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Biochar Systems for Climate Change Mitigation and Soil Restoration in Sub-Saharan Africa: A Comprehensive Systematic Review

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Abstract

This systematic review assesses the policy implications of advancing biochar systems for climate mitigation, soil restoration, and climate-resilient agriculture in Sub-Saharan Africa (SSA), using Kenya as a focal case. Following PRISMA 2020 guidelines, it analyzes peer-reviewed literature from 2010-2025. Biochar derived from agricultural and forestry residues consistently improves soil structure, pH, water retention, and nutrient availability, with field-scale crop yield increases typically ranging from 10% - 40%. Benefits are most pronounced in degraded, acidic soils when biochar is combined with organic or inorganic fertilizers. It also reduces nitrous oxide and methane emissions through improved soil aeration and nitrogen retention, while stabilizing soil organic carbon, specifically, from high-temperature, lignin-rich feedstocks. Africa's substantial biomass resource, exceeding 500 million tonnes of annual crop residues, presents significant technical potential. Case studies from Kenya, Nigeria, Ethiopia, South Africa, and the Sahel demonstrate agronomic, climate, and energy co-benefits within circular bioeconomy frameworks. However, scaling adoption faces pervasive challenges requiring targeted policy intervention. Technical constraints include rudimentary kilns and heterogeneous feedstocks producing inconsistent biochar quality. Institutional barriers involve weak Measurement, Reporting, and Verification (MRV) systems and fragmented policies failing to integrate biochar across agriculture, energy, waste, and climate sectors. Socioeconomic obstacles, such as high reactor costs, labor-intensive feedstock collection, limited credit access, and immature carbon markets, can further restrict smallholder uptake. Ethical concerns regarding residue competition, land-use change, and equitable benefit-sharing remain under-addressed in current governance frameworks. The SSA experience, exemplified by a number of countries including Kenya, encapsulates this duality: clear benefits for yields and mitigation contrast with the absence of long-term trials, national standards, and certified carbon methodologies. We conclude that unlocking biochar's potential as a strategic pillar of climate-smart agriculture requires coherent policy action. Priorities include developing Africa-appropriate reactor technologies and quality standards; establishing robust, low-cost MRV frameworks to access carbon finance; enacting sustainable feedstock safeguards; and fostering inclusive, equity-sensitive governance. Ultimately, coordinated regional research networks and integrated policy alignment across sectors are essential to realize biochar's environmental and socioeconomic benefits continent-wide.

Subject Areas

Environmental Sciences

Keywords

Biochar, Climate Change Mitigation, Soil Ammendments,
Greenhouse Gas Reduction, Agricultural Residues, Sub-Saharan Africa,
Circular Bioeconomy

1. Introduction

Sub-Saharan Africa (SSA) confronts intensifying climate and environmental pressures threatening agricultural productivity, ecosystem stability, and rural livelihoods. Although contributing less than 4% of global greenhouse gas emissions, the region experiences severe climate impacts such as recurrent droughts, erratic rainfall, heatwaves, desertification, and widespread soil degradation. Over 60% of Africa's population depends on rain-fed agriculture, with more than 500 million hectares exhibiting low soil organic carbon, high acidity, nutrient depletion, and poor water-holding capacity. These constraints undermine yields and reinforce chronic food insecurity.

Against this backdrop, biochar has emerged as a strategically important climate-soil intervention. Produced through controlled pyrolysis of organic biomass, biochar contains stable aromatic carbon structures persisting in soils for decades to centuries, providing durable carbon sequestration. Its application enhances soil structure, increases cation exchange capacity, moderates acidity, improves hydrology, and supports beneficial microbial communities. Across SSA, field studies consistently report 10% - 40% yield increases when biochar is co-applied with compost or mineral fertilizers.

Africa's abundant agricultural residues, including maize stover, rice husks, cassava peels, coffee husks, millet residues, and sugarcane bagasse, offer significant untapped potential. The continent generates over 500 million tonnes of residues annually, much openly burned or wasted. Converting these residues to biochar aligns with circular bioeconomy goals by transforming waste into soil amendments and carbon-negative products. Kenya, Nigeria, Ethiopia, and South Africa have begun piloting biochar systems linked to soil rehabilitation, clean cooking, and renewable energy co-benefits. Few SSA countries provide an instructive case due to their diverse agroecological zones and broad feedstock base. Local research demonstrates biochar's ability to improve soil fertility, moisture stabilization, and emissions reduction. However, adoption remains constrained by inconsistent reactor technologies, variable biochar quality, limited long-term field data, and gaps in policy, financing, and Measurement, Reporting, and Verification (MRV) systems; these are some of the challenges that reflect broader continental constraints. Weak extension services, competing residue uses, seasonal availability, and high transport costs further limit scalable production and farmer uptake.

Given the region's urgent need for climate-resilient agriculture, sustainable waste management, and verifiable carbon sequestration pathways, this systematic review evaluates biochar systems across SSA, laying emphasis on selected SSA countries, Kenya among them, with a view to assessing feedstock potential, production approaches, soil and climate mechanisms, field-level outcomes, and institutional factors shaping implementation. By integrating findings from over a decade of research, the review identifies practical opportunities, persistent knowledge gaps, and strategic actions needed to scale biochar as a robust, equitable, and scientifically grounded pillar of Africa's climate-smart agriculture transition.

2. Methodology

This review follows PRISMA 2020 guidelines for systematic reviews. We formulated research questions such as:

1) What biochar feedstocks, pyrolysis temperatures, and modifications have been used in African studies, especially in Kenya?

2) What mechanisms have been documented for GHG mitigation (adsorption, microbial suppression, etc.)?

3) How do biochar applications affect soil physical, chemical, and biological properties, and crop yields in field settings?

4) What are the barriers, cost issues, and policy frameworks relevant to scaling in Africa in general and Kenya in particular?

3. Search Strategy (PRISMA 2020 Guidelines)

This systematic review followed PRISMA 2020 guidelines to comprehensively assess biochar systems for climate mitigation and soil restoration in Sub-Saharan Africa, with a number of countries such as Kenya as focal cases. The search strategy targeted Web of Science, Scopus, CAB Abstracts, and Google Scholar using combinations of keywords including "biochar," "Africa," "greenhouse gas," "soil amelioration," "amine modification," and "pyrolysis." Filters limited publications to peer-reviewed articles, field studies, pot experiments, and soil incubation studies published between 2010 and 2025. A total of 250 records were identified across all databases. After duplicate removal and title-abstract screening, 132 records met the pre-established inclusion criteria requiring quantitative measures of GHG emissions or adsorption, soil physical/chemical changes, yield outcomes, and use of African or comparable tropical soils. Of these, 91 full-text articles were successfully downloaded and subjected to detailed review and synthesis (Table 1).

Table 1. Summary of studies and articles included for detailed review.

