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Biochar enhanced agroforestry systems for carbon sequestration, soil health and climate resilience

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Abstract
Biochar-based agroforestry systems (AFS) have emerged as a promising strategy to restore soil fertility, enhance crop productivity, and contribute to climate change mitigation. This review synthesizes global evidence on the integration of biochar into AFS, highlighting both ecological and socioeconomic outcomes. Across diverse contexts, biochar application significantly improved soil health by increasing soil organic matter and soil organic carbon; for example, in Bangladesh, litchi- and mahogany-based AFS increased SOC from 0.28% to 1.87% and SOM from 0.49% to 3.23% over 30 years. In Nepal, combining 5 Mg ha^{-1} biochar with 20 Mg ha^{-1} farmyard manure improved soil pH and plant vegetative growth in coffee AFS, while in banana-based systems, urine-biochar plus compost raised yields by 41–102% and reduced poverty levels by 30%. Dryland studies in Ethiopia reported a 44% increase in new culms of *Yushinia alpina* and a 266% biomass increase under biochar plus deficit irrigation. Similarly, Colombian coffee plantations using 8–16 Mg ha^{-1} coffee-pulp biochar recorded a 20% yield increase and 34% reduction in chemical fertilizer demand, while Brazilian silvopastoral systems showed carbon stock gains of 2.5–4.2 Mg C ha^{-1} and forage productivity improvements of 20%. This review highlights that biochar–AFS synergies improve soil health, crop productivity, and rural livelihoods while strengthening ecosystem resilience. Scaling up these practices can enhance carbon sequestration, reduce reliance on chemical fertilizers, restore degraded lands, and support sustainable land management under climate change.

Keywords Biochar, Agroforestry systems, Soil fertility, Carbon sequestration, Sustainable land management

1 Introduction

Climate change, soil degradation, and food insecurity represent some of the most pressing global challenges of the 21st century. These interrelated issues are driven by increasing population pressures, urbanization, and shifts in dietary preferences, necessitating innovative and sustainable solutions. Climate change disrupts agricultural productivity by altering temperature and precipitation patterns, leading to reduced crop yields and increased food price volatility [1]. Vulnerable populations, particularly in regions such

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as South Asia and Sub-Saharan Africa, are at heightened risk of food insecurity due to these climate-induced disruptions [2]. Concurrently, soil degradation through erosion, nutrient depletion, and organic matter loss further threatens agricultural productivity, making it essential to implement effective soil management practices, including conservation agriculture and agroforestry systems (AFS) [2–4].

Among sustainable land management strategies, AFS have emerged as a viable solution to address environmental and economic challenges. AFS integrate trees, crops, and livestock into a single system, fostering ecological balance and improving agricultural system productivity. The benefits of AFS include enhanced biodiversity, improved soil health and nutrient cycling, and increased carbon (C) sequestration [5–8]. Moreover, AFS provides economic advantages by diversifying farmers' income sources through timber, fruits, and livestock products, thereby improving food security and resource efficiency [7–8]. However, challenges to its adoption remain, including high initial costs, socio-cultural resistance, and a lack of policy support and professional extension [6, 8]. Addressing these barriers through policy support and education is critical for the widespread implementation of AFS.

One promising innovation in AFS is the incorporation of biochar, a C-rich soil amendment produced through pyrolysis (the thermal breakdown of organic matter in the absence of oxygen). Biochar has gained attention for its ability to enhance soil health, improve nutrient retention, and promote C sequestration [9]. Its unique physicochemical properties improve soil structure, increase water retention, and create a hospitable environment for microbial communities essential for nutrient cycling [10]. Additionally, biochar serves as a long-term C sink, sequestering C for extended periods and reducing greenhouse gas emissions [9, 11]. Studies indicate that biochar-amended soils can further absorb atmospheric CO_2, amplifying their C sequestration potential [11]. However, the effectiveness of biochar varies depending on feedstock type, pyrolysis conditions, and application rates, necessitating further research to optimize its use in different AFS [10].

