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Integrating Biochar and Basaltic Rock for Carbon Dioxide Removal via Enhanced Silicate Weathering in Semi-Arid Agroecosystems: A Critical Review

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Abstract

Enhanced silicate weathering (ESW) has emerged as a promising nature-based carbon dioxide removal (CDR) strategy that accelerates the natural weathering of silicate minerals to sequester atmospheric CO_2. However, its application in semi-arid agroecosystems remains comparatively underexplored, despite the importance of these environments for agricultural production and their vulnerability to climate variability, land degradation, and water limitation. In addition, the effectiveness of ESW in semi-arid agroecosystems is severely constrained by limited soil moisture, high temperatures, and degraded soil conditions. This review critically examines the integration of biochar with basalt as a synergistic approach to overcome these constraints, synthesizing evidence that has not previously been brought together within a dryland context. The review covers the geochemical mechanisms of ESW, the physicochemical properties of biochar, and potential synergistic mechanisms through which biochar may modify the soil conditions governing basalt weathering under water-limited conditions. Key co-benefits include improved soil water holding capacity, enhanced cation exchange capacity, release of plant-available base cations, increased crop productivity, and reduced nitrous oxide emissions.

Environmental risks such as trace metal mobilization and life cycle considerations are evaluated. The review concludes that biochar-enhanced basalt weathering represents a potentially promising CDR approach for semi-arid agroecosystems; however, direct empirical evidence for the combined application under semi-arid field conditions remains limited.

Keywords: Carbon dioxide removal; enhanced silicate weathering; biochar; basalt; semi-arid agriculture; Zamfara State; climate change mitigation; sub-Saharan Africa

1. Introduction

Climate change represents one of the most significant environmental challenges of the twenty-first century, driven largely by the continuing increase in atmospheric greenhouse-gas concentrations from pre-industrial levels. Although emission reduction remains essential, carbon dioxide removal (CDR) is increasingly considered a complementary component of pathways for limiting net atmospheric CO_2 concentrations and achieving long-term climate targets (IPCC, 2021, 2022). Although emission reduction strategies remain essential, growing scientific consensus indicates that emission reductions alone are insufficient to achieve global climate targets set under the Paris Agreement (IPCC, 2022). Carbon dioxide removal (CDR) has, therefore, emerged as one of the critical components of global climate stabilization pathways (Minx *et al*., 2018).

Among emerging CDR approaches, enhanced silicate weathering (ESW) has gained increasing attention as a terrestrial carbon-removal strategy that accelerates the dissolution of reactive silicate minerals. During weathering, atmospheric or soil-respired CO_2 can be incorporated into dissolved inorganic carbon, principally bicarbonate, while mineral dissolution releases elements such as Ca, Mg, and Si that may contribute to soil fertility and plant nutrition (Hartmann et al., 2013; Beerling et al., 2020). Finely ground basalt, due to its suitable mineral composition and fast dissolution, is widely regarded as one of the most viable feedstocks for ESW applications in agricultural soils (Hartmann *et al*., 2013; Kelland *et al*., 2020). However, the existing evidence base for ESW is heavily skewed toward temperate agricultural systems in Europe and North America, while semi-arid ecosystems particularly those across sub-Saharan Africa, where land degradation and climate vulnerability converge most acutely remain critically underexplored.

Covering about 40% of the Earth's terrestrial surface, semi-arid environments support over 38% of the global population including millions of small holder farmers in Africa who are among the most exposed to climate-driven vulnerabilities such as land degradation (Reynolds *et al*., 2007; Niang *et al*., 2014). In these systems, soils are generally characterised by conditions such as low cation exchange capacity (CEC), neutral to alkaline pH, poor water holding capacity most of which limit weathering reactions and constrain agricultural productivity (Lal 2004; Taylor *et al*., 2021). Low soil moisture significantly reduces mineral dissolution potentials of the soil thereby undermining the carbon sequestration efficiency of basalt amendments under dryland conditions.

Biochar has been proposed as a synergistic co-amendment capable of addressing several of the above constraints. Biochar may significantly enhance basalt weathering rates and CDR efficiency in water-limited environments by improving soil water retention, enhancing microbial activity, increasing cation exchange capacity, and providing reactive surface area for mineral interactions, (Lehmann & Joseph, 2015; Ahmad *et al*., 2014; Liu *et al*., 2023). The integration of biochar and basalt therefore represents a CDR approach that potentially addresses soil degradation and agricultural productivity, in addition to carbon sequestration in semi-arid agroecosystems.

Despite this potential, our literature search identified limited empirical evidence directly evaluating biochar–basalt co-application for enhanced weathering and CDR under semi-arid field conditions, particularly in sub-Saharan Africa. This gap becomes clearer in sub-Saharan Africa, where semi-arid environments dominate vast agricultural landscapes, local basalt deposits provide easily accessible feedstock resources, and abundant agricultural residues provide readily available biochar feedstocks. Ongoing field research in Zamfara State, northwestern Nigeria is actively investigating these mechanisms under real-world conditions.

This review, therefore, aims to: (1) examine the geochemistry and mechanism of ESW and the role of basalt as a CDR feedstock; (2) characterise the physicochemical properties of biochar relevant to mineral weathering enhancement; (3) synthesise the mechanistic interactions through which biochar enhances basalt weathering under water-limited conditions; (4) evaluate the unique challenges and opportunities of semi-arid agroecosystems for integrated CDR deployment; (5) assess the agricultural co-benefits, environmental risks, and life cycle considerations of the combined approach; and (6) identify priorities for future field research and implementation in sub-Saharan Africa. A synthesis of key literature that form the basis of

these aims is presented in Table 1, following the description of the methodological framework in Section 2.

2.0 Methodology

The integration of biochar and enhanced silicate weathering (ESW) in semi-arid agroecosystems spans multiple disciplines, geochemistry, soil science, agronomy, and climate policy making a systematic meta-analytic approach impractical given the heterogeneity of study designs, outcome measures, and environmental contexts in the existing literature. For this reason, this review adopts a critical narrative synthesis approach (Baumeister & Leary, 1997; Grant & Booth, 2009), combining the breadth of a narrative review with systematic literature identification. This design prioritises mechanistic synthesis and contextual interpretation over quantitative aggregation. A comprehensive literature search was conducted across Scopus, Web of Science, Google Scholar, and ScienceDirect. After screening, 78 peer-reviewed studies met the inclusion criteria (Table 1 summarizes key contributions). The selected studies were analysed through thematic synthesis, with findings organised around geochemical mechanisms, amendment interactions, environmental constraints, co-benefits, and implementation opportunities.

2.1 Search Strategy

A structured literature search was conducted across Scopus, Web of Science, Google Scholar, and ScienceDirect using predefined combinations of terms relating to enhanced silicate weathering, basalt weathering, biochar, mineral amendments, carbon dioxide removal, semi-arid agriculture, and dryland systems. Searches were restricted primarily to peer-reviewed English-language publications from 2000 to 2026, while earlier studies identified through reference tracking were considered where directly relevant.