Thematic Group	No. of articles	Sources	Sub-topics Covered	Summary of Main Conclusions
GHG Emissions & Inventories	12	[1]-[12]	National/regional GHG inventories; sectoral emissions (agriculture, energy, industry); drivers of anthropogenic emissions; emission trends 1990-2018	Africa contributes growing GHG emissions driven by agriculture, energy use, and land-use change. Most countries lack robust, up-to-date national inventories. Reducing agricultural and energy sector emissions is critical for climate commitments across the continent.
Climate Change Science & Impacts	9	[10] [12]-[19]	IPCC physical science basis; extreme temperature events; desertification; flooding & water quality; coastal impacts; food insecurity; disease vectors (malaria)	Multi-domain impacts (desertification, flooding, food insecurity, disease) compound across semi-arid and coastal regions, demanding integrated adaptation.
Biochar Properties & Production	8	[20]-[27]	Feedstock types and effects; pyrolysis temperature; physicochemical properties; low-tech production methods; IBI standards; biochar stability	Feedstock and pyrolysis temperature determine properties; low-tech methods suit developing-world contexts. IBI protocols ensure quality and reproducibility.
Biochar & Soil Health	13	[28]-[40]	Soil fertility; pH improvement; nutrient availability (NPK); soil biota and microbial communities; soil organic carbon; aggregate stability; acid soil reclamation	Biochar improves fertility, pH, nutrient retention, and microbial diversity—most effective on degraded, acidic, or sandy African soils. Biochar-compost combinations amplify gains.
Biochar & GHG Mitigation	12	[34] [41]-[50]	N_2O and CH_4 emission reduction; meta-analyses on biochar-GHG relationships; carbon sequestration; biochar as CDR strategy; biochar in climate policy	Biochar cuts N_2O emissions and sequesters carbon; meta-analyses confirm net GHG reductions across agroecosystems, establishing it as a viable nature-based CDR tool.
Biochar in Africa: Opportunities & Constraints	9	[10] [51]-[59]	Biochar adoption in SSA; socioeconomic barriers; smallholder farming contexts; country-specific reviews (Ghana, Tanzania, Uganda, Cote d'Ivoire, Kenya); bibliometric trends	Cost, feedstock access, and knowledge gaps constrain uptake—yet smallholder tropical soils offer high returns. Policy support, carbon markets, and training are the critical scaling levers.

Continued

Biomass, Feedstocks & Bioenergy	**10**	[52] [60]-[68]	Agricultural residues for biochar/energy; biomass potential (Ghana, Sudan, Egypt); charcoal production; date palm waste; nano-biochar; woody biomass; higher heating values	Africa has abundant underutilised biomass (rice husk, straw, wood). Pyrolysis-based valorisation of agricultural residues aligns with circular economy principles.
Crop Yield & Agricultural Productivity	**12**	[28] [29] [38] [42] [43] [68]-[73]	Biochar effects on crop yields; maize, teff, rice, wheat; smallholder farm trials; nitrogen use efficiency; enzyme activity; long-term agronomic experiments	Biochar lifts yields across crops and farming systems, especially on nutrient-poor soils, with effects sustained over multiple seasons. Kenya and Ghana farm trials confirm realistic application rates work.
Carbon Markets & Climate Finance	**5**	[74]-[78]	Voluntary carbon markets; soil carbon certificates; carbon crediting credibility; LCA for MRV; cost of CDR; blue carbon accounting; forest carbon crediting	Carbon markets can incentivise land-based CDR, but MRV credibility gaps persist. Soil carbon certificates show promise but need robust LCA frameworks; permanent CDR costs remain high.
Land Use, Degradation & Restoration	**9**	[15] [79]-[86]	Land use/land cover change; land degradation neutrality; conservation agriculture; bush encroachment; landscape restoration; desertification; soil rotation systems	Degradation undermines productivity and ecosystem services. Remote sensing (LULC) and conservation agriculture provide scalable monitoring; biochar-integrated rotations aid rehabilitation.
Climate Change Adaptation & Policy	**7**	[14] [84] [85] [87]-[90]	Energy demand & GHG policy (Kenya); climate variability perceptions; adaptation barriers in SSA; climate education; aquaculture and emissions; agricultural GHG mitigation policy	Technical interventions need policy backing—energy efficiency and agricultural GHG policies remain underdeveloped. Closing the gap between farmer perception and scientific evidence is essential for CSA uptake.
Soil Biogeochemistry & Trace Gases	**6**	[21] [35] [39] [66] [70] [91]	Soil microbial control of trace gases (N_2O, CH_4, CO); paddy soil aggregation; soil C and N dynamics; redox properties; faecal sludge in agriculture	Microbial communities, regulated by organic carbon inputs including biochar, control trace gas fluxes from agricultural soils. Understanding these pathways is foundational for emission reduction design.

4. Inclusion/Exclusion Criteria

Included: studies reporting quantitative and qualitative measures of GHG emissions or adsorption, soil physical/chemical changes, yield changes, using African or comparable tropical soils. Excluded: studies only modeling without empirical data, non-soil/biochar adsorbent work unless directly relevant (e.g., highly similar feedstocks).

5. Data Extraction and Synthesis

For each study, we extracted: feedstock type; pyrolysis conditions (temperature, time); any modifications (e.g., amine, metal); soil type; biochar application rate; outcome metrics (CO_2 adsorption, CH_4/N_2O emissions, SOC, pH, CEC, water retention, yield); and study duration. Accordingly, results were grouped thematically by mechanism (adsorption vs. soil-mediated), geography (Kenya vs. other African countries), and scale (lab vs. field). Because this was a systematic review rather than a meta-analysis, the synthesis was primarily qualitative in nature.

This table provides a comparative overview of the dominant greenhouse gas (GHG) emission sources across twelve African countries, distinguishing between rural, urban, and geological/natural contributions. It also highlights regions with high potential for biochar-based mitigation, linking agricultural residue management to emission reduction and soil restoration opportunities. The dataset integrates national and subnational inventories, published literature, and modelled estimates of residue-derived carbon offsets. Major emission drivers include biomass and residue burning, enteric fermentation, fossil fuel combustion, and waste-derived methane (CH_4). Geological and geothermal sources (e.g., Rift Valley degassing and volcanism) are comparatively minor but included for completeness. Geological GHGs include degassing and geothermal sources (notably in Ethiopia, Kenya, and Tanzania).

6. Limitations

Potential biases include publication bias (positive results reported more often), heterogeneity in reporting (units, measurement protocols), scarcity of long-term data, and relatively few studies on amine-modified biochars in African field conditions.

7. Dynamics and Rationale for Biochar Adoption in Sub-Saharan Africa

Greenhouse gases, which are primarily CO_2, CH_4, and N_2O, are the chief drivers of global warming, intensifying droughts and destabilizing ecosystems. Although Africa contributes less than 4% of global GHG emissions, it experiences disproportionate climate impacts: recurrent droughts, rapid desertification, erratic rainfall, widespread soil degradation, and crop failure, reinforcing persistent food insecurity. Kenya exemplifies these inequities, with over 80% of its land arid or semi-arid, making it highly vulnerable to climatic shocks. Agriculture remains a major emission source through livestock methane, fertilizer-derived N_2O, manure mismanagement, open residue burning, deforestation, and inefficient biomass energy use. Productivity is further constrained by declining soil organic carbon (SOC), nutrient depletion, and extensive land degradation.

GHG emissions vary across African countries. Rural emissions are dominated by biomass burning and livestock methane, while urban emissions stem from transport and unmanaged waste [87]. Geological emissions are locally significant in Rift Valley regions [92]. Despite minimal global contribution, Sub-Saharan Africa (SSA) faces severe climate consequences, including droughts, heat extremes, desertification, and disease shifts such as malaria expanding into highlands [13]. Dependence on rain-fed agriculture and widespread degradation weaken resilience, driving various humanitarian crises. Addressing these inequalities requires international support such as climate-responsive financing, technology transfer, and compensation for climate-induced losses. Table 2 summarizes these major GHG sources and the mitigation potential of biochar across 12 African countries.

