficult to separate due to reporting gaps (Gholamahmadi et al., 2023). Lu et al. (2024) reported more favorable erosion effects for some non-wood feedstocks and lower pyrolysis temperatures, illustrating that the literature does not yet support a universal temperature rule. The safer interpretation is that feedstock-temperature combinations should be selected to produce the physical and chemical properties required by the target soil.

Recent ecotoxicity and remediation studies clarify practical safeguards. Coelho et al. (2025) evaluated nine biochars and concluded that vineyard pruning and shredded Acacia biochars had lower toxicity, whereas olive pomace and vine-stalk alternatives require pre-application screening for PAHs and salinity. Chávez-García et al. (2023) reported that biochar generally improved bulk density, moisture, organic carbon and cation exchange capacity in arid-zone mine tailings, but arsenic risks and salinization from local feedstocks require attention. Henaut et al. (2026) found that vineyard by-product biochars reduced copper concentrations in leachates and pore water and improved plant growth in copper-contaminated vineyard soils. Marques et al. (2024) found that urban pruning waste biochar increased pH and strength in Brazilian Ultisol mixtures but raised concerns about leaching and permeability. These studies show that erosion control, restoration and remediation benefits can align, but only with quality control.

DISCUSSION

1. Boundary Conditions

1.1 Climate and Rainfall Regime

Climate influences biochar efficacy through rainfall erosivity, antecedent moisture, drying-rewetting cycles, vegetation response, and soil constraints. The 2023 meta-analysis found that erosion reduction in tropical latitudes was about three times stronger than in temperate latitudes, while runoff reduction was significant mainly in temperate studies (Gholamahmadi et al., 2023). One likely explanation is that tropical soils and crops often have more room for biochar-induced improvements in plant growth, pH, and soil function, allowing vegetation-mediated erosion control to be stronger (Glaser et al., 2002; Jeffery et al., 2017; Zhang et al., 2025). Another explanation is methodological: tropical studies in the earlier dataset were more often field-based, longer, and exposed to natural rainfall, whereas temperate studies included more short laboratory experiments (Gholamahmadi et al., 2023). The newer literature, with more field studies in Mediterranean, Loess Plateau, karst, and subtropical systems, should allow future meta-analysis to separate climate from experimental design (Gholamahmadi et al., 2025a; Li et al., 2024b; Yin et al., 2024; Zi et al., 2025).

Rainfall pattern matters as much as the climate zone. Li et al. (2024b) showed that runoff and soil-loss reductions differed among rainfall clusters, and that high-depth, high-duration, high-erosivity events remained challenging even with biochar. Gholamahmadi et al. (2025a) emphasized atmospheric-river events and antecedent moisture in Mediterranean vineyards. Liu et al. (2025) and Liu et al. (2026) show why these matters: rainfall erosivity estimation and projection are themselves changing research frontiers, and erosion-control measures must be evaluated under the extreme-event regimes that will dominate risk. Biochar is not a substitute for runoff routing, terracing, ground cover, or catchment-scale planning under extreme rainfall; it is one component of a portfolio whose effectiveness depends on storm structure.

1.2 Soil Texture, Structure and Initial Degradation State

Soil texture repeatedly emerges as a moderator. The 2023 meta-analysis found significant erosion reductions in medium and coarse-textured soils but not in fine-textured soils, and Lu et al. (2024) found the highest reduction in coarse-grained soils and insignificant effects in fine-grained soils. Coarse-textured soils may benefit more from increases in water retention and aggregation, whereas fine-textured soils may be controlled by swelling, crusting, dispersion, shrink-swell dynamics or macropore continuity (Gholamahmadi et al., 2023; Lu et al., 2024; Razzaghi et al., 2020). However, the texture rule is not absolute. Bagarello et al. (2025) found that biochar affected hydraulic properties in a clay-loam rill context, and Si et al. (2025) examined limestone soils in karst areas. Therefore, texture should be reported with structure, bulk density, organic carbon, aggregate stability, crusting susceptibility and hydrophobicity.

Initial degradation state also matters. Compacted vineyard soils, mine tailings, post-mining land, wildfire-degraded soils, erodible loess, karst hillslopes and acidic tropical soils respond through different constraints (Chávez-García et al., 2023; De Francesco et al., 2025; Junaidi et al., 2023;

Prats et al., 2021; Zhao et al., 2025; Zi et al., 2025). In severely degraded soils, biochar may simultaneously reduce bulk density, improve water retention, provide pH buffering and support vegetation establishment. In already well-structured soils, the marginal effect may be smaller, and risks such as nutrient leaching or hydrophobicity may dominate. This is why universal rate recommendations are weaker than diagnostic recommendations based on baseline soil function.

1.3 Dose, Placement and Elapsed Time

Dose is the most actionable design variable, but it is also the easiest to misuse. The convergence between the 0.6-2.5% optimum in the 2023 meta-analysis and the 0.8-2% optimum in Lu et al. (2024) provides a reasonable starting hypothesis for mineral topsoils, especially when the goal is erosion control rather than maximum carbon addition (Gholamahmadi et al., 2023; Lu et al., 2024). Yet individual studies show exceptions. Gholamahmadi et al. (2025a) applied 4% biochar to Mediterranean vineyard soil and reported significant hydrological and erosion benefits. Zhao et al. (2025) found pronounced reductions in detachment and rill erodibility at 4% in loss. Conte et al. (2025) identified a 5% target for rill erosion and structural connectivity. At the same time, Li et al. (2025b) found that very high rates could increase detachment capacity during early years, and the 2023 meta-analysis found no significant benefit at high topsoil concentrations (Gholamahmadi et al., 2023; Li et al., 2025b). The dose-response curve is therefore shaped by soil, biochar particle size, incorporation depth, rainfall and time.

Placement is equally important. Shallow incorporation generally targets the layer where raindrop impact, crusting, infiltration and interrill detachment are initiated, and the 2023 meta-analysis reported stronger erosion and runoff reductions with shallower application depths (Gholamahmadi et al., 2023). Surface-layer strategies can work when biochar is combined with mulch, but exposed light biochar can also be mobilized by runoff or wind if not stabilized (Canedo et al., 2025; Prats et al., 2018; Prats et al., 2021). In rill studies, the location of biochar relative to flow incision affects pore connectivity and sediment-biochar export (Bagarello et al., 2025; Conte et al., 2025). A practical rule is to place biochar where the limiting process occurs: near the surface for crusting and interrill erosion, within the root zone for sponge function and plant establishment, and in combination with surface cover where raindrop impact dominates.