The following search term combinations were used: “enhanced silicate weathering” AND “carbon dioxide removal”; “basalt weathering” AND “agriculture” OR “agroecosystem”; “biochar” AND “carbon sequestration” OR “mineral weathering”; “biochar-mineral interactions” AND “soil amendment”; “semi-arid” AND “soil carbon” OR “weathering” OR “basalt”; “rock dust” AND “agriculture” OR “crop yield”; “dryland” AND “carbon dioxide removal” OR “CDR”.

2.2 Inclusion and Exclusion Criteria

Studies included in the review: (1) examined ESW mechanisms, basalt weathering rates, or basalt application in agricultural soils; (2) investigated biochar properties, biochar and soil interactions, or biochar effects on carbon sequestration; (3) assessed co-applications of mineral amendments and organic amendments in soil systems; (4) examined soil conditions, agricultural productivity, or CDR potential in semi-arid or dryland environments; or (5) provided life cycle assessments or socioeconomic analyses relevant to ESW or biochar deployment. About 78 peer-reviewed studies were, therefore, identified for the review. A summary of key contributions from the retained literature is presented in Table 1 below.

2.3 Limitations of the Review

This review has several limitations that should be acknowledged. First, the restriction to English-language publications may have excluded relevant studies from non-English speaking regions, particularly from francophone West Africa where semi-arid research is active. Second, the geographic concentration of ESW research in temperate regions (Europe, North America, Australia) limits the availability of empirical data from semi-arid Africa, constraining the evidence base for region-specific conclusions. Third, publication bias toward positive results is a recognized challenge in environmental and CDR research, as studies reporting significant effects are more likely to be published than those reporting null or negative results. Fourth, the heterogeneity of experimental methodologies across studies including varying basalt application rates, particle sizes, feedstock types, pyrolysis conditions, and CDR quantification methods makes direct comparison and meta-analysis challenging. Fifth, the exclusion of grey literature (technical reports, unpublished theses) may have omitted relevant field data from non-academic sources. Despite these limitations, the systematic approach adopted provides a robust foundation for synthesizing current knowledge and identifying priority research directions for semi-arid agroecosystems.

Table 1: Summary of Key Literature on Enhanced Silicate Weathering, Biochar, and Their Integration

Focus Area	Key Authors	Major Findings	Geographical Context	Knowledge Gaps Identified
ESW Fundamentals	Hartmann *et al*. (2013)	ESW uses basalt to capture CO_2 via bicarbonate formation; releases Ca, Mg, K for soil fertility	Global review	Field validation needed
	Schuiling & Krijgsman (2006)	First proposed enhanced weathering as CDR; olivine and basalt most suitable	Theoretical	Translating lab to field
	Renforth *et al*. (2015)	Dissolution kinetics of olivine in soil; CDR quantification methods	Laboratory (UK)	Particle size optimization
ESW Field Trials	Beerling *et al*. (2020)	Large-scale CDR potential in croplands; 0.2-0.5 t CO_2 t^{-1} basalt	Temperate (UK, US, Australia)	Semi-arid data absent
	Kelland *et al*. (2020)	Basalt increased sorghum yields 15-25% + CDR	Temperate (US)	No semi-arid validation

	Haque *et al*. (2019)	Wollastonite amendment increased pH, Ca, and CDR	Temperate (Canada)	Long-term monitoring needed
Biochar Properties	Ahmad *et al*. (2014)	High porosity, CEC, water retention, functional groups (-COOH, -OH)	Global review	Optimization for CDR
	Lehmann & Joseph (2015)	Biochar stability (decades-centuries); pyrolysis controls properties	Global review	Soil-specific formulations
	Woolf *et al*. (2010)	Biochar carbon sequestration potential 0.3-2.6 Gt CO_2 yr^{-1}	Global modelling	LCA for smallholders
Biochar in Drylands	Basso *et al*. (2013)	Biochar increased water holding capacity 15-30% in sandy soils	Temperate (US)	Semi-arid field data
	Kimetu *et al*. (2008)	Biochar increased maize yields 30-100% in degraded soils	Semi-arid (Kenya)	Interaction with minerals

	Jeffery *et al*. (2011)	Meta-analysis: 10% average yield increase; greater in acidic/sandy soils	Global	Mechanisms unclear
Biochar + Minerals	Liu *et al*. (2023)	Synergistic effects on CDR, nutrient retention, soil aggregation	Laboratory/Greenhouse	Long-term field validation
	Zhang *et al*. (2024)	Biochar-mineral interactions; surface chemistry (SEM, FTIR, XPS)	Laboratory	Field mechanisms
	Joseph *et al*. (2010)	Biochar surfaces provide nucleation sites for carbonates	Laboratory	Soil formation rates
Semi-Arid Constraints	Taylor *et al*. (2021)	Water limitation reduces weathering kinetics; biochar may help	Conceptual	No empirical CDR rates
	Reynolds *et al*. (2007)	Semi-arid regions cover 40% of Earth; support 38% of population	Global review	CDR feasibility unknown

	Lal (2004)	Low soil organic matter (<1%), poor structure, high erosion risk	Global review	Restoration strategies
Nigerian Context	Dada *et al*. (2013)	Basaltic deposits in Zamfara (River Bunsuru) suitable for ESW	Nigeria (Zamfara)	Characterization needed
	Adeyemi *et al*. (2020)	Smallholder farming (<2 ha), rainfed, low inputs, degraded soils	Nigeria	Adoption barriers

3.0 Theoretical Foundations of Enhanced Silicate Weathering

Enhanced silicate weathering operates through a series of geochemical reactions in which atmospheric CO_2 is captured and stored as inorganic carbon. As shown in Equation (1), CO_2 dissolves in soil water to form carbonic acid (H_2CO_3), which serves as the primary reactive agent driving mineral dissolution (Hartmann *et al*., 2013).

A critical CDR pathway in ESW is the leaching of dissolved bicarbonate (HCO_3^-) from soils into groundwater, rivers, and oceans. Following mineral dissolution (Equations 2-4 below), the HCO_3^- produced enters soil solution and is transported downward by percolating water, eventually reaching streams and coastal oceans where the carbon remains stored for tens of thousands of years (Renforth & Henderson, 2017). This bicarbonate leaching accounts for 60-80% of total carbon removed in ESW field studies (Kelland *et al*., 2020; Amann *et al*., 2020). However, in semi-arid environments, low rainfall and high evapotranspiration reduce leaching efficiency, making this pathway less effective than in humid regions (Taylor *et al*., 2021).

$$\mathbf{CO_2 + H_2O \rightleftharpoons H_2CO_3} \qquad 1$$

This weak acid then attacks silicate minerals, breaking them down and releasing dissolved cations and bicarbonate ions. Equation 2 illustrates the weathering of calcium-rich plagioclase feldspar ($CaAl_2Si_2O_8$), one of the most abundant minerals in basalt (Hartmann *et al*., 2013):