Table 2. Comparative analysis of greenhouse gas (GHG) emission sources and biochar mitigation potential across selected African countries.

Country	Major GHG Sources	Major Urban GHG Sources	Geological/Natural GHGs	References
Nigeria	Enteric fermentation, Savannah burning, residue open burning	Fossil fuel combustion, waste CH_4, transport	Minor natural emissions; limited volcanic activity	[2] [93]
Kenya	Biomass burning, manure, post-harvest loss	Transport, landfill, industry	Rift Valley geothermal degassing (low)	[88]
Ghana	Residue burning, charcoal production	Urban energy, waste CH_4, transport	Negligible volcanic sources	[89] [94]
Tanzania	Residue burning, livestock CH_4	Transport, municipal waste	Volcanic/tectonic zones (northern Rift)	[95]
Uganda	Residue burning, livestock CH_4	Waste, transport	Rift geothermal seeps (low)	[60]
South Africa	Field burning, manure, coal use	Coal power, transport, landfill CH_4	Minor; no active volcanism	[3]
Ethiopia	Cereal straw burning, livestock CH_4	Transport, industry, landfill	Active volcanism/geothermal in Rift	[4]
Egypt	Rice straw burning, irrigation losses	Urban fossil CO_2, waste CH_4	Limited geological GHGs	[5]
Sudan	Savanna burning, crop residues	Urban combustion, landfill CH_4	Natural seepage (low)	[6]
Morocco	Cereal straw, olive residues	Transport, industry, landfill	No major volcanic sources	[7]
Algeria	Cereal straw, date-palm residues	Urban fossil emissions, waste CH_4	Hydrothermal degassing (minor)	[8]
Senegal	Groundnut shells, millet straw burning	Waste, transport	Coastal marsh CH_4; minimal geological	[9]

This table provides a comparative overview of the dominant greenhouse gas (GHG) emission sources across twelve African countries, distinguishing between rural, urban, and geological/natural contributions. It also highlights regions with high potential for biochar-based mitigation, linking agricultural residue management to emission reduction and soil restoration opportunities. The dataset integrates national and subnational inventories, published literature, and modelled estimates of residue-derived carbon offsets. Major emission drivers include biomass and residue burning, enteric fermentation, fossil fuel combustion, and waste-derived methane (CH_4). Geological and geothermal sources (e.g., Rift Valley degassing and volcanism) are comparatively minor but included for completeness. Geological GHGs include degassing and geothermal sources (notably in Ethiopia, Kenya, and Tanzania).

National GHG inventories across Africa remain incomplete partially because spatially explicit data are scarce, and agriculture and waste emissions are poorly captured. These gaps weaken mitigation baselines and complicate biochar interventions. Strengthening monitoring networks and technical capacity is therefore essential for refining emission estimates.

Broader mitigation efforts are constrained by limited financial resources, weak Measurement, Reporting, and Verification (MRV) systems, and competing development priorities. High technology costs and uncertain returns inhibit adoption of soil-centered options among smallholder farmers. Within this context, biochar presents a promising pathway: it relies on local residues, restores degraded soils, improves crop productivity, and offers scalable carbon sequestration.

Biochar is a porous, carbon-rich material from pyrolysis that is known to enhance soil structure, water retention, nutrient efficiency, and microbial function while reducing CH_4 and N_2O emissions. Its functionality depends on feedstock, pyrolysis parameters, and post-treatment. For example, lignin-rich materials yield persistent char while cellulose-rich feedstocks produce more reactive forms [41]. Similarly, slow pyrolysis (300˚C - 600˚C) maximizes carbon retention; fast pyrolysis (>600˚C) generates stability but reduces yield [96]. Recent advances for Biochar modifications such as amine functionalization enhance CO_2 capture [24], but inconsistent characterization across African studies limits scalability [79] [97].

Adoption in SSA is hindered by structural and policy constraints. For example, production relies on low-efficiency kilns with high emissions, and most farmers lack access to reliable pyrolysis technologies and characterization facilities. High equipment costs, weak extension services, and inadequate policy support impede upscaling. Weak MRV systems also limit carbon market access due to high verification costs and absence of Africa-specific methodologies, weakening investment incentives. Competition for biomass in mixed crop-livestock systems further compounds feedstock challenges [20]. Various studies show that purpose-grown feedstocks risk land-use conflict and food-fuel competition and only a few African studies link feedstock characteristics to field outcomes [71]. This scenario is duplicated locally with Kenya lacking specific feedstock profiling which in turn lead to reliance on generic pyrolysis protocols.

Overcoming these barriers requires a policy change that will improve investment in low-emission pyrolysis technologies, streamline localized feedstock supply chains, and standardize MRV protocols. Embedding biochar into soil-health and climate-smart agriculture policy frameworks is therefore essential. International climate finance should prioritize biochar initiatives delivering both mitigation and adaptation benefits such as improved soil fertility, better water retention, and durable carbon sinks. Such strategies can transform Africa's climate vulnerability into an opportunity for resilient, sustainable development.

8. Potential for Biochar Production and Application in Africa

Table 3. Biochar economic & carbon potential from agricultural residues by country.

Country	Dominant Agric. Residue	Avoided CO_2e (Mt yr^{-1})	Est. Economic Potential (US$ M yr^{-1})	Selected References
Nigeria	Cassava/maize residues	20.16 - 27.00	US$958 - 1,283M (carbon: 403 - 540 + agronomy: 554 - 743)	[31]
Ethiopia	Cereal (teff/maize straw)	4.32 - 18.72	US$205 - 889M (carbon: 86 - 374 + agronomy: 119 - 515)	[98]
Kenya	Maize stover, banana, coffee husks	2.66 - 5.00	US$135 - 267M (carbon: 53 - 100 + agronomy: 82 - 167)	[71]
Ghana	Cocoa pod husk, cassava peel, rice husk	14.04	US$672M (carbon: 281 + agronomy: 386)	[52]
South Africa	Sugarcane bagasse, fruit pruning residues	4.86	US$243M (carbon: 97 + agronomy: 134)	[55] [71]
Tanzania	Rice straw, sisal residues, sugarcane bagasse	0.14 - 5.40	US$7 - 271M (carbon: 3 - 108 + agronomy: 4 - 163)	[71] [77]
Egypt	Rice straw, maize stalks, date palm	7.2 - 9.0	US$362 - 435M (carbon: 144 - 180 + agronomy: 198 - 255)	[5]
Sudan	Sorghum, millet residues	3.6 - 7.2	US$181 - 362M (carbon: 72 - 144 + agronomy: 99 - 218)	[63]
Morocco	Olive mill waste, cereal straw	1.8 - 4.3	US$91 - 218M (carbon: 36 - 86 + agronomy: 55 - 132)	[99]
Algeria	Wheat/barley straw, date palm residues	1.44 - 3.6	US$73 - 181M (carbon: 29 - 72 + agronomy: 44 - 109)	[71] [100]
Senegal	Groundnut shells, millet residues	0.72 - 2.16	US$36 - 109M (carbon: 14 - 43 + agronomy: 22 - 66)	[101] [102]
Uganda	Banana residues, maize stover	1.8 - 3.6	US$91 - 181M (carbon: 36 - 72 + agronomy: 55 - 109)	[54] [101]

Agricultural residues represent one of Africa's most significant underutilized opportunities for climate mitigation and agricultural productivity enhancement through biochar production. Nigeria, Ghana, and Ethiopia collectively generate over 150 million tonnes of crop residues annually sufficient to produce approximately 50 million tonnes of biochar and offset up to 60 million tonnes of CO_2-equivalent emissions [69]. The economic potential is substantial with estimates ranging from US$34 million in Senegal to over US$1.2 billion in Nigeria [61]. Table 3 provides a comparative overview of feedstock availability, mitigation gains, and economic value across 12 African countries. It is estimated that Africa's broader biomass resource base exceeds 500 million tonnes of agricultural residues annually [28] [54].