Elapsed time deserves special attention. Some effects appear quickly because bulk density, pore distribution, pH and water retention change immediately after incorporation (Gholamahmadi et al., 2025a; Zanutel et al., 2024a). Other effects develop over seasons as roots, microbial activity, aggregate stability and organic-carbon associations respond (Amoakwah et al., 2020; Li et al., 2025a; Li et al., 2025b). Still others decay or become nonsignificant as biochar ages, pores clog, traffic compacts the soil or the amendment is diluted in the profile (De Francesco et al., 2025; Zanutel et al., 2024a; Zanutel et al., 2024b). Future experiments should therefore distinguish immediate physical effects, growing-season biological effects and multi-year aging effects.

2 Integrated Soil Conservation Systems

The recent literature increasingly shows that biochar is most credible when integrated with other soil conservation practices. Mulch provides surface protection, reduces raindrop impact, slows flow and directly cuts sediment detachment. Fan et al. (2023) reported that mulching reduced runoff and soil loss by 47.4% and 76.2%, respectively, on average across a global meta-analysis. Canedo et al. (2025) found that mulch-containing treatments produced the largest reductions in runoff and interrill erosion in vineyard and olive-orchard soils, and that the mulch plus biochar treatment performed best overall. Vahidi et al. (2025) found that organic amendments reduced erosion and that biochar was particularly effective as a surface mulch, with benefits increasing over time. Prats et al. (2021) showed that straw-biochar mulching can mitigate erosion from wildfire-degraded soils during extreme rainfall events. These studies suggest that biochar should often be paired with a protective surface layer rather than applied alone to bare soil.

Vegetation filter strips represent another integrated strategy. Li et al. (2025c) examined vegetation filter strips with biochar under continuous rainfall and found that the combination achieved stable reductions in nitrogen and phosphorus losses across repeated events. This is significant because filter strips alone can lose efficiency under prolonged rainfall, and because nutrient loss can shift from sediment-associated pathways to soluble runoff or subsurface flow (Li et al., 2025c; Maisyarah et al., 2023). Biochar in filter strips can increase retention and reduce nutrient concentrations, while vegetation provides roughness, root macropores, and nutrient uptake. However, root-induced macropore flow can complicate surface-runoff control, so the system should be monitored for both surface and subsurface nutrient pathways (Li et al., 2025c; Nuruzzaman et al., 2025).

Cropping-system design can also amplify biochar effects. Ridge-furrow technology combined with biochar improved alfalfa yield and reduced erosion on sloping land, illustrating that microtopography, water harvesting and soil amendment can be designed together (Zhao et al., 2024). Pasture studies show that biochar can alter functional group dominance and legume abundance, with implications for livestock nutrition and soil cover in Mediterranean systems (Jongen et al., 2026; Pierini et al., 2026). Vineyard studies demonstrate that biochar can improve the soil sponge function and vegetation cover in high-value perennial systems exposed to Mediterranean drought and extreme rainfall (Gholamahmadi et al., 2025a; Gholamahmadi et al., 2025b; Henaut et al., 2026). These examples point toward land-use-specific biochar design rather than generic soil amendment.

Restoration and remediation contexts expand the conservation value but require stronger safeguards. In mine tailings, arid-zone reclamation and post-coal-mining land, biochar can improve physical conditions and plant growth, but metal mobility, salinity and local feedstock chemistry may determine acceptability (Chávez-García et al., 2023; Junaidi et al., 2023). In copper-contaminated vineyards, vineyard by-product biochar reduced copper levels in leachate and pore water, restoring plant growth and enzymatic activity (Henaut et al., 2026). In Brazilian Ultisol mixtures, urban pruning biochar improved pH and strength but increased permeability, highlighting leaching concerns (Marques et al., 2024). In diffuse agricultural pollution, biochar-based interventions must be evaluated alongside nutrient management, pesticide reduction, runoff control and monitoring of sedimentation and leaching pathways (Nuruzzaman et al., 2025; Xing et al., 2025). A top-tier conservation framework must therefore treat water erosion, water quality and contaminant mobility as connected outcomes.

3 Trade-offs and Safeguards

The first safeguard is feedstock and production screening. Biochar is not a single material. Feedstock controls ash, mineral nutrients, contaminants and structure; pyrolysis temperature controls aromaticity, surface chemistry, hydrophobicity, pH and stability; post-processing controls particle size and dust; and storage or activation can alter soluble compounds (Ali et al., 2024; Coelho et al., 2025; Nguyen et al., 2024; Prakongkep et al., 2013; Qin et al., 2017; Zornoza et al., 2016). Coelho et al. (2025) show why these matters for restoration: wood-derived biochars were safer in tested soils, while olive pomace and vine-stalk alternatives required PAH and salinity screening. The older hydrophobicity literature similarly cautions that water repellency can be shaped by pyrolysis conditions and may interact with soil water retention (Mao et al., 2019; Zornoza et al., 2016). Screening should include pH, electrical conductivity, ash, particle-size distribution, volatile or labile compounds, PAHs, potentially toxic elements and water-extractable nutrients.

The second safeguard is pathway accounting. A treatment that reduces sediment loss may increase dissolved nutrient loss, fine-particle export or subsurface transfer. Maisyarah et al. (2023) found that percolation was the dominant pathway for soluble nutrient loss in biochar-treated sloped sandy soil, and Xing et al. (2025) found that biochar reduced several nutrient losses but could increase the loss of particles smaller than 20 micrometers. Li et al. (2025c) found that vegetation filter strips combined with biochar stabilized nutrient reduction under continuous rainfall but also highlighted surface-subsurface interactions. Zi et al. (2025) showed that karst surface and subsurface pathways can respond in opposite directions. Therefore, erosion experiments should measure sediment fractions, particle-size distribution, dissolved carbon, nitrogen and phosphorus, exchangeable potassium, total suspended solids, leachate chemistry and groundwater-relevant losses where appropriate.

The third safeguard is rate discipline. High biochar rates may be useful in particular engineered contexts, but meta-analyses and field studies warn against assuming more is always better (Gholamahmadi et al., 2023; Lu et al., 2024). High rates can reduce bulk density and increase porosity, but they can also alter contact among mineral particles, reduce cohesion, increase biochar export, change infiltration pathways, induce hydrophobicity or elevate salinity and pH beyond the crop optimum (Coelho et al., 2025; Li et al., 2025b; Mao et al., 2019; Zornoza et al., 2016). The practical starting point should be a mechanistically justified dose range, adjusted by soil texture, initial organic matter, crop system, target depth and biochar density, rather than a fixed mass per hectare copied across soils.

The fourth safeguard is long-term monitoring. Short-term studies can overestimate benefits if they capture immediate porosity changes before traffic, aging or pore clogging; they can underestimate benefits if they miss root development, aggregate stabilization and organic-carbon accumulation (De Francesco et al., 2025; Li et al., 2025a; Li et al., 2025b; Zanutel et al., 2024a; Zanutel et al., 2024b). Gholamahmadi et al. (2025a) recommend monitoring over a full hydrological cycle to capture seasonal and atmospheric-river effects in Mediterranean vineyards. Li et al. (2024b) show that four-year rainfall clusters reveal event dependence that short simulations would miss. Future field trials should therefore include pre-treatment baselines, immediate post-application measurements, at least one full hydrological cycle, and ideally multi-year monitoring through vegetation development and amendment aging.