In semi-arid environments, where soil temperatures fluctuate significantly between day and night, the reversible nature of Equation 1 becomes particularly important. Temperature influences the carbonate-system equilibria and mineral-weathering kinetics; however, in semi-arid soils the effect of elevated temperature cannot be considered independently of rapid evapotranspiration and declining soil-water availability. Consequently, the net effect of temperature on field-scale weathering depends on the interaction between reaction kinetics and soil hydrology (Stumm & Morgan, 1996). This reverse reaction reduces the availability of carbonic acid for silicate mineral dissolution (Equation 2), thereby temporarily suppressing weathering rates during hot periods. At night, cooler temperatures shift the equilibrium right, allowing carbonic acid to reform. However, the net effect of these diurnal cycles is a reduction in overall weathering efficiency compared to systems with stable, moderate temperatures. This phenomenon is especially relevant in semi-arid regions like Zamfara State, where daytime soil surface temperatures can exceed 40°C followed by nighttime cooling to below 20°C).

$$CaAl_2Si_2O_8 + 2H_2CO_3 + H_2O \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + 2HCO_3^- \quad 2$$

The bicarbonate ions (HCO_3^-) formed during mineral dissolution represent a stable pool of inorganic carbon. Once in soil solution, they are transported downward by percolating water into groundwater, rivers, and eventually the oceans, where the carbon remains stored over timescales of tens of thousands of years (Renforth *et al*., 2015). In humid temperate systems this pathway is highly efficient, but as discussed in Section 7.2, the low rainfall characteristic of semi-arid regions substantially reduces leaching fluxes, making surface carbonate precipitation a proportionally more important carbon storage pathway in drylands (Taylor *et al*., 2021).

In agricultural applications involving basalt, the weathering of Mg-rich olivine (Mg_2SiO_4) represented by Equation 3 below, shows that magnesium silicates capture significant amounts of atmospheric CO_2 while releasing plant-available magnesium and soluble silicon (Beerling *et al*., 2020):

$$Mg_2SiO_4 + 4CO_2 + 4H_2O \rightarrow 2Mg^{2+} + 4HCO^{3-} + H_4.SiO_4 \quad 3$$

Under favorable environmental conditions, dissolved calcium ions released during weathering may further react with carbonate species to form stable carbonate minerals, as shown in Equation 4 (Manning, 2008):

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3\ (s) \quad 4$$

This secondary carbonate precipitation provides an additional pathway for long-term carbon stabilization in soil systems. Collectively, Equations 1 and 4 demonstrate that ESW efficiency depends on several interacting environmental controls. Soil moisture is the most critical factor, as weathering requires liquid water for carbonic acid formation and transport of dissolved products (White & Brantley, 2003). Soil pH influences dissolution kinetics; most silicate minerals dissolve faster under acidic conditions (pH 4-6) due to higher proton availability, whereas alkaline conditions (common in semi-arid Africa) slow weathering (Hartmann *et al*., 2013). Temperature increases reaction rates via the Arrhenius relationship but also increases evapotranspiration, reducing soil moisture in drylands (Strefler *et al*., 2018). Mineral surface area, increased by fine grinding, accelerates dissolution but requires significant energy input (Beerling *et al*., 2020). Microbial activity enhances weathering through organic acid production and CO_2 generation (Uroz *et al*., 2009). In semi-arid agroecosystems, limited water

availability and alkaline pH significantly constrain ESW, but biochar may partially mitigate these limitations (Taylor *et al*., 2021).

While Equation 4 shows $CaCO_3$ precipitation, Mg released from olivine and pyroxene weathering (Equation 3) can similarly form $MgCO_3$ via the reaction: $Mg^{2+} + CO_3^{2-} \rightarrow MgCO_3$**.** In many basalts, Mg content is comparable to or even exceeds Ca making Mg-carbonate formation also a significant carbon storage pathway. Furthermore, Mg is an essential nutrient for plants as the central atom in the chlorophyll molecule, and its release during weathering contributes directly to soil fertility and crop productivity (Kelland *et al*., 2020). In semi-arid soils where Mg deficiency can limit plant growth, basalt weathering provides a valuable source of this nutrient. The overall process of biochar-enhanced basalt weathering from atmospheric CO_2 capture to long-term carbon storage via bicarbonate leaching, carbonate precipitation, and biochar recalcitrance is summarized in Figure 1.

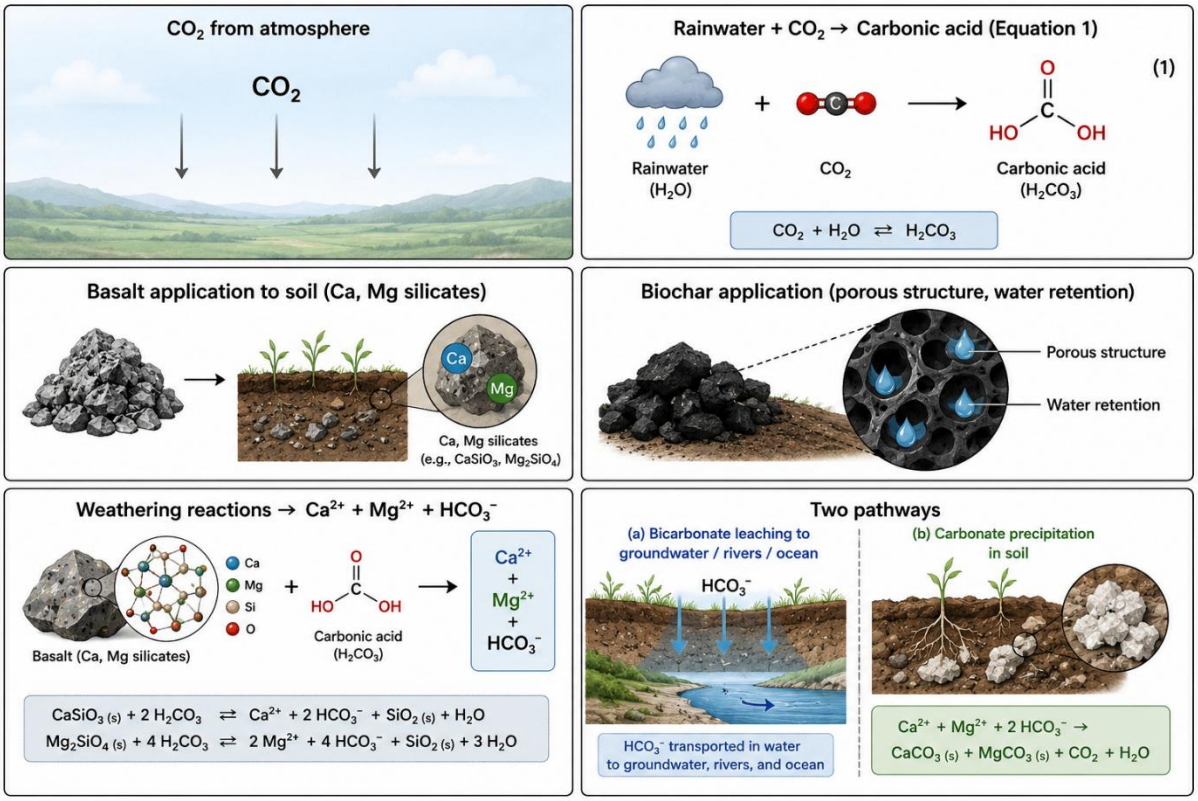


Figure 1. Conceptual framework of biochar-enhanced basalt weathering for carbon dioxide removal in semi-arid agroecosystems.