This table presents a comparative assessment of agricultural residue availability, potential greenhouse gas (GHG) mitigation, and corresponding economic benefits arising from biochar conversion in twelve African countries. The analysis integrates estimates of biomass supply, avoided CO_2-equivalent (CO_2e) emissions, and dual-value economic potential derived from both carbon sequestration and agronomic yield improvements. High-biomass nations such as Nigeria, Ghana, and Ethiopia exhibit the largest mitigation and economic return potential, whereas medium-scale contributors (Kenya, South Africa, Egypt) present strong opportunities for integrated climate-agriculture policies. Even smaller producers like Senegal, Algeria, and Uganda show measurable benefits under targeted local applications.

Much is currently burned or left to decompose, contributing GHG emissions and particulate pollution yet it has been demonstrated that converting residues to biochar aligns with circular-economy principles which confer advantages by transforming waste into soil amendments while supporting cleaner cooking and climate-smart agriculture. Kenya, Nigeria, Ethiopia, and South Africa have begun piloting these pathways, though operational guidelines, standardized metrics, and long-term monitoring remain limited. Table 4 shows biochar initiatives across selected African countries, including feedstocks, applications, and associated co-benefits.

Table 4. Suitable biochars and recommended co-amendments depending on soil types.

Country	Dominant soil types	Recommended Biochar (Feedstock; ˚C)	Co-amendments/Management	Key Refs.
Nigeria	Ferralsols, Acrisols, sandy loams	Cassava/maize-stover; 400˚C - 550˚C (meso/micro porosity, nutrient-rich)	Biochar + manure compost; split N-PK doses; pelletizing	[29]
Kenya	Ferralsols, Luvisols, Andosols (highland)	Banana & coffee-husk; 350˚C - 500˚C (ash-rich, liming effect)	Co-compost with manure; lime where needed; Zn micronutrients	[51]
Ghana	Ferralsols, Acrisols	Cocoa pod/cassava; 350˚C - 500℃ (K-rich, liming)	Compost/manure integration; phosphate placement in acidic soils	[52]
Tanzania	Ferralsols, Vertisols	Maize/rice-straw; 400˚C - 600˚C (balanced porosity)	Compost-biochar blends; residue retention; small N top-ups	[53]
Uganda	Ferralsols, Nitisols	Banana/maize; 350˚C - 500˚C	Farmyard manure co-application; mulching for wettability	[54]
South Africa	Chromic Luvisols, Mollisols, sandy soils	Sugarcane/wood; 600˚C - 700˚C (stable C, long-term SOC)	Manure/green compost; targeted P management on calcareous soils	[30]
Ethiopia	Vertisols, Nitisols, Andosols	Cereal-straw/woody mix; 450 - 650˚C (suits Vertisols)	Compost co-application; conservation tillage; gypsum on sodic patches	[31]

Continued

Egypt	Nile alluvial soils, Calcisols	Rice-husk/maize-stalk; 500˚C - 700˚C (silica-rich, useful in paddy)	N management in rice; compost for structure; residue retention	[62]
Sudan	Arenosols, Vertisols	Cereal-straw; 400˚C - 600˚C	Mulch + biochar for wind erosion; manure composting; N inputs	[63]
Morocco	Calcisols, Cambisols	Olive-mill/cereal; 400˚C - 600˚C (variable ash)	Organic compost; gypsum on saline spots; irrigation scheduling	[64]
Algeria	Calcisols, Regosols	Cereal straw/date-palm; 400˚C - 600˚C	Compost + biochar; salt management (leaching, gypsum)	[65]
Senegal	Ferralsols, Arenosols	Groundnut shell/millet straw; 350˚C - 550˚C	Biochar-compost blends; mulching; targeted fertilizer	[32]

Soil-biochar compatibility across twelve African countries, detailing optimal feedstocks, indicative pyrolysis temperatures, and co-amendments for enhanced soil fertility and resilience. Biochar properties (porosity, surface chemistry, ash alkalinity, and nutrient content) are matched to dominant soil types (Ferralsols, Acrisols, Andosols, Vertisols, Calcisols, and others) to maximise agronomic performance. Each entry specifies the most suitable biochar type (s) and compatible co-management practices, including composting, liming, and mulching.

Various studies show that SSA's potential can be strengthened by diverse

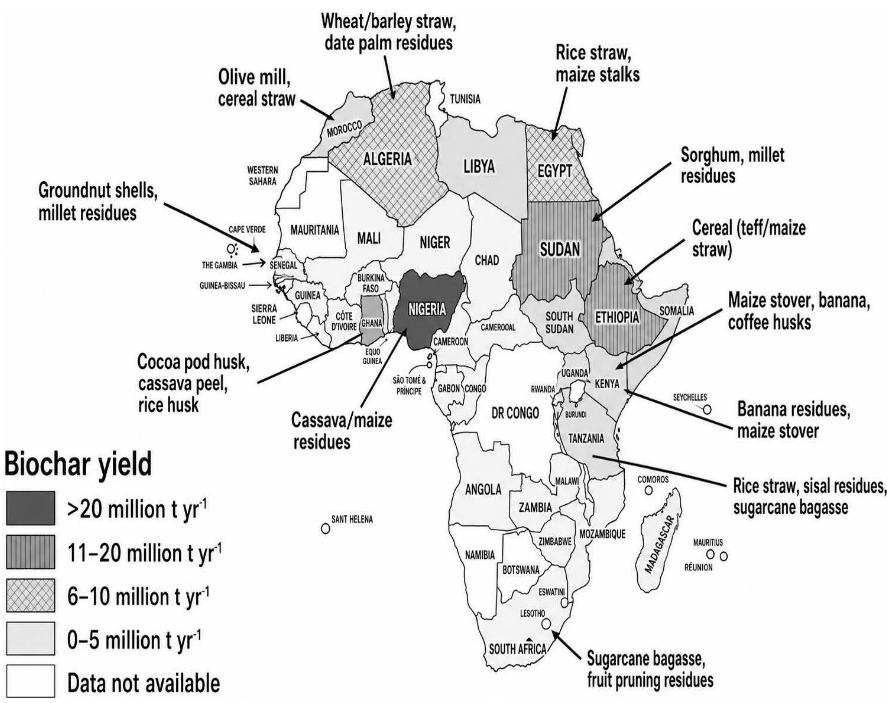

Figure 1. Distribution of agricultural biomass residues and potential biochar yield across Africa. This map illustrates the major types of agricultural biomass residues available in selected African countries and their estimated annual potential for biochar production. Countries are shaded according to projected biochar yield, ranging from less than 5 million tonnes to more than 20 million tonnes per year.

feedstocks: maize stover [58] [69], cassava peels, sugarcane bagasse, and rice husks [28] [55]. **Figure 1** illustrates residue distribution and biochar-yield potential, while **Figure 2** highlights biomass availability patterns in selected African Countries. The source references for the two figures are the same as those listed in **Table 4**.