Integrating biochar into AFS has the potential to create synergistic effects that enhance soil health, boost crop productivity, and increase climate resilience. Biochar improves water retention, making AFS more resilient to droughts, while also neutralizing soil acidity and enhancing microbial activity. Furthermore, its ability to stabilize organic matter and increase nutrient-use efficiency provides a sustainable approach to soil restoration [12]. Research indicates that biochar application in AFS can lead to improved tree growth and biomass production, further increasing C sequestration potential [13]. The biochar-AFS nexus thus represents a transformative strategy for sustainable land management.

Despite its potential, several research gaps remain in the study of biochar-enhanced AFS. First, long-term field studies are needed to assess the enduring impacts of biochar application, as most existing research relies on short-term experiments [12]. The specific mechanisms by which biochar interacts with soil microbiota, nutrient cycles, and plant roots in AFS contexts also require further investigation [13]. Additionally, there is limited research on the socioeconomic viability and farmer adoption of biochar technologies, including cost-benefit analyses and policy incentives to promote its use. Another critical gap is the need for standardized biochar production and application guidelines tailored to specific AFS contexts to ensure consistency and effectiveness. Furthermore, environmental trade-offs such as the impact of large-scale biochar feedstock harvesting on biodiversity and the production of methane and NO_x gases during char production must be thoroughly assessed through lifecycle analysis studies [14].

Addressing these research gaps is essential for scaling up biochar-enhanced AFS as a climate-resilient land management strategy. This paper aims to explore the role of biochar in AFS, evaluate its potential for C sequestration and soil health improvement, and analyze its socioeconomic viability. By integrating biochar into AFS, farmers can enhance soil fertility, mitigate climate change, and improve food security while maintaining ecosystem stability. As global environmental challenges intensify, investing in research and policy support for biochar-AFS offers a promising path toward a more sustainable and resilient agricultural future.

2 Biochar mechanisms in AFS

Biochar's C structure is largely aromatic, characterized by irregular stacks of stable aromatic rings that form the backbone of its recalcitrance in soil environments [15]. This chemically inert structure provides highly recalcitrant C inputs that resist microbial decomposition, enabling substantial fractions of C to persist in soils for centuries to millennia [15]. In AFS, such stability enhances soil C storage and supports ecosystem functioning by contributing to the long-term buildup of stable soil organic carbon (SOC) pools [16]. Beyond direct C inputs, biochar modifies soil chemistry by elevating pH and stimulating the precipitation of iron (Fe^{3+}) and aluminum (Al^{3+}) oxides, which bind organic molecules into Fe- or Ca-associated complexes, particularly stabilizing SOC in acidic soils [17]. Its porous structure and functional surfaces also create microhabitats for soil microbes, enhancing microbial biomass carbon (MBC) and contributing persistent residues via the microbial C pump [17]. Additionally, biochar can stimulate enzymes such as polyphenol oxidase, promoting the polymerization of phenolics and other recalcitrant compounds that become strongly adsorbed onto mineral surfaces [17]. Its high carbon and low nitrogen content result in elevated C: N ratios, causing it to act as a nitrogen sink in soils [18]. Studies have shown that biochars with C: N ratios ranging from 118 to 154 can cause nitrogen immobilization, as soil microbes utilize available inorganic nitrogen (NH_4^+-N and NO_3^--N) to balance the carbon-rich biochar substrate. Similarly, woody biochars, despite their low mineralizable carbon content, have been found to reduce plant-available nitrogen through microbial immobilization driven by their high C: N ratio. Therefore, unless biochar is inoculated or applied alongside nitrogen fertilizer, high-C: N biochars may temporarily limit nitrogen availability to plants [18–19].