4.0 Basalt as a Feedstock for Enhanced Weathering

Basalt is a fine-grained mafic (Ca- and Mg-rich) igneous rock predominantly composed of Ca- and Mg-bearing silicate minerals, making it highly suitable for ESW applications (Hartmann *et al*., 2013). The generalized dissolution of Ca- bearing plagioclase feldspar, one of the dominant minerals in basalt, is expressed in Equation (5):

$$\mathbf{CaAl_2Si_2O_8 + 2CO_2 + 3H_2O \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + 2HCO_3^-} \quad 5$$

Equation 5 demonstrates that carbon dioxide dissolved in soil water promotes mineral dissolution, resulting in the release of Ca ions and HCO_3^- species that contribute directly to long-term carbon sequestration. Similarly, the weathering of Mg-rich olivine within basalt captures atmospheric CO_2 while releasing soluble Si and Mg ions — a reaction already presented as Equation 3 in Section 3, and here designated Equation 6 to reflect its role as the second principal basalt weathering reaction in this section (Kelland Equation 3, captures atmospheric CO_2 while releasing soluble Si and Mg ions (Kelland *et al*., 2020):

As illustrated in Equations 5 and 6, basalt weathering not only sequesters carbon but also releases essential plant nutrients. Mg contributes to chlorophyll synthesis, while Si enhances plant resistance to drought stress, disease pressure, and mechanical damage (Epstein, 2009). The effectiveness of basalt weathering is strongly influenced by particle size, with Beerling *et al*. (2020) reporting that particle sizes below 100 μm significantly improve weathering kinetics and carbon capture efficiency. However, the energy requirements associated with grinding basalt to fine particle sizes may increase operational costs and influence the overall life-cycle carbon balance of ESW systems.

Soil pH also plays an important role in basalt dissolution. Acidic soils generally promote faster mineral dissolution due to increased proton activity, while alkaline soils reduce weathering rates because of lower proton availability (Taylor *et al*., 2021). This relationship becomes particularly important in semi-arid African soils, where alkaline conditions are frequently observed due to low rainfall and high evaporative salt accumulation.

5.0 Biochar as a Synergistic Amendment

Biochar is a carbon-rich, porous material produced through the thermochemical conversion of biomass under oxygen-limited conditions (pyrolysis). Because of its high surface area, chemical stability, porosity, and reactive surface functional groups, biochar has emerged as a

promising material for improving the performance of mineral-based CDR systems (Lehmann & Joseph, 2015; Ahmad *et al*., 2014).

The water retention capacity of biochar varies significantly with feedstock and pyrolysis temperature. High temperature biochar from lignocellulosic feedstocks (e.g., maize cobs, groundnut shells) develop extensive micropore networks that retain water within pore structures (θ_r), as shown in Equation 7 (Basso *et al*., 2013):

$$\theta_b = \theta_s + \theta_r \quad (7)$$

Biochar typically retains between 5-15% of plant-available water in sandy soils per 20-40 th^{-1}. This retained water sustains the hydration reactions involved in carbonic acid formation (Equation 1), thereby supporting continued silicate dissolution under moisture-limited conditions. Similarly, CEC is strongly influenced by biochar production conditions. Low-temperature biochar retain oxygen-containing functional groups that provide negatively charged exchange sites (BC^-), as illustrated in Equation (8). However, high-temperature biochar lose these functional groups, resulting in lower CEC despite higher porosity (Ahmad *et al*., 2014):

$$2BC^- + M^{2+} \rightleftharpoons (BC)_2M \quad (8)$$

Where BC^- represents a negatively charged exchange site on the biochar surface and M^{2+} represents a divalent cation such as Ca^{2+} or Mg^{2+}. The expression is a conceptual representation of cation retention by exchange sites rather than a single molecular surface complex.

Figure 2 illustrates the relationship between biochar production characteristics, physicochemical properties, and the potential interactions between biochar and basalt during enhanced weathering.

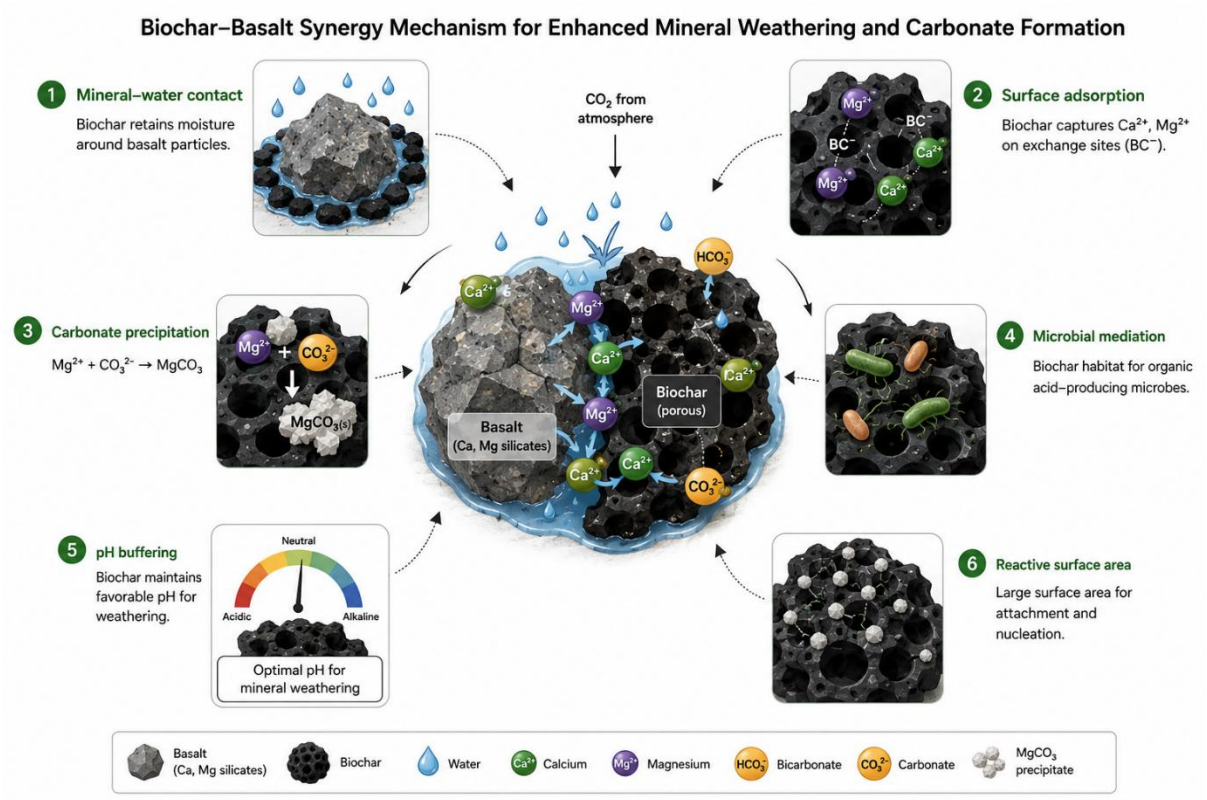


Figure 2. Conceptual relationship between biochar production characteristics, physicochemical properties, and potential interactions with basalt during enhanced silicate weathering.