4 Future Reporting and Synthesis Needs

The field now needs a reporting standard. The 2023 meta-analysis emphasized that interactions among predictor variables were difficult to test because auxiliary variables were patchily reported (Gholamahmadi et al., 2023). A new Mediterranean organic-matter meta-analysis similarly highlights how heterogeneity can be driven by methodology, scale and timing (Avikasis Cohen et al., 2026). Future studies should report biochar feedstock, pyrolysis temperature, residence time, ash, pH, electrical conductivity, particle-size distribution, specific surface area where available, bulk density of the biochar, application rate in both mass per area and soil concentration, incorporation depth, soil texture, soil organic carbon, pH, bulk density, slope, rainfall intensity or natural rainfall event structure, antecedent moisture, vegetation cover and study duration (Gholamahmadi et al., 2023; Lu et al., 2024; Schmidt et al., 2021). Without these variables, meta-analysis can estimate average effects but cannot identify design rules.

Measurement should also shift from endpoint-only runoff and soil loss to mechanism-rich monitoring. The most useful response set includes runoff coefficient, time to runoff, infiltration, stored water, percolation, soil water retention, bulk density, aggregate stability, mean weight diameter, cohesion, critical shear stress, detachment capacity, rill erodibility, splash loss, fine-earth and coarse-fragment erosion, sediment particle-size distribution, vegetation cover, biomass, root traits and nutrient losses (Bagarello et al., 2025; Gholamahmadi et al., 2025a; Li et al., 2025b; Li et al., 2025a; Maisyarah et al., 2023; Zhao et al., 2025; Zanutel & Bielders, 2023). Such measurements allow researchers to ask whether biochar reduced erosion by reducing runoff, reducing detachment at a given flow, increasing cover, altering sediment availability, or shifting flow into another pathway.

Scale is the next challenge. Plot and lysimeter experiments are essential, but hillslope and catchment responses can differ due to flow convergence, rill network formation, macropore connectivity, topographic position, land use, and management operations (de Pagter et al., 2026; Guo et al., 2024; Wang et al., 2025). UAV-based erosion assessment in Mediterranean orchards offers one route for bridging plot experiments and spatially explicit monitoring, especially when treatments such as mulch and biochar are applied in heterogeneous perennial systems (de Pagter et al., 2026). Machine learning can support rainfall erosivity fusion and biochar production prediction, but it should be used to improve interpretability and design rather than replace field mechanisms (Liu et al., 2026; Nguyen et al., 2024). Explainable modeling is especially relevant because biochar properties are high-dimensional and interact with soil and climate variables.

Meta-analysis should also evolve. Random-effects response-ratio models remain useful for average effects, but the next synthesis should use multilevel models, hierarchical moderators and interaction terms that distinguish laboratory simulations, natural rainfall, study duration, land use, climate zone, soil texture, biochar rate, application depth, vegetation cover and co-amendment (Lu et al., 2024; Tufanaru et al., 2015). It should also separate runoff, interrill loss, rill detachment, splash, coarse fragments, fine particles, dissolved nutrient losses, subsurface runoff and groundwater-relevant percolation. This would prevent a single effect size from hiding mechanism-specific trade-offs.

5 Precision Framework

A precision framework begins with diagnosis. The practitioner should identify whether the dominant problem is infiltration-excess runoff, saturation-excess runoff, surface crusting, interrill detachment, rill incision, wind or traffic compaction, nutrient loss, acidity-limited vegetation, drought-limited cover, contaminant toxicity, or subsurface leakage. Biochar is best matched to problems involving poor structure, low organic carbon, low water retention, acidity, weak vegetation establishment and erodible aggregates (Blanco-Canqui, 2017; Gholamahmadi et al., 2023; Lu et al., 2024; Zhang et al., 2025). It is less likely to be sufficient alone when extreme rainfall, steep slopes, concentrated flow, or exposed bare soil dominate, without complementary cover or runoff routing (Fan et al., 2023; Li et al., 2024b; Prats et al., 2021; Vahidi et al., 2025).

The second step is material selection. For acidic, low-fertility soils, alkaline biochars that improve pH and nutrient availability may increase plant cover and root reinforcement, especially in tropical or strongly acidic systems (Glaser et al., 2002; Jeffery et al., 2017; Zhang et al., 2025). For structural erosion in coarse or medium-textured soils, biochars that improve aggregate stability, cohesion and water retention without excessive salinity or hydrophobicity are preferred (Gholamahmadi et al., 2023; Lu et al., 2024; Zanutel et al., 2024a). For contaminated or restored soils, sorptive capacity and contaminant immobilization matter, but arsenic, copper, PAHs and leaching risks must be screened (Chávez-García et al., 2023; Coelho et al., 2025; Henaut et al., 2026; Marques et al., 2024). In arid, drought-prone cropping systems, water retention and plant stress recovery may be key (Condori-

Ataupillco et al., 2025; Dengxiao et al., 2024; Mazibuko et al., 2025).

The third step is rate and placement. For many mineral topsoil applications, 0.8-2% by mass can be treated as an initial design window because it is supported by independent meta-analytic evidence (Gholamahmadi et al., 2023; Lu et al., 2024). This is not a ceiling or a rule. Vineyard, loess and rill-connectivity studies show that 4-5% may be effective in selected contexts, while high mass-per-hectare rates can be harmful early after application in others (Conte et al., 2025; Gholamahmadi et al., 2025a; Li et al., 2025b; Zhao et al., 2025). Application should be shallow enough to affect the topsoil processes that drive runoff and interrill detachment but incorporated enough to avoid biochar export unless intentionally used as part of a protected mulch layer (Canedo et al., 2025; Gholamahmadi et al., 2023; Prats et al., 2018).

The fourth step is pairing with vegetation and surface cover. Biochar should rarely be the only conservation measure on erosion-prone slopes. Cover crops, pasture mixtures, straw mulch, vegetation filter strips, ridge-furrow systems and wildfire mulch can provide the immediate surface protection that biochar alone may not supply (Canedo et al., 2025; Fan et al., 2023; Jongen et al., 2026; Li et al., 2025c; Prats et al., 2021; Zhao et al., 2024). Biochar can then play a slower role in improving the soil environment that sustains cover, roots, and water storage. This temporal complementarity is one of the most promising directions for management.