At the soil physical level, biochar fosters macro-aggregate formation that physically protects organic matter from decomposition, thereby improving SOC retention and overall soil structure [20]. The presence of carboxyl and hydroxyl functional groups further increases cation exchange capacity (CEC), improving nutrient retention, limiting leaching, and indirectly stabilizing SOC by supporting higher plant and microbial productivity [21]. These properties also enhance water-holding capacity, nutrient availability, and pH buffering, leading to greater biomass input and organic matter accumulation [22]. Studies have demonstrated that biochar improves nutrient-use efficiency by enhancing soil nutrient retention and aligning nutrient release with plant uptake needs. For instance, biochar application was shown to boost potassium-use efficiency in green beans by increasing both soil K availability and plant absorption [23]. Similarly, biochar's high porosity, surface charge, and cation exchange capacity help minimize nutrient losses—particularly nitrogen and phosphorus—thus enhancing nutrient availability and overall crop utilization [24]. Moreover, biochar interacts synergistically with beneficial soil microbes such as plant growth-promoting rhizobacteria (PGPR), stimulating nutrient cycling and microbial activity, and further promoting soil C sequestration and ecosystem resilience (Fig. 1) [25].

3 Synergies between agroforestry and Biochar

When integrated into AFS, biochar's mechanisms generate powerful synergies that enhance C sequestration, soil health, and climate resilience. For C storage, biochar provides long-term stabilization of SOC through its recalcitrant aromatic structure [26–28], while trees simultaneously accumulate C in woody biomass at rates of 2–5 Mg C ha^{-1}yr^{-1} in mature stands [29]. Field evidence shows that biochar application in Ferralsols (World Reference Base for soil classification; characterized by a ferralic horizon rich in Fe and Al oxides) under tree cultivation raises SOC density by 15–30%, creating a combined C sink that can deliver carbon-negative outcomes when coupled with sustainable biomass production [27, 30–31]. The synergies between biochar and AFS are summarized in Fig. 2.

For soil health, biochar enhances nitrogen (N) and phosphorus (P) availability, thereby mitigating the effects of nutrient competition between trees and crops rather than directly reducing it. Its high surface area and porosity improve nutrient retention and lower nitrate (NO_3^--N) and ammonium (NH_4^+-N) leaching by 20–40%. However, several studies have noted that un-inoculated biochar, owing to its exceptionally high C: N ratio, can initially act as a nitrogen sink in soils lacking additional N inputs, potentially limiting short-term N availability [32–33]. Biochar-enriched soils also exhibit improved microbial biomass P (up to 35%) and higher nitrogen-use efficiency [34], while the alkaline pH of wood-derived biochar helps solubilize phosphates bound in the Fe/Al-oxides

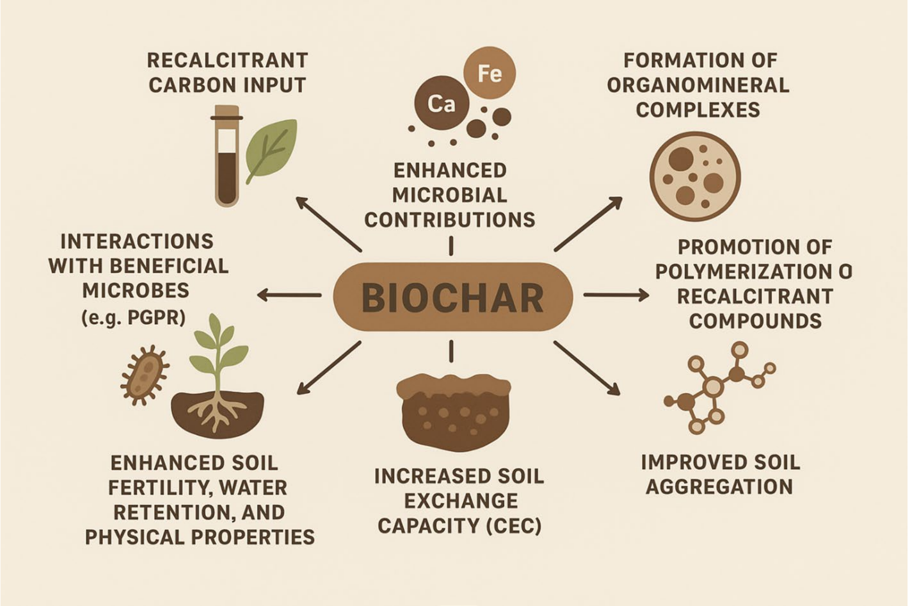

Fig. 1 Mechanisms by which Biochar Enhances Soil C in AFS (Original figure)