5.1 Influence of Feedstock and Pyrolysis Temperature on Biochar Properties

The effectiveness of biochar in enhancing soil water retention, cation exchange capacity (CEC), and mineral weathering is highly dependent on its production conditions, particularly feedstock type and pyrolysis temperature. In semi-arid regions such as Zamfara State, locally available feedstocks include maize cobs, rice husks, and groundnut shells, each yielding biochar with distinct physicochemical properties (Ahmad *et al*., 2014; Lehmann & Joseph, 2015).

Pyrolysis temperature is a primary determinant of biochar properties. Low-temperature biochar (300 – 400 ^{0}C) retains more oxygen-containing functional groups (-COOH, -OH, -C_6H_5OH), which contribute directly to high CEC (typically 50-100 cmol kg^{-1}). However, low-temperature biochar has lower porosity, less surface area, and lower stability in soil (Keiluweit *et al*., 2010). In contrast, high-temperature biochar (600 – 700 ^{0}C) develops greater porosity, higher surface area (300 - 800 m^2 g^{-1}), and enhanced water retention capacity due to well-developed micropores, but its CEC decreases significantly (often below 20 cmol kg^{-1}) as functional groups are destroyed during carbonization (Mukherjee *et al*., 2011; Weber & Quicker, 2018).

Feedstock type also strongly influences biochar properties. Maize cobs, which are rich in lignin and cellulose, produce biochar with moderate porosity (200 - 400 $m^2\ g^{-1}$) and good water retention, making them suitable for moisture-limited soils (Yaman, 2004). Rice husks, high in silica, produce biochar with lower carbon content but excellent porosity and water absorption capacity due to their inherent cellular structure (Meyer *et al*., 2017). Groundnut shells, a dense lignocellulosic feedstock, produce biochar with high carbon stability, moderate CEC, and good surface area (Ahmad *et al*., 2014). For semi-arid applications where both water retention and nutrient retention are critical, a mixed feedstock appr**o**ach or an intermediate pyrolysis temperature (450 – 550 ^{0}C) may provide the optimal balance: sufficient functional groups for CEC (>30 cmol kg^{-1}) and adequate porosity for water retention (surface area >200 $m^2\ g^{-1}$) (Lehmann & Joseph, 2015).

The practical implication for semi-arid agroecosystems is that biochar production parameters must be optimized locally. For example, biochar produced from rice husks at 500 ^{0}C may be ideal for sandy soils requiring water retention, while biochar from groundnut shells at 450°C may better serve clayey soils needing CEC enhancement. Similar interactions occur with Mg, K, and other nutrient cations. Biochar also influences microbial processes that indirectly affect mineral weathering. Equation 9 describes microbial respiration, which produces CO_2 within the soil environment, contributing to carbonic acid formation (Warnock *et al*., 2007):

$$\mathbf{C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + Energy} \qquad 9$$

5.2 Effects of Biochar pH on Enhanced Silicate Weathering

Biochar is typically alkaline (pH 7 - 10) due to the concentration of ash residues (carbonates, oxides, and hydroxides of Ca, Mg, K, and Na) during pyrolysis (Lehmann & Joseph, 2015). The liming effect of biochar on soil pH can either enhance or hinder ESW rates depending on the initial soil pH and environmental context.

In acidic soils (pH 4.5 - 6.0), which are common in tropical regions with high rainfall, biochar-induced pH increase provides multiple benefits. First, it alleviates Al and Mn toxicity, improving soil conditions for plant growth and microbial activity (Jeffery *et al*., 2011). Second, it increases the availability of phosphorus and other nutrients that may otherwise be fixed at low pH (Brady & Weil, 2016). Third, while silicate weathering rates are highest at around pH 4-6, the increase to pH 6 - 7 still supports adequate dissolution while improving overall soil

fertility (Hartmann *et al*., 2013). In such contexts, biochar pH enhancement is beneficial for ESW.

In neutral to alkaline soils (pH 7.0 - 8.5), which are common in semi-arid regions like Zamfara State due to low rainfall and accumulation of base cations, the addition of alkaline biochar may further raise soil pH, reducing the availability of protons (H^+) necessary for silicate mineral dissolution (Equation 2, Section 3). As shown in Equation 16 (Section 7.2), higher pH corresponds to lower proton concentration. The dissolution rates of plagioclase feldspar and olivine decrease significantly as pH increases above 7 (Pokrovsky & Schott, 2000; White & Brantley, 2003). In such environments, biochar's pH-raising effect may hinder ESW rates by creating less favourable chemical conditions for weathering.

The net effect of biochar on ESW in semi-arid soils depends on the balance between its negative effect (reduced weathering kinetics due to higher pH) and its positive effects (improved water retention, CEC, microbial habitat, and nutrient supply). In many semi-arid systems, the positive effects may outweigh the pH-related negative effects, particularly when basalt weathering is already moisture-limited (Taylor *et al*., 2021). In biochar-amended soils, increased microbial habitat availability intensifies localized carbon cycling and improves weathering efficiency. Beyond its indirect effects, biochar itself contributes to long-term carbon sequestration due to its chemical recalcitrance (the resistance of its aromatic carbon structures to microbial decomposition). These structures enable biochar to persist in soils for decades to centuries (Woolf *et al*., 2010). Therefore, combining biochar with basalt creates a dual carbon sequestration pathway involving both geochemical inorganic carbon storage (via silicate weathering) and stable organic carbon storage (via biochar persistence).

To minimize the negative pH effect in alkaline semi-arid soils, several strategies are available. First, use low-temperature biochar (300-450°C**)**, which tends to have lower pH (7-8) than high-temperature biochar (9-10) while retaining more functional groups for CEC (Ahmad *et al*., 2014). Second, apply acid-washed biochar or co-compost biochar with acidic organic materials to neutralize its alkalinity (Meyer *et al*., 2017). Third, use lower application rates (see Section 5.3) to moderate pH change. Fourth, rely on in-situ acidification from microbial organic acid production (Equation 13, Section 6.4) to create localized acidic microsites on biochar surfaces, even in bulk alkaline soils (Uroz *et al*., 2009).