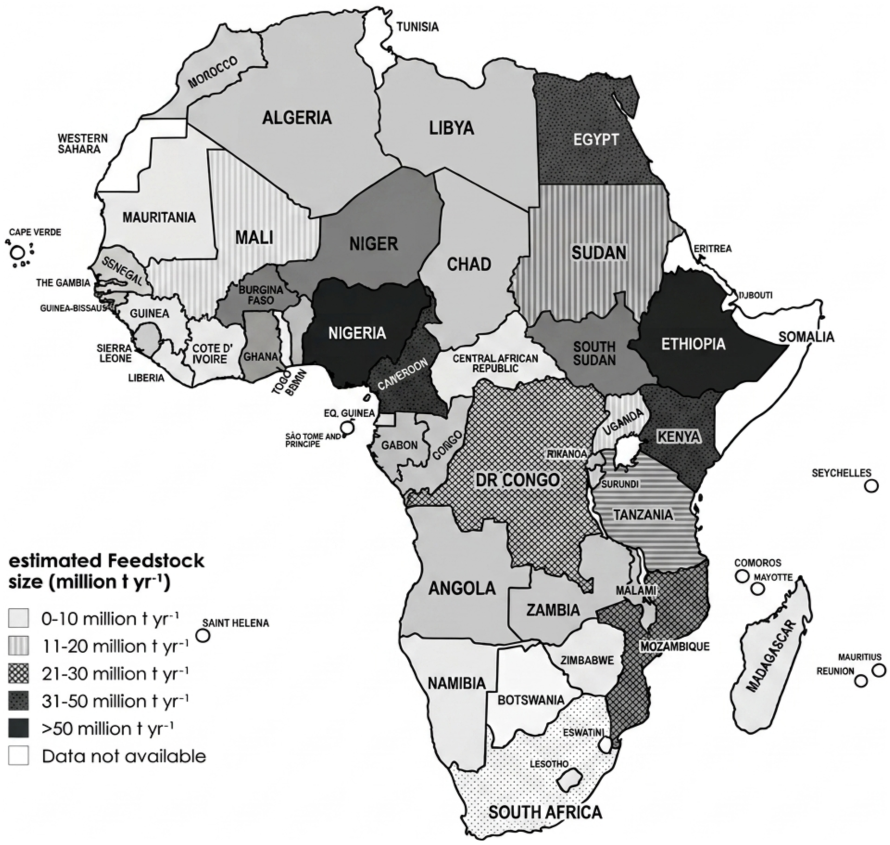

Figure 2. Estimated agricultural biomass feedstock availability across African Countries.

Estimated annual agricultural biomass feedstock availability across selected African countries (million tonnes/year). Countries are colour-coded into five tiers (<10, 11 - 20, 21 - 30, 31 - 50, and >50 million tonnes/year); white shading indicates missing or incomplete data. Nigeria, Ethiopia, Egypt, and Ghana emerge as high-yield priority regions for large-scale bioresource and biochar production. Feedstock estimates encompass cereal straw, maize stover, rice husks, sugarcane residues, legume and root-crop by-products, and other region-specific agricultural residues. The map is intended to inform regional planning for bioenergy, biochar production, climate-smart agriculture, and circular bioeconomy strategies.

When pyrolyzed, these residues could impact of mitigate open burning, reduce GHGs, and generate fertilizer alternatives. Africa could benefit from uptake of biochar, a product that has been demonstrated to improve soil fertility and moisture retention, increase carbon stocks, and improve ecosystem productivity [66].

Despite this promise, deployment across sub-Saharan Africa (SSA) remains constrained by systemic challenges such as competition for residues as livestock feed, fuel, or bedding. Seasonal supply fluctuations and fragmented supply chains are common in this region. Localized residue mapping, cooperative aggregation models, and pre-processing strategies (densification, drying hubs, pelletization) could reduce supply volatility and improve feasibility [10].

Availability estimates often overlook competing uses and opportunity costs, potentially overstating sustainable potential. From the foregoing, localized assessments incorporating socio-economic and ecological constraints are essential. Emerging solutions based on policies that focus on development of community cooperatives, decentralized aggregation points, and access to mobile pyrolysis units could bridge theoretical and practical potential while strengthening rural value chains. Biochar technologies also been demonstrated to have a potential to provide energy and climate-resilience co-benefits. For example, small-scale gasifier cookstoves and community pyrolysis systems could deliver cleaner cooking energy while generating biochar as by-product. While generation of policies to enhance and enforce these practices is still at its nascent stage, Kenya, Nigeria, and South Africa are advancing pilot projects that are integrating biochar into national climate strategies and clean-energy agendas [56] [84] [103]. With supportive, robust frameworks, stronger capacity, and market linkages, SSA could become a global hub for sustainable biochar innovation.

Yet scale-up remains limited by high pyrolysis equipment costs, inadequate maintenance, and insufficient demand aggregation. Blended finance mechanisms incorporating public-private grants, microcredit, concessional funding, and subsidies could strengthen business models, alongside enterprise incubation and government procurement for land restoration. These efforts, which generally align with climate commitments and livelihood priorities, would in turn accelerate deployment while ensuring long-term environmental and socio-economic benefits.

9. Mechanisms of Biochar for Climate Mitigation in Africa

Biochar constitutes a robust pathway for transferring biogenic carbon from short-lived pools such as crop residues, agroforestry biomass, manures, and organic wastes into long-lived soil carbon reservoirs. Through oxygen-limited thermochemical conversion, biomass carbon transforms into highly aromatic, carbon-rich solids composed of condensed polyaromatic structures that resist microbial decomposition for decades to millennia [33] [34] [42]. These black-carbon matrices enable durable climate benefits alongside agronomic co-benefits.

The carbon sequestration potential arises from three interlinked mechanisms. First, pyrolysis conversion efficiency determines carbon retention in char. Slow pyrolysis (350˚C - 550˚C) produces higher char yields, while higher temperatures promote greater aromatic condensation but lower yield; a trade-off requiring process optimization [104]. Second, intrinsic molecular recalcitrance is driven by fused aromatic clusters resisting degradation [45]. Third, soil-mineral interactions enhance stability through sorption onto clay minerals, organo-mineral complexation, and physical occlusion. These processes are significantly pronounced in weathered tropical soils where iron and aluminum oxides provide additional protection [35].

Beyond direct carbon storage, biochar reduces non-CO_2 greenhouse gases. It lowers nitrous oxide (N_2O) emissions by increasing aeration, enhancing nitrogen retention, which in turn shifts microbial pathways, and elevating soil pH [43] [44]. In flooded systems, biochar reduces methane (CH_4) generation and release by altering redox conditions and suppressing methanogenic archaea [85]. Biochar also improves fertility and water-holding capacity, enabling yield gains that reduce pressure for land conversion; an indirect mitigation pathway [105]. Global modelling estimates that sustainably sourced biochar could sequester 0.3 - 2.0 Gt CO_2-equivalent annually [22]. When integrated with renewable energy co-products, pyrolysis systems further enhance climate performance and rural energy access [22].