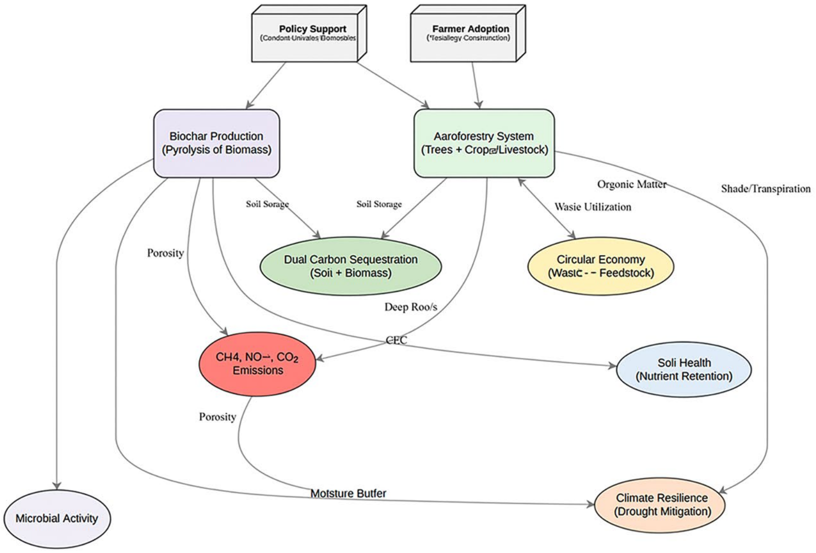

Fig. 2 Conceptual Framework of Biochar-AFS Synergies

of acidic soils [32]. Biochar's alkaline pH (8–12) can raise soil pH, reducing toxic aluminum and manganese in acidic soils and improving plant health. It also transforms P from less available forms into plant-accessible forms, enhancing nutrient availability [35]. Moreover, by altering soil pH, biochar supports beneficial microbial communities, including P-solubilizing bacteria, further increasing P availability [36]. AFS complement these effects. Tree roots reduce bulk density and improve soil porosity, which enhances water infiltration and root penetration. Tree litter and root exudates increase soil organic C, improving nutrient retention and microbial activity. Biodiversity in AFS supports a diverse soil microbial community that contributes to nutrient cycling and suppresses pathogens, while tree presence mitigates soil erosion and enhances fertility, leading to improved crop-tree coexistence and resilience against climatic stresses [37].

Biochar's benefits extend to stress resilience. Its alkaline buffering, water-holding capacity, nutrient availability, and microbial support enhance photosynthesis, nutrient uptake, water-use efficiency, biomass production, and crop quality, while reducing stress-induced senescence [38]. It further improves soil porosity, cation exchange capacity (CEC), organic matter, and macro-aggregation, while lowering bulk density and enhancing enzymatic activity [21, 38]. In parallel, biochar's architecture makes it a favorable substrate for microbial inoculants, amplifying beneficial microbial communities and regulating nutrient cycles by minimizing leaching losses while improving bioavailability [21, 39–40]. Similarly, AFS enhances soil resilience by improving structure, organic matter, and water retention, reducing vulnerability to drought and erosion [41]. Studies indicate that biochar improves soil water-holding capacity by enhancing field capacity, available water content, and overall porosity. A meta-analysis reported that biochar addition increased available water content by approximately 28.5% and field capacity by around 20.4% on average [42]. This improvement is primarily attributed to biochar's highly porous structure and large surface area, which store water within internal and external pores, while also modifying soil physical properties by lowering bulk density and adjusting pore-size distribution [43]. Nonetheless, the magnitude of these effects varies with factors such as biochar feedstock, pyrolysis temperature, soil type, and application rate; in some cases, excessive biochar or coarse-textured soils may exhibit minimal or even negative impacts on water retention [44]. It also strengthens soil microbial communities, maintaining soil functions under stress, and modifies microclimates, mitigating temperature extremes and supporting plant productivity [41].