The fifth step is monitoring. A minimum monitoring package should include baseline and post-application bulk density, aggregate stability, infiltration, water retention, runoff, sediment, vegetation cover and soil pH. Where water quality matters, it should include dissolved nitrogen, phosphorus, organic carbon and sediment particle size. Where contamination matters, it should include leachate metals or organics. Where karst or deep drainage matters, it should partition surface and subsurface pathways (Li et al., 2025c; Maisyarah et al., 2023; Zi et al., 2025). The monitoring period should include at least one full hydrological cycle and, preferably, multiple years (Gholamahmadi et al., 2025a; Li et al., 2024b; Li et al., 2025a).

Table 2. Precision application, safeguards and reporting priorities for biochar-based soil and water conservation.

Target setting and dominant problem	Recommended strategy, rate, and placement	Key expected outcome	Required safeguards and monitoring	Ref.
Mediterranean vineyards and orchards with seasonal drought, intense rainfall, and bare inter-rows	Use woody or vineyard-residue biochar integrated with vegetation or mulch; shallow incorporation or protected surface layer; test 2–4% soil concentration where justified	Higher infiltration, greater stored water, improved vegetation cover, and reduced runoff and erosion fractions	Monitor atmospheric-river events, antecedent moisture, vegetation cover, runoff response, sediment loss, and leachate chemistry	Gholamahmadi et al. (2025a); Canedo et al. (2025)
Loess Plateau and similar erodible silt loams with high detachment capacity, rill erosion, and event-dependent runoff	Apply local biochar with controlled rate and particle size; use moderate rates initially; avoid excessive rates until aging effects are known; test 1–4% and relevant particle-size classes	Lower detachment capacity, reduced rill erodibility, increased cohesion, and lower soil loss	Measure cohesion, mean weight diameter, soil organic carbon, critical shear stress, rill erodibility, and response to high-erosivity storms	Li et al. (2024b); Li et al. (2025a); Zhao et al. (2025)

Karst hillslopes with dual surface–underground runoff and fissure-associated soil loss	Use biochar only with pathway-specific water accounting and complementary vegetation or surface cover; apply small to moderate rates; avoid assuming that higher infiltration always reduces surface erosion	Potential reduction in subsurface runoff, underground fissure flow, and subsurface soil loss	Monitor surface runoff, underground flow, fissure flow, pore connectivity, aggregate disruption, and surface soil loss	Yin et al. (2024); Zi et al. (2025)
Acidic tropical or subtropical croplands with low pH, yield gap, and poor cover establishment	Use alkaline, nutrient-supportive biochar matched to crop requirement and soil pH; apply low-to-moderate topsoil concentration with root-zone incorporation	Higher crop cover, improved root development, better soil pH, and indirect erosion control through vegetation reinforcement	Avoid overliming and salinity; monitor pH, CEC, biomass, nutrient balance, crop response, and vegetation cover	Jeffery et al. (2017); Zhang et al. (2025)
Riparian buffers and drainage margins with nitrogen and phosphorus transfer during repeated rainfall	Combine biochar with vegetation filter strips; apply biochar within the filter-strip matrix; tested rates include 30–90 t ha^{-1}	More stable reduction of nutrient losses than vegetation alone, especially under repeated rainfall events	Monitor dissolved nitrogen and phosphorus, surface runoff, subsurface runoff, macropore bypass, and filter-strip performance over time	Li et al. (2025c); Nuruzzaman et al. (2025)
Wildfire-degraded or bare slopes with hydrophobic surface, exposed ash, and intense raindrop impact	Use straw-biochar mulch or protective organic mulch combinations; prioritize surface protection rather than unprotected biochar exposure	Reduced raindrop impact, lower runoff velocity, improved surface protection, and reduced postfire sediment loss	Monitor biochar export, ash interaction, runoff generation, sediment detachment, and erosion response under extreme rainfall	Prats et al. (2018); Prats et al. (2021)
Compacted perennial systems with machinery-induced bulk-density increase and reduced porosity	Use biochar as part of traffic and cover management, not as a stand-alone solution; incorporate before traffic trials; compare 16–32 Mg ha^{-1} or local equivalent rates	Short-term buffering of compaction and potential improvement in soil porosity and infiltration	Monitor repeated machinery passes, slope position, soil moisture, bulk density, penetration resistance, and persistence over several years	De Francesco et al. (2025)
Contaminated soils and mine tailings with poor structure, low fertility, and metal toxicity	Use screened biochar with high sorption capacity and low contaminant risk; determine dose based on pH, EC, metal mobility, and plant bioassays	Improved moisture retention, organic carbon, CEC, plant establishment, and contaminant immobilization	Screen for arsenic, PAHs, salinity, leaching risk, ecotoxicity, and plant response before field-scale application	Chávez-García et al. (2023); Coelho et al. (2025); Henaut et al. (2026)

Minimum reporting standard for future studies where patchy metadata limits synthesis and transferability	Report feedstock, pyrolysis conditions, rate, depth, soil properties, rainfall characteristics, vegetation cover, and study duration; use both mass per area and soil concentration	Improved comparability across studies and stronger basis for meta-analysis, design rules, and precision recommendations	Measure runoff, sediment, infiltration, storage, erodibility, nutrients, vegetation, application depth, and surface exposure	Gholamahmadi et al. (2023); Lu et al. (2024)

6 Research Agenda

The priority is factorial field experimentation. The field needs experiments that cross biochar rate, particle size, feedstock, pyrolysis condition, application depth and vegetation cover under natural rainfall. The older literature contained many comparisons but limited interaction testing, and the newer literature demonstrates that interactions are where the useful design rules lie (Gholamahmadi et al., 2023; Lu et al., 2024; Zhao et al., 2025). Factorial designs should be conducted in course, medium and fine-textured soils; humid, Mediterranean, arid, tropical and karst climates; and land uses including cropland, vineyards, orchards, pastures, postfire hillslopes and mine tailings.

The second priority is process partitioning. Studies should report whether biochar reduces rainfall-runoff generation, detachment under a given flow, sediment transport capacity, splash detachment, rill incision, soluble nutrient export or subsurface flow. This requires combining rainfall simulation, natural rainfall monitoring, flume tests, aggregate tests, pore imaging, NMR or CT where feasible, plant measurements and water-quality analysis (Bagarello et al., 2025; Conte et al., 2025; Gholamahmadi et al., 2025a; Maisyarah et al., 2023; Zhao et al., 2025; Zi et al., 2025). The reward is a predictive framework that can explain why biochar reduces erosion in one soil but increases a loss pathway in another.

The third priority is temporal dynamics. Immediate effects, one-season effects and three-year effects differ. Cohesion and mean weight diameter may dominate early rill-resistance response, while total organic carbon may become more important later (Li et al., 2025a; Li et al., 2025b). Traffic can erase short-term compaction benefits (De Francesco et al., 2025). Century-old biochar may not preserve the same detectable physical effects observed after fresh application (Zanutel et al., 2024a; Zanutel et al., 2024b). Therefore, biochar erosion trials should be designed as time-series studies rather than one-time tests.