Despite these positive attributes, a persistent challenge is the disconnect between grassroots implementation and verified mitigation outcomes in Sub-Saharan Africa as far as biochar uptake is concerned. A review of available literature shows that many smallholder initiatives lack standardized MRV frameworks. Additionally, Weaknesses in biomass documentation, production variation, and limited soil-carbon measurement capacity contribute to uncertainty in quantifying benefits. These constraints are exacerbated by insecure land tenure, weak institutions, and inequitable benefit-sharing. These hurdles severely limit carbon market participation and climate finance access [14]. Without demonstrable proof of carbon permanence, communities remain excluded from voluntary markets and Paris Agreement Article 6.4 mechanisms [74].

Addressing these bottlenecks requires a multi-prong approach such as strengthening of community-centered MRV systems, access to low-cost soil sampling tools, improved digital data management, a robust remote sensing platform for biomass tracking, and simplified carbon-accounting protocols tailored to smallholder contexts. Aligning local initiatives with national climate strategies and Nationally Determined Contributions (NDCs) would enhance policy coherence. Transparent benefit-sharing, secure land tenure, and inclusive governance are also critical for communities to capture economic and ecological gains. When effectively integrated, biochar transitions from a niche amendment to a credible, scalable, and equitable solution for long-term carbon sequestration, rural livelihoods, and sustainable land management.

10. Application of Biochar for Soil Remediation in Africa

Sub-Saharan Africa (SSA) faces intersecting climate and agricultural challenges that elevate biochar's strategic importance for soil restoration and climate mitigation. The region's vulnerability to droughts, heatwaves, erratic rainfall, erosion, and desertification partially stems from dependence on rain-fed agriculture and fragile land resources. Across East, West, and Southern Africa, over 500 million hectares are degraded, with productivity constrained by low soil organic carbon (SOC), nutrient depletion, high acidity, and poor water retention [80] [106]. These limitations directly contribute to food insecurity, underscoring the need for scalable soil-regeneration options.

Biochar's value lies in its physicochemical stability and capacity to rebuild soil health. Containing stable aromatic carbon persisting for decades to centuries [46], its porous architecture enhances water retention, soil aggregation, and cation exchange capacity (CEC) in weathered tropical soils [80]. Field trials in Kenya, Ethiopia, Nigeria, and South Africa document yield increases of 10% - 40% when biochar is co-applied with compost or mineral fertilizers [51]-[53].

Chemically, biochar demonstrably raises pH, enhances CEC, and improves nutrient availability [36]. As a mild liming agent, it reduces acidity, alleviates aluminum toxicity, and increases phosphorus availability. Such benefits would significantly improve soil quality in most of Africa, including western and central Kenya where soils tend to be acidic [42] [47] [107]. On the other hand, enhanced CEC limits nutrient leaching in coarse-textured soil, an attribute that could benefit most soils along Kenya's coast and across the Sahel [66]. Studies report pH increases of 0.3 - 0.8 units and yield improvements in maize and vegetables [108], while enhancing micronutrient cycling and soil-microbiome interactions [109].

Despite demonstrable benefits of biochar, knowledge gaps persist in most African set ups. Interactions between biochar and highly weathered tropical soils dominated by kaolinite and sesquioxides remain poorly understood. Limited long-term trials, weak extension systems, and lack of standardization constrain adoption. Scaling requires strengthening soil-analytical hubs, access to subsidized testing, establishment of national quality standards, and integration of biochar into MRV policy frameworks [68].

Biochar initiatives are expanding through diverse models. Kenya's Biochar for Sustainable Soils Project, South Africa's invasive-wood pyrolysis, and Nigeria's rice-husk enterprises programs demonstrate country-specific efforts to deliberately tailor the uptake of biochar in different contexts [51]. Such programs report yield gains up to 55% alongside improved soil moisture, while rice-husk and cassava-residue biochars [110]. **Table 5** provides an overview of avaiable feedstocks, applications, and documented co-benefits associated with Biochars. In addition, community efforts in Tanzania, Uganda, and Côte d'Ivoire have demonstrated advantages for biochar utilization that result to improved access to improved household energy efficiency [53]. However, most pilots remain small-scale and lack rigorous impact assessments.

Biochar improves soil physical properties critical for climate resilience by reducing bulk density, increasing porosity, strengthening aggregate stability, and improving moisture retention [111] with different studies showing 5% - 25% increases in plant-available water [112]. Moderate application rates of biochar (2 - 10 t ha^{-1}) improves infiltration, especially with organic amendments. Studies in

Kenyan have reported improved soil infiltration leading to reduces crusting which in turn stabilize yields during drought [29]. Despite these potential and realized advantages of due of biochar for soil amendment barriers to update still exist.

Table 5. Overview of biochar initiatives across selected African countries: feedstocks, applications, and documented co-benefits.

Country	Key Projects/Focus	Feedstock & Production	Primary Applications & Benefits	Selected References
Kenya	Biochar production & energy use	Agricultural waste (crop residues, woody biomass); pyrolysis	Maize yield response to biochar on smallholder farms	[113]
South Africa	Faecal sludge & sewage treatment	Wood chips; invasive alien plants; industrial pyrolysis	Reduces wastewater bacteria & inorganic contaminant leaching	[114]
Ghana	Biochar for soil improvement	Sugarcane, maize, rice, cocoa, oil palm, sorghum, millet	Improves nutrient retention, water-holding capacity & C sequestration	[52]
Nigeria	Carbon sequestration & crop yield	Rice, millet, maize, groundnut, tomatoes, okra, onions	Climate change mitigation; improved maize growth & yield	[48]
Tanzania	Biochar effects on soil fertility & yields	Coffee, maize cobs	Climate change mitigation; improved crop growth & yield	[53] [110]
Côte d'Ivoire	Biochar as clean energy source	Low-income household energy (no grid access)	Biogas purification; cooking fuel briquettes	[58]
Senegal	Biochar effects on soil fertility	Cotton sorghum, millet stems, *Typha australis*	Increased fertilizer efficiency, C sequestration, pH management in sandy soils	[32]
	Biophysical properties of crop-residue biochar	Rice, millet, groundnut, banana grain & residues	C sequestration potential & co-benefits of crop residue biochars	[54]

This table summarizes ongoing and recent biochar initiatives across Africa, emphasizing how diverse biomass resources are being transformed into value-added products through pyrolysis technologies. Each project demonstrates region-specific innovation in biochar production, application, and knowledge transfer, mainly focused on linking climate mitigation, soil health restoration, and rural livelihoods. The listed initiatives include both research-led and community-based models spanning East, West, and Southern Africa, with a focus on feedstock type, scale of production, and observed or reported benefits. Collectively, these initiatives highlight the continent's emerging biochar transition pathways, addressing both agricultural productivity and low-carbon development goals.

11. Long-Term Soil Carbon Persistence and Productivity

Gains from Biochar in Sub-Saharan Africa: Biochar contributes to climate mitigation through agronomic benefits and direct reductions in N_2O and CH_4 emissions by improving soil aeration, enhancing nitrogen retention, and supporting microbial pathways that convert N_2O to N_2. Emerging modified biochars such as amine-functionalized and metal-doped variants show promise for cost-effective carbon capture in African contexts [10] [61]. In addition, Biochar aligns well with Nationally Determined Contributions (NDCs) and rural development priorities.