In practice, biochar-amended AFS creates a sustainable biomass-to-soil loop. Residues from coffee, cacao, and oil palm systems can be pyrolyzed into biochar, which improves degraded tropical soils by boosting aeration, water retention, and microbial symbiosis [45]. Field studies confirm these benefits: in Nepal, co-application of farmyard manure compost with 5 Mg ha^{-1} biochar increased SOC, pH, and CEC while lowering bulk density, with yield gains of 21–67% across crops, and optimal performance at 15 Mg ha^{-1} [46]. Forestry trials in Australia similarly reported improved soil chemistry and tree establishment with 1–6 Mg ha^{-1} biochar [47]. A global review of over 150 studies reinforces these findings, confirming biochar's consistent role in enhancing soil structure, nutrient dynamics, water retention, drought tolerance, and pest resistance in tree-based systems, though outcomes remain site-specific [13].

Finally, biochar and trees jointly buffer AFS against drought. Biochar's capacity to increase soil moisture by 10–25% in coarse soils [48] complement deep-rooted species such as *Leucaena* and *Gliricidia*, which access subsoil water during dry periods [49]. Together, under controlled soil water conditions, they maintain plant water potentials 30–50% higher compared to plants without biochar or trees [50], while biochar's reduction of soil bulk density (by 0.1–0.3 g cm^{-3}) facilitates deeper root penetration [51]. Zambia's ClimateChar AFS Initiative demonstrates these combined benefits in practice: pigeon pea residues were converted into biochar with simple on-farm methods, improving soil moisture by up to 3%, raising yields by 12–37% with 4 Mg ha^{-1} application, and increasing soil C sequestration. Farmers also benefited economically through local biochar markets, highlighting both livelihood and environmental gains from biochar-based AFS [52].

4 Global case studies of biochar-based AFS

Biochar-based AFS has emerged as an innovative strategy to enhance soil fertility, improve crop productivity, and sequester C across diverse landscapes. A growing body of case studies from Asia, Africa, and Latin America demonstrates how integrating biochar into AFS delivers both ecological and socioeconomic benefits.

In the Nepal mid-hills, Gautam et al. (2017) investigated the application of biochar at 5 Mg ha^{-1} combined with 20 Mg ha^{-1} of farmyard manure in a coffee AFS [53]. Their findings revealed significant improvements in soil pH and soil organic matter, along with a notable enhancement in vegetative growth such, as plant height, although yield increases were relatively modest. The authors emphasized that while plant growth responded quickly, more time might be required for soil property changes to translate into higher crop yields. Similarly, in Indonesia, a three-year field trial in hybrid rice–AFS shows the application of biochar briquettes demonstrated effectiveness in reducing N losses [54]. In addition, biochar has been shown to mitigate greenhouse gas emissions in livestock systems. For example, a pen trial with steers demonstrated that supplementing diets with "fit-for-purpose" biochars reduced enteric methane (CH_4) emissions by ~ 8.8–12.9% [55]. A meta-analysis across 110 in-vivo studies found that biochar as a feed additive reduced methane production on average by ~ 21% [56]. Feeding cattle a pine-derived biochar diet reduced manure NH_4-N concentration and organic-matter extractability by about 13%, although it did not significantly affect total N_2O emissions during composting [57]. These short-term benefits were particularly evident in N dynamics, suggesting biochar's potential role in improving nutrient management in rice-based AFS.

In northern Ethiopia, applying 38 g kg^{-1} soil biochar with deficit irrigation increased *Yushinia alpina* new culms by 44% compared to the control, demonstrating that biochar enhances woody seedling growth under water-limited conditions [58]. The study in Nepal hills found that the use of urine-biochar with compost increased banana yield by 41% compared to NPK fertilizer and by 102% compared to compost alone. Moreover, poverty levels in the biochar village declined from 66% to 36%, whereas in the control village poverty fell from 40% to 21%, highlighting both productivity gains and livelihood benefits from biochar adoption [59].