6. Mechanistic Interactions between Biochar and Basalt

Six synergistic mechanisms explain how biochar enhances basalt weathering under water-limited conditions. The first mechanism involves enhancement of mineral-water contact. Weathering reactions require continuous interaction between mineral surfaces and soil solution. The dissolution rate of silicate minerals, expressed in Equation 10, depends directly on the exposed mineral surface area (A) and the concentration gradient between equilibrium (Ceq) and actual (C) dissolved ion concentrations (Liu *et al*., 2023):. The term k is the weathering rate constant, which varies with pH (higher under acidic conditions, lower under alkaline), temperature (increases exponentially with heat via the Arrhenius relationship), and mineral composition (olivine weathers faster than pyroxene and plagioclase). Biochar does not change k directly, but it increases the effective dissolution rate by maintaining moisture around basalt particles and sustaining chemical gradients necessary for continued mineral dissolution (Lehmann & Joseph, 2015).

$$R_d = kA(Ceq - C) \qquad 10$$

The second mechanism involves surface adsorption and ion exchange. During basalt dissolution, calcium, magnesium, and potassium ions are released into soil solution. In coarse-textured or low organic matter soils common in semi-arid environments, these ions may be lost through leaching before contributing to plant nutrition or carbonate formation. Biochar addresses this through surface adsorption and ion exchange (the chemical retention of cations on negatively charged biochar surfaces). Equation (11) illustrates how biochar surfaces temporarily retain magnesium ions released from basalt weathering, reducing nutrient losses and supporting subsequent geochemical reactions (Ahmad *et al*., 2014):

$$2BC^{-} + Mg^{2+} \rightleftharpoons (BC)_2Mg \qquad 11$$

This retention is particularly important because magnesium and calcium ions contribute to carbonate precipitation and long-term inorganic carbon storage.

The third mechanism is secondary carbonate precipitation. Manning (2008) showed that dissolved cations released from basalt (Equation 12), may combine with carbonate ions to form stable carbonate minerals, providing permanent carbon sequestration:

$$Mg^{2+} + CO_3^{2-} \rightarrow MgCO_3\ (s) \qquad 12$$

Carbonate precipitation is favoured under conditions of high pH (typically above 7.5), elevated concentrations of Ca^{2+} and Mg^{2+}, and during soil drying when evapotranspiration concentrates ions in solution. Conversely, precipitation is constrained under acidic pH (below 6.0) where carbonates remain dissolved, and in well-drained soils where rapid leaching removes cations and bicarbonate before nucleation can occur. In semi-arid environments, the balance between precipitation and leaching is highly seasonal: carbonate precipitation may dominate during dry periods when water evaporates, while bicarbonate leaching dominates during the rainy season (Taylor *et al*., 2021).

By retaining divalent cations in the soil environment (Equation 11), biochar increases the probability of carbonate mineral formation.

The fourth mechanism involves microbial mediation. Equation 13 shows how microbial decomposition of organic substrates generates organic acids and CO_2, both of which contribute to mineral dissolution (Uroz *et al*., 2009):

$$\mathbf{C_6H_{12}O_6 \rightarrow Organic\ Acids + CO_2 + Energy} \qquad 13$$

In biochar-amended soils, enhanced microbial colonization intensifies these reactions, accelerating weathering processes.

The fifth mechanism is soil pH buffering. Basalt dissolution proceeds more rapidly under acidic to moderately acidic conditions because increased proton activity promotes silicate bond breakdown (Taylor *et al*., 2021). Depending on feedstock and production temperature, biochar can either increase or buffer soil pH, creating chemically favourable microzones that support continued mineral dissolution.

The sixth mechanism is the provision of reactive surface area. Biochar's high surface area provides attachment sites for basalt particles, bringing the two materials into close contact, and provides nucleation sites for carbonate minerals to precipitate (Joseph *et al*., 2010; Zhang *et al*., 2024).

The six synergistic mechanisms described above are illustrated in Figure 3.

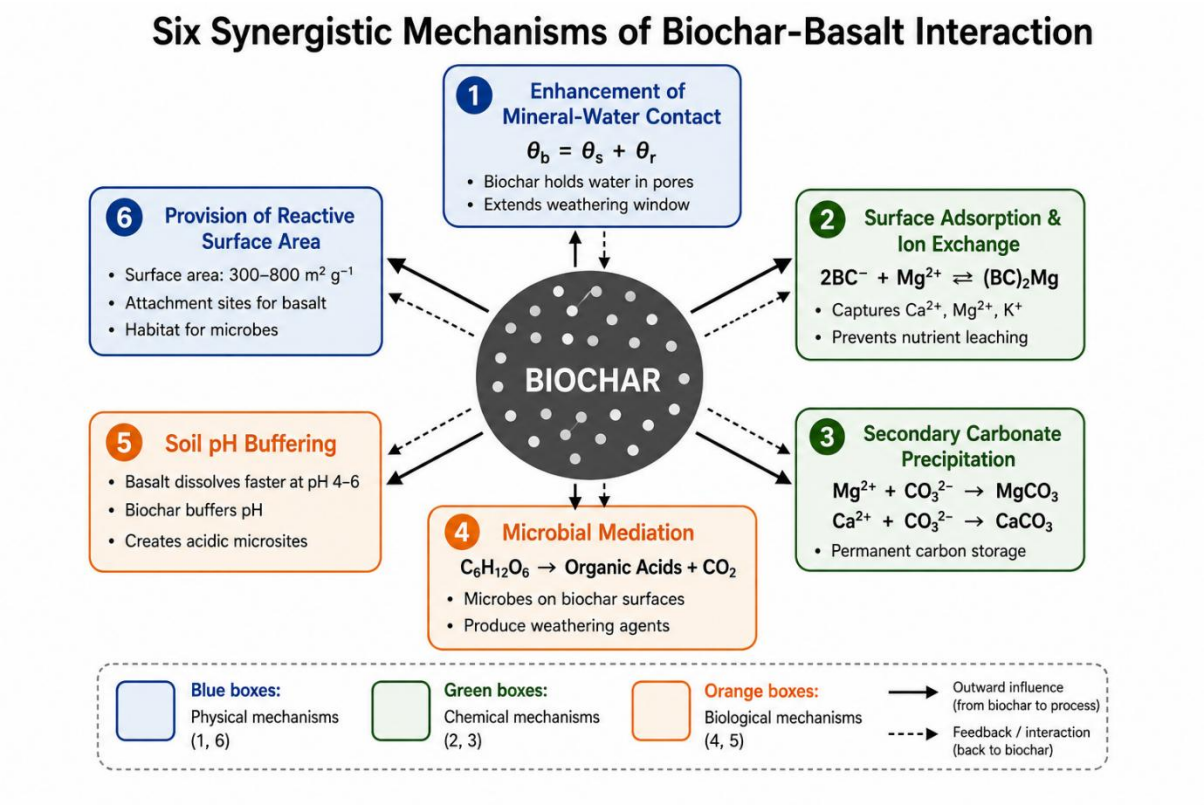


Figure 3. Proposed mechanisms through which biochar may modify the soil microenvironment and influence basalt weathering under semi-arid conditions.