The fourth priority is integrated conservation economics and sustainability. Biochar competes with other biomass uses, and high rates can be expensive. Locally available feedstocks can support circular agriculture, but they may pose risks of salinity, PAH, metal, or nutrient release (Chávez-García et al., 2023; Coelho et al., 2025; Farré & Hoshide, 2025; John et al., 2025). Life-cycle benefits depend on carbon stability, production energy, transport distance, avoided erosion, water savings, yield response and pollution reduction (Ali et al., 2024; Bruckman et al., 2015; Schmidt et al., 2021; Ullah et al., 2024). Precision biochar should therefore be judged not only by sediment reduction per plot, but by the ratio of ecosystem-service benefits to cost, risk and biomass demand.

CONCLUSION

The literature now supports a balanced conclusion: biochar can be an effective tool for reducing runoff and water erosion, but only when designed for the soil, climate, vegetation system and erosion pathway. The 2023 global meta-analysis established the first direct quantitative baseline, showing average reductions in runoff and erosion, and identified tropical settings, intermediate topsoil concentration, shallow application, and medium-to-coarse texture and vegetation cover as favorable conditions (Gholamahmadi et al., 2023). Recent meta-analysis and field studies strengthen this picture, with evidence of roughly 28% erosion reduction in synthesis, multi-year runoff and soil-loss reductions on the Loess Plateau, and strong Mediterranean vineyard improvements in runoff coefficient, infiltration, water storage, erosion fractions and vegetation cover (Gholamahmadi et al., 2025a; Gholamahmadi et al., 2025b; Li et al., 2024b; Lu et al., 2024).

The deepest insight from the updated evidence is that biochar works through a sponge-stability-vegetation nexus. It can improve rainfall acceptance and storage, increase aggregate and rill-flow resistance, and promote vegetation that reduces raindrop energy and reinforces soil. Yet those mechanisms can also generate trade-offs: phosphorus percolation, fine-particle export, hydrophobicity, salinity, ecotoxicity, high-rate detachment increases, traffic-related compaction and karst surface-flow responses all require monitoring (Coelho et al., 2025; De Francesco et al., 2025; Li et al., 2025b; Maisyarah et al., 2023; Xing et al., 2025; Zi et al., 2025). The next generation of biochar erosion research should therefore abandon generic amendment claims and adopt precision design, mechanism-rich reporting and multi-year field validation. Biochar is not a replacement for vegetation, mulch, contour management or runoff control; it is a complementary amendment that can make these measures more durable by improving the soil environment that supports them.

Declaration by Authors

Acknowledgement: None

Source of Funding: None

Conflict of Interest: No conflicts of interest declared.

REFERENCES

1. Ali, B., Razak, S. A., Arshad, A., Javed, M. A., Batool, R., Hafeez, A., Ali, S., Khan, M. N., Singh, N., Garhwal, V., & Fahad, S. (2024). Biochar: an overview. https://doi.org/10.1016/B978-0-443-24137-6.00001-X
2. Amoakwah, E., Arthur, E., Frimpong, K.A., Parikh, S.J., & Islam, R. (2020). Soil organic carbon storage and quality are impacted by corn cob biochar application on a tropical sandy loam. Journal of Soils and Sediments, 20(4), 1960-1969. https://doi.org/10.1007/s11368-019-02547-5
3. Avikasis Cohen, T., Cotlier, G., Daliakopoulos, I., Zdruli, P., Baram, S., & Brook, A. (2026). Methodological advancements in soil erosion: a meta-analysis of organic matter content and erosion in the Mediterranean region. https://doi.org/10.1016/j.catena.2026.109793
4. Bagarello, V., Conte, P., Ferro, V., Iovino, M., Librici, C., Nicosia, A., Palmeri, V., Pampalone, V., & Zanna, F. (2025). How Rilling and Biochar Addition Affect Hydraulic Properties of a Clay-Loam Soil. https://doi.org/10.1111/ejss.70034
5. Barrow, C.J. (2012). Biochar: Potential for countering land degradation and for improving agriculture. Applied Geography, 34, 21-28. https://doi.org/10.1016/j.apgeog.2011.09.008
6. Beesley, L., Moreno-Jiménez, E., Gomez-Eyles, J.L., Harris, E., Robinson, B., & Sizmur, T. (2011). A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. Environmental Pollution, 159(12), 3269-3282. https://doi.org/10.1016/j.envpol.2011.07.023
7. Blanco-Canqui, H. (2017). Biochar and soil physical properties. Soil Science Society of America Journal, 81(4), 687-711. https://doi.org/10.2136/sssaj2017.01.0017
8. Blanco-Canqui, H. (2019). Biochar and water quality. Journal of Environmental Quality, 48(1), 2-15. https://doi.org/10.2134/jeq2018.06.0248
9. Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., Bagarello, V., Oost, K.V., Montanarella, L., & Panagos, P. (2017). An assessment of the global impact of 21st century land use change on soil erosion. Nature Communications, 8(1). https://doi.org/10.1038/s41467-017-02142-7