Beyond South Asia and Africa, case studies from Latin America also demonstrate the multifunctional role of biochar in AFS. In Colombian coffee plantations, Sánchez-Reinoso et al. (2023) reported that applying 8–16 Mg ha^{-1} of coffee-pulp biochar increased soil respiration by 50–60% and improved soil pH, while reducing the need for chemical fertilizers by 34% [60]. This biochar-based AFS also enhanced soil organic C by 3.5% and increased crop yields by 20% compared to conventional practices. In Brazil, biochar integration within silvopastoral systems consisting of *Brachiaria* pastures and native trees showed promising results, with C stocks elevated by 2.5–4.2 Mg C ha^{-1} and forage productivity improved by 20% in degraded lands [61–62]. While typical well-managed silvopastoral systems in the Cerrado achieve total soil C stocks of 106–130 Mg C ha^{-1} to 100 cm depth, the biochar-amended system demonstrates that addition of biochar can accelerate carbon accumulation in degraded pastures to rates comparable to or exceeding those of conventional systems [63–64].

5 Knowledge gaps and future research

Despite growing research on biochar, critical knowledge gaps remain, particularly regarding its long-term (>10 years) effects in AFS. While some studies have explored biochar's role in C sequestration and soil health, comprehensive data on its decade-scale impacts are still lacking. For instance, research highlights uncertainties about biochar's prolonged influence on soil C dynamics, with adoption hindered by inconsistent feedstock availability and insufficient understanding of long-term soil interactions [65–66]. Additionally, while biochar is considered a stable C storage solution, some studies suggest it may increase soil C efflux over time, emphasizing the need for extended investigations [66].

Socioeconomic barriers, such as high production costs and limited farmer awareness, also impede widespread adoption. Financial constraints, including upfront expenses and uncertain economic returns, disproportionately affect small-scale farmers. Studies indicate that factors like education, income, and farm size influence adoption rates, with limited access to financing and technical knowledge posing major challenges [67]. Furthermore, insufficient awareness about biochar's benefits and application methods remains a key obstacle, calling for targeted education, incentives, and policy support to facilitate broader use [68–69].

Emerging solutions aim to address these gaps, including biochar-microbe cocktails to enhance tree growth and soil health. Research shows that biochar improves soil structure, nutrient retention, and microbial activity, and when combined with beneficial microbes, it can further boost plant productivity [70]. Its porous structure also serves as an ideal habitat for microorganisms, making it an effective carrier for microbial inoculants that enhance soil fertility.

Although customized biochar blends may initially seem unaffordable for poor farmers, published studies show that affordability depends heavily on production methods, regional contexts, and integration strategies. In high-income countries, biochar production costs range between \$325–\$550 USD per ton and may reach as high as \$5,000 USD per ton in the UK and USA [22], while a broader review reported costs between \$449 USD and \$2,077 USD per ton, posing challenges for resource-poor farmers [71]. In contrast, developing regions such as India and the Philippines report costs of less than \$100 per ton due to low labor and accessible feedstock [22], and in Western Africa, integrating rice husk biochar with inorganic fertilizers led to higher gross margins and long-term profitability despite high first-year costs [72]. Farmer-centered methods like the "burn and soil cover" (B-SC) technique allow in-field, low-cost biochar production, making it more economically viable than industrial methods [22]. Furthermore, co-application of biochar with organic or inorganic inputs in India increased returns significantly—for example, 8.5 Mg ha^{-1} of biochar with organic fertilizer yielded ₹82,692 per hectare, while combinations with FYM or *Azospirillum* improved benefit–cost ratios to near 2:1 [22]. Similarly, in Northern Uganda, maize stover biochar alone improved soil chemistry and boosted tomato yields, even without fertilizers [73]. Innovative approaches such as nutrient-enriched biochar from human excreta have been shown to supply up to 15% of P, 17% of N, and 25% of potassium globally [74], while in Nepal, urine-enriched biochar from cattle was found to provide fertilizer worth over NRs 10,000 (US \$84) per half-hectare and increase yields by 20–300% [75]. Another promising approach is the use of machine learning (ML) to optimize biochar properties for specific climates. Advanced ML models can predict biochar yield and composition based on production conditions, enabling tailored formulations for different environmental needs [76]. Additionally, ML techniques have been used to analyze biochar's efficiency in removing contaminants, demonstrating its potential for environmental remediation [77].

Future research should prioritize long-term field trials, socioeconomic studies on adoption incentives, and scalable innovations such as biochar-microbe blends and ML-driven design to maximize biochar's benefits in AFS.