The temporal behaviour of biochar is central to understanding its long-term sequestration potential. Immediately after application, biochar increases soil pH, CEC, and water-holding capacity, whose effects are strengthened when co-applied with compost or fertilizer [20]. Over longer periods, biochar persistence varies with feedstock quality, pyrolysis temperature, and soil conditions. For example, High-temperature biochars form decomposition-resistant structures lasting decades to centuries, while lower-temperature chars break down more rapidly [51] [73] [88]. Gains in soil organic carbon (SOC), porosity, and structure often persist for over a decade following sustained treatment with biochar [67] [115]. Data reviewed showed that in SSA, where baseline SOC is low, use of biochar represent meaningful long-term sequestration. Kenyan trials for example show that a single application can sustain moisture retention and nutrient availability improvements for 3 - 10 years [58] [97]. Other African field trials often report larger effects, with substantial yield increases in maize, teff, and vegetables [71] [82] [109].

Co-application with compost or nitrogen fertilizers further enhances these outcomes [116]-[118]. Interactions with iron and aluminium oxides common in tropical soils may further stabilize biochar through organo-mineral complexes that slow decomposition [35]. Other studies show that co-application of biochar with other enhancers could contribute to global yield gains of 10% - 25% [54] [56]. **Table 4** shows suitable Biochars and recommended co-amendments depending on soil types.

12. Biochar-Microbe Interactions and Their Influence on GHG Dynamics in African Soils

Biochar strongly influences soil microbial communities, playing a central role in regulating greenhouse gas emissions in African soils. Its porous, redox-active surfaces create protected microhabitats favoring beneficial microbes while suppressing nitrous oxide (N_2O) and methane (CH_4) production. Biochar facilitates denitrification by acting as an electron shuttle, enabling complete reduction of N_2O to inert N_2 [21]. Across Sub-Saharan Africa, field studies report 25% - 60% N_2O reductions following biochar application, attributed to improved aeration disrupting anaerobic microsites [55] [56]. Other studies show that in flooded systems, biochar suppresses methanogenesis by reducing substrate availability and stimulating methanotrophs, achieving 20% - 50% CH_4 reductions [39] [68] [70]. Biochar also enhances nutrient cycling by promoting nitrifiers, phosphate-solubilizing bacteria, and mycorrhizal fungi. Kenyan studies document increased microbial biomass and diversity, including Actinobacteria and Proteobacteria [39] [73]. It also promotes carbon sequestration through enhanced microbial necromass formation and reduced CO_2 emissions via increased carbon-use efficiency [48].

Despite these potential benefits of biochar application, microbial responses remain context dependent, varying with feedstock, temperature, soil type, and moisture [39] [70] and persistent monitoring gaps across SSA limit validation of microbial-driven mitigation, underscoring the need for improved MRV capacity.

13. Cross-Cutting Issues in Biochar Uptake in Sub-Saharan Africa

Biochar development across Sub-Saharan Africa (SSA) is constrained by an interconnected set of technical, institutional, socioeconomic, and environmental barriers that collectively limit scalability and verified climate mitigation. While pilot interventions in Kenya, Nigeria, South Africa, Tanzania, Ghana, and the Sahel have yielded promising outcomes, these successes remain localized rather than systemwide [97]. Persistent gaps in mechanistic understanding under African conditions further complicate scaling, alongside unresolved ethical concerns over land-use change, residue competition, and benefit-sharing equity. **Table 6** below provides a matrix summarising these gaps, while **Table 7** summarises climatic vulnerabilities identified for Africa in this review.

Table 6. Gap-analysis: Biochar limitations, drivers and key impacts across Kenya and three SSA regions.

Issue	Kenya/East Africa	West Africa	Southern Africa
1. Characterisation	No harmonised protocols (KEBS); fragmented cross-border data → poor comparability, slow standard-setting ▲	Labs exist but data not harmonised; short donor cycles miss economies of scale ◙	Centralised facilities inaccessible to small projects → limited advanced modification uptake ◙
2. Carbon & LCA	Few tropical trials; sparse transport/energy data → weak MRV and uncertain GHG accounting ▲	LCAs ignore informal supply chains; seasonal variability → overestimated mitigation ▲	Rural emissions under-reported; long transport distances → risk of negative net emissions ▲
3. GHG Flux Monitoring	Near-zero automated chambers or eddy-covariance sites; no coordinated networks → patchy mitigation evidence ▲	Funding skewed to short-term studies; limited field flux tools → weak quantification ◙	Stations not networked; siloed programs → limited temporal coverage ◙
4. Feedstock Supply	Competing uses (fodder, fuel); seasonal bottlenecks; unaccounted cross-border flows → unreliable supply ▲	Large residues (rice, cassava) available but food-feed-energy trade-offs constrain sustainability◙	Forestry residues available; land-tenure issues constrain access → unsustainable sourcing risk ◙
5. Reactor Tech & Emissions	Rudimentary kilns; high emissions variability; no low-emission smallholder designs → occupational hazards, reduced GHG gains ▲	Pilots lack after-sales support and spare parts → technology failure and reputational risk ▲	Industrial pyrolysis available; smallholder options lag; investment skewed to large projects → inequitable access ◙
6. MRV, Policy & Standards	Fragmented policies; siloed ministries; no harmonised regional standards → blocked carbon finance access ▲	Emerging carbon initiatives; immature national infrastructure → lost finance opportunities ◙	Stronger policy base but not linked to smallholder support → limited rural scaling ▼

Continued

7. Agronomic Uptake	Inconsistent rates; under-resourced extension services → slow diffusion, variable yield outcomes ▲	High demand potential; weak cooperatives and aggregation challenges → missed livelihood benefits ◙	Training limited in scale; remote populations and capacity gaps → uneven landscape benefits ◙
8. Socioeconomic & Equity	Benefits captured by better-off actors; insecure tenure; vulnerable groups excluded → inequitable outcomes, reduced legitimacy ▲	Weak benefit-sharing; informal and opaque pricing → low community buy-in ▲	Historical inequality biases outcomes; entrenched land/wealth disparities → exacerbated rural inequality ▲

Note: Risk level: ▲ High; ■ Medium; ▼ Lower; Each cell summarises: key limitation(s) → resulting impact. SSA = Sub-Saharan Africa; LCA = Life Cycle Assessment; MRV = Monitoring, Reporting and Verification; KEBS = Kenya Bureau of Standards.

A central technical constraint is the inconsistency in biochar quality driven by widespread reliance on rudimentary production technologies: earth mounds, metal drums, and open burning systems that offer limited control over temperature, residence time, and oxygen availability [45]. Heterogeneous feedstocks processed without standardized protocols amplify uncertainty in pH, cation exchange capacity, volatile matter, and potentially harmful compounds [22]. Improved low-emission reactors exist but remain inaccessible due to high capital costs and limited local engineering capacity [14]. Compounding this, most SSA countries lack formal quality standards or certification systems aligned with International Biochar Initiative guidelines, enabling high-emission, uncertified products to circulate and eroding both farmer trust and carbon finance eligibility [56].