10. Borrelli, P., Robinson, D.A., Panagos, P., Lugato, E., Yang, J.E., Alewell, C., Wuepper, D., Montanarella, L., & Ballabio, C. (2020). Land use and climate change impacts on global soil erosion by water (2015-2070). Proceedings of the National Academy of Sciences of the United States of America, 117(36), 21994-22001. https://doi.org/10.1073/pnas.2001403117
11. Bruckman, V.J., Terada, T., Uzun, B.B., Apaydin-Varol, E., & Liu, J. (2015). Biochar for Climate Change Mitigation: Tracing the in-situ Priming Effect on a Forest Site. Energy Procedia, 76, 381-387. https://doi.org/10.1016/j.egypro.2015.07.845
12. Canedo, J. N. G. V., Coelho, L., Castro, L., Verheijen, F. G. A., & Prats, S. (2025). Biochar and Mulch: Hydrologic, Erosive, and Phytotoxic Responses Across Different Application Strategies and Agricultural Soils. https://doi.org/10.3390/agronomy15040926
13. Chávez-García, E., González-Méndez, B., & Molina-Freaner, F. (2023). Biochar application on mine tailings from arid zones: Prospects for mine reclamation. https://doi.org/10.1016/j.jaridenv.2023.105040
14. Coelho, L., Canedo, J., Custódio, M., Flores, D., Mourão, P., Palma, P., & Prats, S. (2025). Feedstock and pyrolysis conditions of biochars: influence on soil phytotoxicity and water ecotoxicity. https://doi.org/10.1016/j.soilbio.2025.109935
15. Condori-Ataupillco, T., Flores-Marquez, R., Quispe, K., Quispe-Rodriguez, J., Velásquez-Mantari, J., & Solórzano-Acosta, R. (2025). Biochar-Amended Soils: A Water-Saving Strategy for Quinoa Cultivation in the Andes. https://doi.org/10.1002/sae2.70036
16. Conte, P., Librici, C., Nicosia, A., Palmeri, V., Pampalone, V., & Ferro, V. (2025). Wood-Biochar Influence on Rill Erosion Processes and Hydrological Connectivity in Amended Soils. https://doi.org/10.1002/hyp.70093
17. De Francesco, F., Mastrolonardo, G., Fantoni, G., Ungaro, F., & Baronti, S. (2025). Can Biochar Alleviate Machinery-Induced Soil Compaction? A Field Study in a Tuscan Vineyard. https://doi.org/10.3390/soilsystems9030081
18. de Pagter, T., Canedo, J. N. G. V., Pijl, A., Coelho, L., Nunes, J. P., & Prats, S. (2026). UAV-Based Soil Erosion Assessment in Mediterranean Agricultural Orchards. https://doi.org/10.3390/agronomy16060645
19. Dengxiao, Z., Hongbin, J., Wenjing, Z., Qingsong, Y., Zhihang, M., Haizhong, W., Wei, R., Shiliang, L., & Daichang, W. (2024). Combined biochar and water-retaining agent application increased soil water retention capacity and maize seedling drought resistance in Fluvisols. https://doi.org/10.1016/j.scitotenv.2023.167885
20. Edeh, I.G., Mašek, O., & Buss, W. (2020). A meta-analysis on biochar's effects on soil water properties – New insights and future research challenges. Science of the Total Environment, 714. https://doi.org/10.1016/j.scitotenv.2020.136857
21. Fan, D., Jia, G., Wang, Y., & Yu, X. (2023). The effectiveness of mulching practices on water erosion control: A global meta-analysis. https://doi.org/10.1016/j.geoderma.2023.116643
22. Farré, N. S., & Hoshide, A. K. (2025). Formiguer Fertilization: Historical Agricultural Biochar Use in Catalonia and Its Modern-Day Resource Implications. https://doi.org/10.3390/resources14080120
23. Gholamahmadi, B., Jeffery, S., Gonzalez-Pelayo, O., Prats, S. A., Bastos, A. C., Keizer, J. J., & Verheijen, F. G. A. (2023). Biochar impacts on runoff and soil erosion by water: A systematic global scale meta-analysis. Science of the Total Environment, 871, 161860. https://doi.org/10.1016/j.scitotenv.2023.161860
24. Gholamahmadi, B., Ferreira, C. S. S., Gonzalez-Pelayo, O., Bastos, A. C., & Verheijen, F. G. A. (2025a). Soil conservation benefits of biochar in Mediterranean vineyards: enhancing the soil sponge function and mitigating water erosion. https://doi.org/10.1007/s42773-025-00483-x
25. Gholamahmadi, B., Gonzalez Pelayo, O., Isaka, S., Campos, I., Martins, M., Bastos, A. C., Jongen, M., & Verheijen, F. G. (2025b). The impact of biochar application on sponge function, water erosion, and vegetation cover in a Mediterranean vineyard soil.

https://doi.org/10.1016/j.jenvman.2025.125916

26. Glaser, B., Lehmann, J., & Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - A review. Biology and Fertility of Soils, 35(4), 219-230. https://doi.org/10.1007/s00374-002-0466-4
27. Guo, J., Chen, J., & Qi, S. (2024). Impact of Land Use/Cover Change on Soil Erosion and Future Simulations in Hainan Island, China. https://doi.org/10.3390/w16182654
28. Henaut, H., Chafik, Y., Sena-Velez, M., Bourgerie, S., & Morabito, D. (2026). Application of viticultural by-product biochar to alleviate soil copper toxicity in vineyard. https://doi.org/10.1007/s41207-026-01098-9
29. Hseu, Z.-Y., Jien, S.-H., Chien, W.-H., & Liou, R.-C. (2014). Impacts of biochar on physical properties and erosion potential of a mudstone slopeland soil. Scientific World Journal, 2014. https://doi.org/10.1155/2014/602197
30. Jeffery, S., Abalos, D., Prodana, M., Bastos, A.C., Van Groenigen, J.W., Hungate, B.A., & Verheijen, F. (2017). Biochar boosts tropical but not temperate crop yields. Environmental Research Letters, 12(5). https://doi.org/10.1088/1748-9326/aa67bd
31. Jeffery, S., Verheijen, F. G. A., Abalos, D., & Bastos, A. C. (2024). Plant productivity with biochar applications to soils. https://doi.org/10.4324/9781003297673-13
32. John, V., Braga, A. R. D. O., Falcão, N. P. D. S., Guerra, J. F. C., & S. C. Marques-dos-Santos, C. (2025). Biochar from biomass wastes: Advancing sustainable circular agriculture and the water-energy-food nexus. https://doi.org/10.1016/B978-0-443-22320-4.00022-0
33. Jongen, M., Bastos, A. C., Jelinčić, A., Simões, L., Gonzalez-Pelayo, O., Niemeyer, J., Unger, S., Domingos, T., & Verheijen, F. G. (2026). Biochar, plant productivity and community structure: a two-year study in a newly sown legume-rich pasture in Portugal under ambient and reduced precipitation. https://doi.org/10.1016/j.agee.2026.110403
34. Junaidi, M., Syahrinudin, Kiswanto, Sudarmadji, T., Ruchaemi, A., & Hartati, W. (2023). Ameliorant application promotes growth performances of Calliandra calothyrsus Meissn. planted on post-coal mining land. https://doi.org/10.1088/1755-1315/1282/1/012051
35. Kammann, C., & Graber, E. R. (2024). Biochar effects on plant ecophysiology. https://doi.org/10.4324/9781003297673-15
36. Lal, R. (2010). Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. BioScience, 60(9), 708-721. https://doi.org/10.1525/bio.2010.60.9.8
37. Li, J., Zhu, X., Xu, Q., Ao, L., Yu, X., & Zhang, S. (2025c). Coupling of vegetation filter strips and biochar reduced the loss of nitrogen and phosphorus nutrients in subtropical riparian areas under continuous rainfall conditions. https://doi.org/10.1016/j.eti.2025.104473
38. Li, X., Song, Z., Lu, Y., Weng, B., Li, J., Liu, Y., Wang, Z., & Gou, Y. (2024a). Evaluation of soil erosion in the Changhua River Basin on Hainan Island based on the Chinese soil loss equation model. https://doi.org/10.1016/j.heliyon.2024.e38291
39. Li, Y., Yang, J., Yang, M., & Zhang, F. (2024b). Exploring biochar addition impacts on soil erosion under natural rainfall: A study based on four years of field observations on the Loess Plateau. https://doi.org/10.1016/j.still.2023.105935
40. Li, Y., Yuan, Y., Zhao, J., Yang, J., Yan, C., Yang, M., Wang, B., & Zhang, F. (2025a). Biochar addition enhances silt loam soil resistance to rill flow: A study based on three years of field monitoring data on China's Loess Plateau. https://doi.org/10.1016/j.still.2024.106320
41. Li, Y., Yang, J., Yang, M., Wang, B., & Zhang, F. (2025b). Biochar application reduces soil detachment capacity by overland flow under a continuous three-year field experiment on the Loess Plateau of China. https://doi.org/10.1016/j.iswcr.2025.04.002
42. Liu, C., Dong, M., Wang, Y., Wang, X., Liu, Q., & Chen, Z. (2025). Prediction of rainfall erosivity in Eastern Monsoon Region in China based on CMIP6 models. https://doi.org/10.1016/j.catena.2025.109459
43. Liu, C., Dong, M., Liu, Q., Wang, W., & Wang, Y. (2026). Multi-Source Rainfall Erosivity Fusion Based on Machine Learning Models. https://doi.org/10.1002/ldr.70496
44. Lu, Y., Gu, K., Shi, B., & Zhou, Q. (2024). Does biochar mitigate rainfall-induced soil