7. Semi-Arid Regions: Challenges and Opportunities

7.1 The Critical Importance of Semi-Arid Regions

The West African Savannah, including Zamfara State, Nigeria, is one of the largest semi-arid regions globally, characterised by mean annual precipitation of 600–900 mm, mean annual temperature of 28°C, and high evapotranspiration rates that routinely exceed precipitation (Nigerian Meteorological Agency, 2022). As noted earlier, semi-arid environments support over 38% of the global population, many of them smallholder farmers whose livelihoods depend entirely on rain-fed agriculture. Soils in these systems typically exhibit low organic matter (<1%), low cation exchange capacity (5–10 cmol kg^{-1}), and poor water holding capacity (Lal, 2004; Adeyemi *et al*., 2020). Climate projections indicate increased frequency of droughts, threatening food security for millions of smallholder farmers (Niang *et al*., 2014).

7.2 Unique Challenges for Enhanced Weathering in Semi-Arid Systems

The water balance in semi-arid agricultural soils, expressed in Equation 14 reveals the primary constraint for ESW (Taylor *et al*., 2021):

$$\mathbf{P = ET + R + \Delta S} \quad 14$$

Where (P) is precipitation, (ET) is evapotranspiration, (R) represents runoff and/or drainage losses as defined for the system boundary, and (**ΔS**) represents the change in soil-water storage over the assessment period.

When evapotranspiration (ET) exceeds precipitation (P), soil water storage (ΔS) declines, limiting the hydration reactions essential for silicate weathering (Equations 1-3). The temperature dependence of a reaction rate constant can be represented conceptually by an Arrhenius relationship, as illustrated in Equation 15 (Strefler *et al*., 2018):

$$\mathbf{k = Ae^{(-Ea/RT)}} \quad 15$$

Where (k) is the rate constant, (A) is the pre-exponential factor, (E_a) is activation energy, (R) is the universal gas constant, and (T) is absolute temperature

While higher temperatures theoretically increase reaction rates, in semi-arid systems elevated temperatures are accompanied by rapid soil moisture loss, offsetting kinetic benefits. Furthermore, semi-arid soils frequently exhibit neutral to alkaline pH (7.0-8.5). As shown in Equation (16), higher pH corresponds to lower proton availability, reducing the efficiency of proton-mediated silicate dissolution reactions (Hartmann *et al*., 2013):

$$\mathbf{pH = -\log[H^+]} \quad 16$$

Operational constraints also limit implementation. Equation (17) presents Bond's comminution principle, showing that achieving smaller particle sizes requires progressively higher energy inputs (Strefler *et al*., 2018):

$$\mathbf{E = 10W_i\ (1/\sqrt{P} - 1/\sqrt{F})} \quad 17$$

In resource-limited agricultural systems across rural Africa, such energy requirements may restrict large-scale adoption unless local processing systems and decentralized supply chains are developed. Socioeconomic constraints, including limited access to mechanization, credit, and extension services, further influence implementation potential (Pretty *et al*., 2011).

7.3 Opportunities Specific to Semi-Arid Regions

Despite these challenges, semi-arid regions present unique opportunities. Abundant agricultural residues (maize stalks, sorghum stover, groundnut shells) provide local biochar feedstock (Woolf *et al*., 2010). Local basalt deposits (e.g., River Bunsuru in Zamfara State) enable local sourcing, reducing transport distances and emissions (Dada *et al*., 2013; Obaje, 2009). Large areas of degraded land require restoration, creating demand for soil amendments that sequester carbon while improving fertility (Lal, 2015). Smallholder farmers are highly responsive to visible yield benefits, and the documented yield increases from basalt and biochar (10-25%) may drive voluntary adoption (Kelland *et al*., 2020; Pretty *et al*., 2011; Gurwick *et al*., 2013). Finally, the large land area under agriculture in semi-arid regions (millions of hectares) creates substantial CDR potential.

The major constraints to enhanced weathering in semi-arid agroecosystems and the potential mechanisms through which biochar may modify these constraints are summarized in Figure 4.

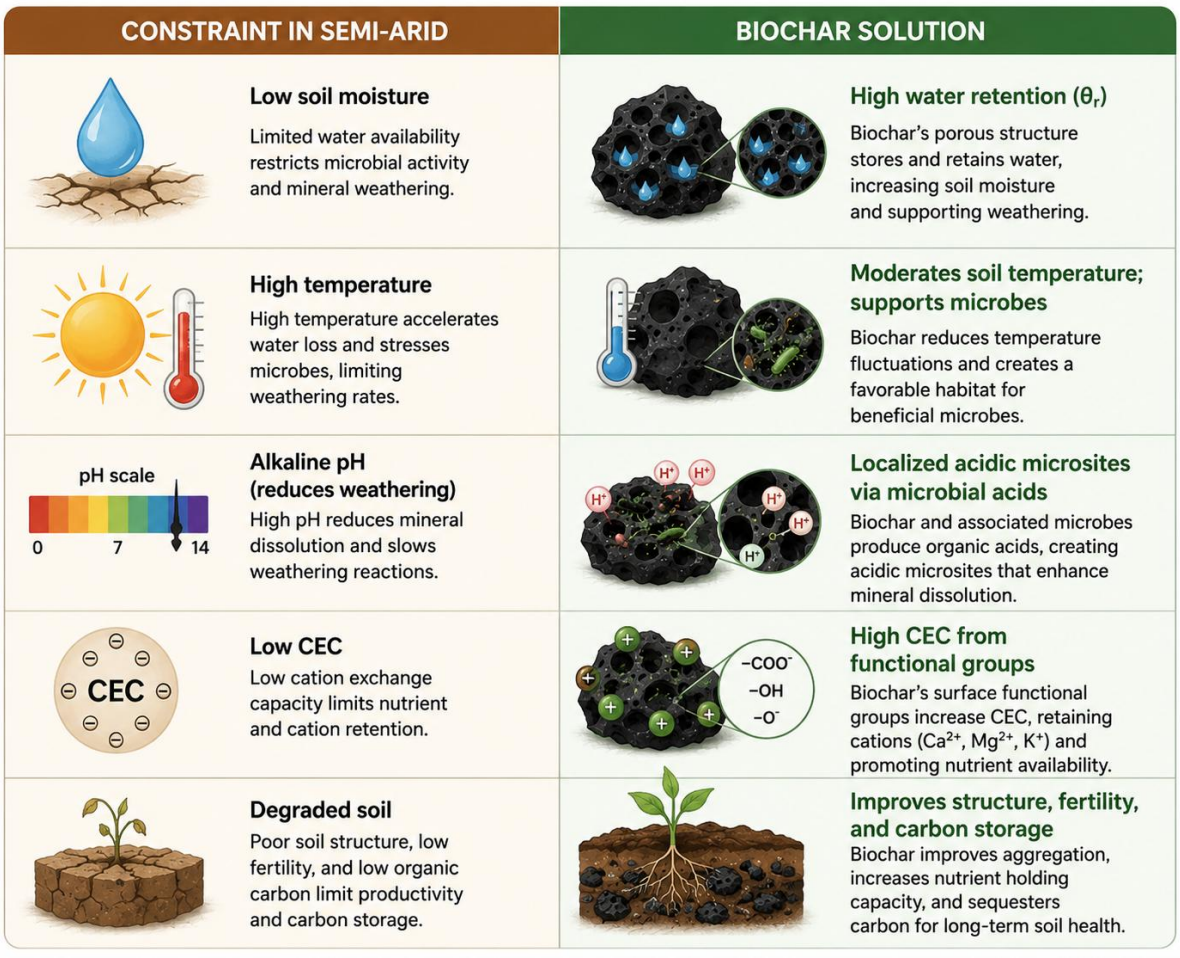


Figure 4. Major constraints to enhanced silicate weathering in semi-arid agroecosystems and potential mechanisms through which biochar co-application may modify these constraints.