Measurement, reporting, and verification (MRV) capacity constitutes a parallel constraint. Fragmented and under-resourced monitoring systems force reliance on default emission factors derived from temperate regions, while biochar is rarely recognized as a distinct mitigation option within national GHG inventories or Nationally Determined Contributions [60]. High transaction costs from complex MRV methodologies render most small-scale projects economically unviable; emerging low-cost solutions, including infrared sensors and remote sensing proxies, remain at early deployment stages [74]. Without regionally harmonized emission factors and open-source protocols, equitable access to carbon finance will remain constrained [110].

Socioeconomic barriers are equally formidable. High production costs, labour-intensive feedstock handling, and uncertain agronomic returns create a pronounced temporal mismatch: costs are incurred immediately, while benefits accrue gradually and unpredictably [80]. Labour burdens fall disproportionately on women and youth; crop residues already serve essential functions as fodder, fuel, and mulch, increasing opportunity costs when diverted to pyrolysis. Market immaturity across SSA, characterised by absent price signals and limited downstream buyers, further constrains adoption, and high MRV costs significantly limit smallholder participation in carbon markets [105].

Feedstock competition intersects these socioeconomic pressures with ecological risk. Evidence from West Africa indicates that removing more than 30% - 40% of cereal residues substantially increases erosion risk and soil degradation [51]. Dedicated biomass plantations can provide reliable feedstock but risk intensifying competition over land, labour, and water, threatening food security and generating tenure conflicts where benefit-sharing mechanisms are absent [36] [57]. Environmentally robust biochar systems require context-sensitive feedstock strategies, incorporating land-use screening, water budgeting, and life-cycle GHG accounting aligned with international sustainability frameworks [36] [107].

Table 7. Key climate vulnerabilities in Sub-Saharan Africa and their drivers.

Vulnerability	Description of Impact	Underlying Drivers	Selected Ref-erences
Extreme temperature rise	Increased heatwaves; reduced labour productivity; crop and livestock heat stress.	Global warming; outdoor labour dependence; low adaptive capacity.	[5] [94]
Recurrent droughts and dry spells	Lower crop yields; livestock deaths; hydropower instability; acute water scarcity.	ENSO variability; declining rainfall reliability; land degradation; weak water storage.	[15] [43] [105]
Desertification and land degradation	Loss of vegetation; declining soil fertility; expansion of bare land; increased dust storms.	Overgrazing; deforestation; climate aridity trends; unsustainable land use.	[57] [80]
Flooding and rainfall extremes	Urban and rural flooding; crop destruction; displacement; infrastructure damage.	Rapid urbanisation; poor drainage; changing rainfall intensity patterns.	[16] [119] [120]
Sea-level rise and coastal erosion	Saltwater intrusion; flooding of low-lying coastal cities; loss of agricultural land.	Ocean warming; land subsidence; inadequate coastal planning.	[12] [113]
Food insecurity from climate shocks	Reduced productivity; livelihood loss; increased reliance on food aid.	Rain-fed agriculture dependence; limited irrigation; weak insurance systems.	[18] [84] [106]
Spread of vector-borne diseases (e.g., malaria)	Expansion into highland areas; prolonged transmission seasons.	Higher temperatures; altered humidity and breeding habitats.	[19] [121]
Water resource vulnerability	Reduced river flows; groundwater depletion; water conflicts.	Population growth; weak governance; climate-driven variability.	[10] [16] [86]

At the institutional level, biochar spans multiple policy domains yet most SSA countries lack dedicated coordination mechanisms or clear lead institutions, resulting in overlapping mandates and fragmented governance [68]. Kenya's experience illustrates this pattern: despite sector-level recognition, inter-ministerial coordination gaps and competing policy incentives over biomass use persist [46] [60]. These governance deficiencies are inseparable from equity concerns; financial gains from carbon credits are frequently captured by developers or large landholders, while rural households bear disproportionate labour costs [80]. Ethically robust deployment requires free, prior, and informed consent, gender-sensitive participation, and transparent benefit-sharing mechanisms embedded in project design and MRV frameworks [68] [74] [122].

Underlying all these domains are significant research gaps. Most biochar studies are based on temperate soils, whereas African Ferralsols, Acrisols, and Nitisols exhibit distinct physicochemical properties that shape pH response, nutrient retention, and microbial dynamics in ways that cannot reliably be extrapolated from existing literature [70] [96] [97]. Long-term field trials remain scarce, advanced isotopic tools are only beginning application in SSA contexts, and socioeconomic analyses that integrate climate finance, labour dynamics, and gender impacts are largely absent [80]. Addressing these gaps requires coordinated regional research networks, shared instrumentation, and strengthened human capacity across soil science, engineering, social science, and policy disciplines. Biochar in Africa cannot be treated as a technical input alone; it demands a multisectoral response that integrates production quality, MRV infrastructure, equitable governance, and context-specific evidence to move from fragmented pilots to scalable, climate-just implementation.

14. Conclusions

This systematic review confirms that biochar systems offer Sub-Saharan Africa a scientifically grounded intervention for concurrently addressing soil degradation, climate mitigation, and agricultural resilience. Across diverse agroecologies, biochar consistently improves soil structure, nutrient retention, and water-holding capacity while reducing nitrous oxide and methane emissions and sequestering stable carbon. Field studies report yield gains of 10% - 40%, particularly when biochar is combined with organic or mineral amendments. With over 500 million tonnes of annual crop residues, Africa possesses substantial feedstock potential to support circular bioeconomy transitions.

However, the evidence also reveals a persistent implementation gap between demonstrated biophysical potential and scalable adoption. Kenya's experience typifies broader continental constraints: clear agronomic benefits contrast sharply with absent national standards, fragmented institutional mandates, underdeveloped MRV systems, and limited access to carbon finance. These are not merely technical deficits but fundamental policy failures.

The central finding of this review is that biochar's trajectory in Africa will be determined less by soil science than by governance. Current policy frameworks remain siloed, failing to integrate biochar across agriculture, energy, waste, and climate portfolios. No country in the review sample possesses dedicated biochar strategies, quality certification systems, or carbon-accounting methodologies tailored to smallholder contexts. This policy vacuum perpetuates reliance on inefficient kilns, inconsistent products, and weak investment incentives.

Scaling biochar therefore requires a deliberate policy realignment. Priorities include: (1) establishing Africa-appropriate quality standards and low-emission reactor certification; (2) developing robust, cost-effective MRV frameworks that enable smallholder access to carbon markets; (3) integrating biochar into Nationally Determined Contributions and national soil-health strategies; (4) implementing feedstock safeguards that prevent residue competition and land-use conflicts; and (5) designing inclusive governance mechanisms ensuring equitable benefit-sharing, particularly for women and vulnerable groups.

Without coherent policy architectures, biochar risks remaining a collection of donor-funded pilots rather than a mainstreamed climate-smart agriculture pillar. Conversely, with strategic policy alignment, Africa can transform its biomass resources into verifiable climate solutions, restored soils, and improved livelihoods. The science is ready; the policy response is not. This gap must close.

Data Availability

The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

This work was not funded by any organization and standard guidelines for ethical access of literature cited were adhered to.

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Author Contribution

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by MK. Initial data collection, manuscript analysis and the first draft of the manuscript was written by MK under guidance from JK. All authors reviewed and improved on the contents of the initial and subsequent drafts. All authors read and approved the final manuscript.

Conflicts of Interest

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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