erosion? A review and meta-analysis. https://doi.org/10.1016/j.bgtech.2024.100096

45. Maisyarah, S., Chen, J.-Y., Hseu, Z.-Y., & Jien, S.-H. (2023). Retention and loss pathways of soluble nutrients in biochar-treated slope land soil based on a rainfall simulator. https://doi.org/10.1016/j.seh.2023.100021
46. Mao, J., Zhang, K., & Chen, B. (2019). Linking hydrophobicity of biochar to the water repellency and water holding capacity of biochar-amended soil. Environmental Pollution, 253, 779-789. https://doi.org/10.1016/j.envpol.2019.07.051
47. Marques, J. P., Vaz, C. M. P., & Rodrigues, V. G. S. (2024). Characterization of mixtures of Brazilian Ultisol with urban pruning waste biochar at two different proportions. https://doi.org/10.1007/s11368-024-03928-1
48. Mazibuko, D. M., Maskey, S., Kurashina, K., Okazawa, H., Oshima, H., Kato, T., & Kikuno, H. (2025). Effects of Biochar on Growth, Response to Water Stress, and Post-Stress Recovery in Underutilized Vegetable Hibiscus sabdariffa from Malawi. https://doi.org/10.3390/crops5020013
49. Nguyen, V. G., Sharma, P., Ağbulut, Ü., Le, H. S., Cao, D. N., Dzida, M., Osman, S. M., Le, H. C., & Tran, V. D. (2024). Improving the prediction of biochar production from various biomass sources through the implementation of eXplainable machine learning approaches. https://doi.org/10.1080/15435075.2024.2326076
50. Nuruzzaman, M., Bahar, M. M., & Naidu, R. (2025). Diffuse soil pollution from agriculture: Impacts and remediation. https://doi.org/10.1016/j.scitotenv.2025.178398
51. Omondi, M.O., Xia, X., Nahayo, A., Liu, X., Korai, P.K., & Pan, G. (2016). Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. Geoderma, 274, 28-34. https://doi.org/10.1016/j.geoderma.2016.03.029
52. Panagos, P., Ballabio, C., Himics, M., Scarpa, S., Matthews, F., Bogonos, M., Poesen, J., & Borrelli, P. (2021). Projections of soil loss by water erosion in Europe by 2050. Environmental Science and Policy, 124, 380-392. https://doi.org/10.1016/j.envsci.2021.07.012
53. Peng, X., Zhu, Q.H., Xie, Z.B., Darboux, F., & Holden, N.M. (2016). The impact of manure, straw and biochar amendments on aggregation and erosion in a hillslope Ultisol. Catena, 138, 30-37. https://doi.org/10.1016/j.catena.2015.11.008
54. Pierini, M., Harjivan, S. G., Sieli, N., Cabrita, M. J., Prats, S., Catarino, S., & Ricardo-da-Silva, J. M. (2026). Effect of Organic Soil Amendments and Vineyard Topographic Position on the Chemical Composition of Syrah, Trincadeira, Alicante Bouschet, and Antão Vaz Grapes (Vitis vinifera L.) in the Alentejo Wine Region. https://doi.org/10.3390/environments13010044
55. Prakongkep, N., Gilkes, R.J., Wiriyakitnateekul, W., Duangchan, A., & Darunsontaya, T. (2013). The effects of pyrolysis conditions on the chemical and physical properties of rice husk biochar. Int. J. Mater. Sci, 3(3), 97-103.
56. Prats, S.A., Abrantes, J.R.C.D.B., Coelho, C.D.O.A., Keizer, J.J., & de Lima, J.L.M.P. (2018). Comparing topsoil charcoal, ash, and stone cover effects on the postfire hydrologic and erosive response under laboratory conditions. Land Degradation and Development, 29(7), 2102-2111. https://doi.org/10.1002/ldr.2884
57. Prats, S.A., Merino, A., Gonzalez-Perez, J.A., Verheijen, F.G.A., & De la Rosa, J.M. (2021). Can straw-biochar mulching mitigate erosion of wildfire-degraded soils under extreme rainfall?. Science of the Total Environment, 761. https://doi.org/10.1016/j.scitotenv.2020.143219
58. Qin, J., Chen, Q., Sun, M., Sun, P., & Shen, G. (2017). Pyrolysis temperature-induced changes in the catalytic characteristics of rice husk-derived biochar during 1,3-dichloropropene degradation. Chemical Engineering Journal, 330, 804-812. https://doi.org/10.1016/j.cej.2017.08.013
59. Razzaghi, F., Obour, P.B., & Arthur, E. (2020). Does biochar improve soil water retention? A systematic review and meta-analysis. Geoderma, 361. https://doi.org/10.1016/j.geoderma.2019.114055
60. Rončák, P., Németová, Z., Vitková, J., Danáčová, M., Toková, L., Aydin, E.,

Valent, P., Honek, D., & Igaz, D. (2023). Effects of the application of biochar on the soil erosion of plots of sloping agricultural and with silt loam soil. https://doi.org/10.2478/johh-2023-0026