7.4 Future Research Priorities for Semi-Arid Regions

Future research priorities in semi-arid regions such as Zamfara State, Nigeria, should include: (1) characterization of local basalt deposits for mineralogical composition and CDR potential; (2) production and optimization of biochar from locally available biomass (e.g., maize cobs, rice husks, groundnut shells); (3) long-term field trials with control, basalt-only, biochar-only, and basalt+biochar treatments under natural wet-dry cycles; (4) quantification of CDR rates, soil fertility changes, and crop productivity responses; (5) assessment of trace element dynamics (Ni, Cr) for environmental safety; and (6) socioeconomic feasibility analysis for smallholder farmers. Addressing these priorities will provide the empirical evidence needed to validate the mechanisms discussed in this review and to develop context-specific implementation frameworks for semi-arid agroecosystems.

8. Co-Benefits for Soil Fertility and Crop Productivity

Beyond CDR, biochar-basalt integration offers multiple agronomic co-benefits. Plant-available water content, defined in Equation (18), increases because biochar raises water content at field capacity (θ_fc) without significantly affecting the permanent wilting point (θ_wp) (Basso *et al*., 2013):

$$\theta aw = \theta fc - \theta wp \quad (18)$$

Cation exchange capacity (CEC) also improves. Equation (19) shows that total CEC equals the native soil CEC plus the biochar CEC multiplied by the biochar application ratio (Lehmann & Joseph, 2015):

$$CEC_total = CEC_soil + (CEC_biochar \times R_biochar) \quad (19)$$

The release of base cations from basalt weathering follows first-order kinetics, as shown in Equation (20), where Q(t) is the cumulative mass released by time t, Q_0 is the total weatherable cation pool, and k is the rate constant (Renforth *et al*., 2015):

$$Q(t) = Q_0 \times (1 - e^{(-kt)}) \quad (20)$$

Crop yield response to combined amendments is expressed in Equation (21), where ε_biochar and ε_basalt are fractional yield increases from individual amendments and ε_synergy represents additional benefit from combined application (Liu *et al*., 2023):

$$\mathbf{Y_response = Y_control \times (1 + \varepsilon_biochar + \varepsilon_basalt + \varepsilon_synergy)} \quad 21$$

Meta-analyses indicate average yield increases of approximately 10%, with greater responses in acidic, sandy, and nutrient-poor soils (Jeffery *et al*., 2011; Biederman & Harpole, 2013). Additionally, biochar reduces N_2O emissions, as shown in Equation (22), where f_reduction typically ranges from 0.3 to 0.5 (Cayuela *et al*., 2014; Borchard *et al*., 2019).

$$\mathbf{N_2O_emission(reduced) = N_2O_emission(control) \times (1 - f_reduction)} \quad 22$$

Since N_2O has a global warming potential approximately 298 times that of CO_2, this reduction is significant for overall climate benefits.

9. Environmental Risks and Life Cycle Considerations

Trace element release, particularly nickel and chromium, is a primary environmental concern. Equation (23) shows that nickel concentration in soil solution depends on the total nickel applied (M_Ni), the soil volume (V_soil), and the fraction released during weathering (f_release) (Pogge von Strandmann *et al*., 2021):

$$\mathbf{C_Ni(solution) = (M_Ni / V_soil) \times f_release} \quad 23$$

where (M_{Ni}) is the total Ni introduced with the amendment, (V_{soil}) is the soil-water or soil-volume basis used for the calculation, and (f_{release}) is the fraction assumed to become mobile.

For typical basalt application (20 t ha^{-1} with 200 mg kg^{-1} Ni), nickel addition ranges from 2-4 kg ha^{-1}, distributed through 1.5 × 10^6 kg of topsoil, representing 1.3-2.7 mg kg^{-1} soil—within natural background ranges (Alloway, 2013). However, long-term monitoring is recommended.

The net carbon balance of the integrated system is expressed in Equation (24), where positive ΔC_net indicates net carbon removal (Strefler *et al*., 2018; Woolf *et al*., 2010):

$$\Delta C_{net} = C_{weathering} + C_{biochar} - E_{mining} - E_{crush} - E_{transport} - E_{pyrolysis}$$ 24

Basalt processing emits 0.1-0.5 t CO_2e t^{-1}, which must be offset by CDR over the weathering period. Using locally sourced materials minimizes transport emissions and is strongly recommended for semi-arid deployment.

10. Conclusion

The central finding of this review is that biochar and basalt are not merely additive amendments, they address fundamentally different but complementary constraints on CDR in semi-arid soils. Basalt supplies the mineral substrate for silicate dissolution and long-term carbon sequestration, while biochar targets the soil physical and biological conditions that determine whether that dissolution can actually proceed under moisture-limited, high-temperature, and alkaline conditions. The six synergistic mechanisms identified in Section 6 collectively explain why their combination has the potential to outperform either amendment alone, though it must be acknowledged that empirical evidence for this synergy under dryland field conditions does not yet exist. Generating that evidence is the most pressing research priority this review has identified. The geochemical logic is compelling; the field proof remains outstanding.

The semi-arid context matters enormously to the outcome. Water limitation, alkaline pH, diurnal temperature extremes, and the energy demands of basalt grinding each reduce ESW efficiency relative to temperate benchmarks. But these same conditions abundant biomass residues, accessible basalt deposits, severely degraded soils, and smallholder farmers acutely responsive to yield improvements also create a distinctive opportunity that temperate agricultural systems do not offer. Sub-Saharan Africa is not simply a harder version of Europe for ESW deployment; it is a qualitatively different environment requiring its own evidence base and implementation logic.

The agronomic co-benefits documented in this review improved plant-available water, enhanced CEC, release of base cations, crop yield increases of 10–20%, and N_2O emission reductions of 40–50% provide a pragmatic entry point for farmer adoption that does not depend on an understanding of CDR. Trace element risks, particularly from nickel, appear manageable at typical basalt application rates, though long-term monitoring and attention to chromium

speciation are warranted. The net carbon balance is achievable with local sourcing but will need careful life-cycle quantification for the Zamfara setting specifically.

Field research currently underway in Zamfara State is well-positioned to address these gaps directly. Results from that programme will be especially valuable if they report CDR rates, weathering proxies, soil fertility indicators, and crop yield data alongside each other, allowing for the first integrated empirical test of the biochar-ESW synergy under real dryland conditions. When those results emerge, this review will have provided the conceptual framework needed to interpret them. What the field still needs is the data to confirm, refine, or challenge that framework — and Zamfara is where that work begins.

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