61. Schmidt, H.-P., Kammann, C., Hagemann, N., Leifeld, J., Bucheli, T.D., Sánchez Monedero, M.A., & Cayuela, M.L. (2021). Biochar in agriculture – A systematic review of 26 global meta-analyses. GCB Bioenergy, 13(11), 1708-1730. https://doi.org/10.1111/gcbb.12889
62. Si, D., Lin, Y., Xu, Q., & Zhang, S. (2025). Effects of biochar on rainwater redistribution, soil water evaporation and desiccation cracking: A case study of limestone soil in karst areas of southwest China. https://doi.org/10.1016/j.scitotenv.2025.178692
63. Smetanová, A., Dotterweich, M., Diehl, D., Ulrich, U., & Dotterweich, N.F. (2013). Influence of biochar and terra preta substrates on wettability and erodibility of soils. Zeitschrift für Geomorphologie, 57(1), 111-134.
64. Smit, B., Janssens, B., Haagsma, W., Hennen, W., Adrados, J.L., Kathage, J., & Domínguez, I.P. (2019). Adoption of cover crops for climate change mitigation in the EU. Adoption of cover crops for climate change mitigation in the EU.
65. Tufanaru, C., Munn, Z., Stephenson, M., & Aromataris, E. (2015). Fixed or random effects meta-analysis? Common methodological issues in systematic reviews of effectiveness. International Journal of Evidence-Based Healthcare, 13(3), 196-207. https://doi.org/10.1097/XEB.0000000000000065
66. Ullah, M. S., Malekian, R., Randhawa, G. S., Gill, Y. S., Singh, S., Esau, T. J., Zaman, Q. U., Afzaal, H., Du, D. L., & Farooque, A. A. (2024). The potential of biochar incorporation into agricultural soils to promote sustainable agriculture: insights from soil health, crop productivity, greenhouse gas emission mitigation and feasibility perspectives—a critical review. https://doi.org/10.1007/s11157-024-09712-4
67. Vahidi, M., Bayat, H., & Ebrahimi, M. (2025). Evaluating the impact of organic amendments on soil erosion dynamics: a comprehensive examination of application methods and timing. https://doi.org/10.1139/cjss-2025-0032
68. Verheijen, F.G.A., Graber, E.R., Ameloot, N., Bastos, A.C., Sohi, S., & Knicker, H. (2014). Biochars in soils: New insights and emerging research needs. European Journal of Soil Science, 65(1), 22-27. https://doi.org/10.1111/ejss.12127
69. Wang, Y.-Y., Yu, X.-X., Fan, D.-X., Jia, G.-D., Niu, J.-Z., Feng, Y.-H., & Wang, Y.-K. (2025). Combined impact of land-use/land-cover and soil property changes on soil erosion in the Yellow River Basin. https://doi.org/10.1016/j.jenvman.2025.127535
70. Weir, C.J., Butcher, I., Assi, V., Lewis, S.C., Murray, G.D., Langhorne, P., & Brady, M.C. (2018). Dealing with missing standard deviation and mean values in meta-analysis of continuous outcomes: A systematic review. BMC Medical Research Methodology, 18(1). https://doi.org/10.1186/s12874-018-0483-0
71. Wu, G.-L., Liu, Y.-F., Cui, Z., Liu, Y., Shi, Z.-H., Yin, R., & Kardol, P. (2020). Trade-off between vegetation type, soil erosion control and surface water in global semi-arid regions: A meta-analysis. Journal of Applied Ecology, 57(5), 875-885. https://doi.org/10.1111/1365-2664.13597
72. Xing, L., Niu, X., Yin, X., Duan, Z., Liu, A., Ma, Y., & Gao, P. (2025). Optimizing Biochar Concentration for Mitigating Nutrient Losses in Runoff: An Investigation into Soil Quality Improvement and Non-Point Source Pollution Reduction. https://doi.org/10.3390/agriculture15010045
73. Yin, X., Zhao, L., Fang, Q., Zi, R., Fang, F., Yang, X., & Ding, G. (2024). Effects of biochar amendment on the surface and underground runoff and soil loss of karst slopes at the microplot scale. https://doi.org/10.1016/j.catena.2024.107857
74. Zanutel, M., & Bielders, C. (2023). Contrasted effects of biochar application on interrill erosion depending on age, application rate and soil type. https://doi.org/10.1016/j.geodrs.2023.e00706
75. Zanutel, M., Garré, S., Sanglier, P., & Bielders, C. (2024a). Biochar modifies soil physical properties mostly through changes in soil structure rather than through its

internal porosity. https://doi.org/10.1002/vzj2.20301

76. Zanutel, M., Lefebvre, A., Garré, S., & Bielders, C. (2024b). Does century-old biochar affect soil interrill erodibility on cropland soils? A study on pre-industrial kiln sites. https://doi.org/10.1016/j.still.2024.106091
77. Zhang, D., Yan, M., Niu, Y., Liu, X., van Zwieten, L., Chen, D., Bian, R., Cheng, K., Li, L., Joseph, S., Zheng, J., Zhang, X., Zheng, J., Crowley, D., Filley, T.R., & Pan, G. (2016). Is current biochar research addressing global soil constraints for sustainable agriculture?. Agriculture, Ecosystems and Environment, 226, 25-32. https://doi.org/10.1016/j.agee.2016.04.010
78. Zhang, W., Pang, J., Qi, J., Lu, Y., Liu, J., Yu, M., Li, H., Wang, E., & Lambers, H. (2025). Biochar's dual impact on soil acidity management and crop yield enhancement in acidic soils: a meta-analysis. https://doi.org/10.1007/s11104-025-07490-8
79. Zhao, J., Yuan, Y., Yan, C., Zhang, F., Luo, J., Yang, J., Chen, J., & Li, Y. (2025). Evaluating and modeling rill detachment and resistance in different rates and particle sizes of biochar application on the Loess Plateau of China. https://doi.org/10.1016/j.jhydrol.2025.133441
80. Zhao, X., Mak-Mensah, E., Zhao, W., Wang, Q., Zhou, X., Zhang, D., Zhu, J., Qi, W., Liu, Q., Li, X., Li, X., & Liu, B. (2024). Optimized ridge-furrow technology with biochar amendment for alfalfa yield enhancement and soil erosion reduction based on a structural equation model on sloping land. https://doi.org/10.1016/j.agwat.2024.108866
81. Zi, R., Yin, X., Fang, F., Chen, T., Han, Z., Hou, R., & Zhao, L. (2025). How does biochar affect surface-underground soil and water loss on soil-mantled hillslopes in karst regions? − Evidence from the soil structure. https://doi.org/10.1016/j.jhydrol.2025.134089
82. Zornoza, R., Moreno-Barriga, F., Acosta, J.A., Muñoz, M.A., & Faz, A. (2016). Stability, nutrient availability and hydrophobicity of biochars derived from manure, crop residues, and municipal solid waste for their use as soil amendments. Chemosphere, 144, 122-130. https://doi.org/10.1016/j.chemosphere.2015.08.046

How to cite this article: Bontor L. Tobing, Fitryane Lihawa, Abdul Samad Hiola, Asda Rauf, Wahyuni K. Baderan. Biochar for climate-resilient soil and water conservation: a critical review. *International Journal of Research and Review*. 2026; 13(5): 536-559. DOI: *https://doi.org/10.52403/ijrr.20260550*

******