6 Socioeconomic and cultural considerations in adoption

Farmer perceptions play a crucial role in the adoption of biochar technology, with attitudes varying based on economic value perception, policy influences, climate change awareness, and renewable energy production. Studies analyzing cotton farmers' intentions to adopt biochar as a sustainable land management strategy highlight that psychosociological motivations, such as environmental awareness and perceived benefits, increase their willingness to use biochar [78–79]. Additionally, gender disparities influence adoption rates, as women often have less access to forest resources and economic opportunities compared to men, limiting their participation in biochar-related activities. However, integrating gender-sensitive approaches—such as developing rocket stoves (a biomass cookstove with an insulated chamber and chimney for efficient, clean burning) that reduce wood consumption and indoor pollution—can empower women and enhance their involvement in AFS. It enhances biochar production by using a design that ensures high, consistent heating, creates a pyrolysis environment (limited oxygen), and recovers heat by burning the gases that volatize out of the biomass [80–81].

Economic viability is another key consideration, with cost-benefit analyses revealing differences between small-scale and industrial biochar production. Small-scale kilns may not be commercially viable, but can be practical for nurseries and on-farm use, especially where materials and skills like welding are readily available. In contrast, large-scale pyrolysis plants require substantial investment, with costs ranging from $275,000 to $687,000 USD for facilities processing over 100 tons per day [82–83]. Labor requirements also affect adoption, as integrating biochar into AFS demands time and effort for production, application, and management. However, limited data on labor needs highlight the necessity for further research to assess scalability [84].

Several studies highlight the socioeconomic potential of biochar adoption in AFS. In Tanzania, smallholder farmers reported yield increases from 1 Mg ha^{-1} to 3 Mg ha^{-1}, alongside reduced fertilizer costs and improved soil quality. Similar benefits were observed in Ghana, where lettuce yields rose by 93% and on-farm biochar production achieved rapid payback within two months. Economic modeling in Brazil indicated profitability for medium to large-scale farms, particularly when supported by C credits, while a global meta-analysis confirmed average yield gains of 15% in tropical AFS. In sub-Saharan Africa, where fertilizer inputs remain low and nutrient depletion is severe, biochar offers a low-cost, sustainable strategy to enhance productivity and soil fertility (Table 1).

Policy incentives can significantly drive biochar adoption. In Kenya, government interventions such as fertilizer subsidies and food aid highlight the role of agricultural policies in shaping farm practices, indicating that future policies could incorporate sustainable solutions like biochar to enhance long-term resilience [89]. Additionally, C markets provide financial incentives, with biochar projects adhering to protocols like the U.S. and Canada Biochar Protocol to quantify and verify climate benefits, enabling C credit generation. Corporate interest, such as Google's purchase of biochar-based C removal credits, further underscores the growing support for biochar as a C sequestration strategy. Addressing these socioeconomic and cultural factors is essential for widespread biochar adoption, ensuring initiatives are economically viable, socially inclusive, and supported by favorable policies [90].

7 Environmental trade-offs and lifecycle analysis (LCA)

While biochar offers significant benefits for C sequestration and soil improvement, it also presents environmental trade-offs that require careful consideration. One key concern is the emissions associated with biochar production, particularly if feedstocks are transported over long distances or processed using unsustainable energy sources, which can offset its C benefits [91]. Additionally, over-application of biochar can raise soil pH beyond the optimal range (around 6.5), potentially reducing crop yields—studies have reported 6–10% yield losses in potato cultivation under such conditions [92–93]. Also applying biochar to acidic soils significantly raised soil pH by an average of 5.6%, with a stronger liming effect observed in soils having an initial pH below 6 and at higher

Table 1 Socioeconomic considerations and quantitative impacts of Biochar adoption in AFS. Sources: [67, 85–88]

Study / Location	Parameter / Indicator	Observation / Result	Socioeconomic Insights
Mbeya and Songwe, Tanzania	Yield	Increased from 1 Mg ha^{-1} to 3 Mg ha^{-1}	Adoption driven by higher yields, reduced input costs, and improved soil quality.
	Yield / Income Benefits	Reported by 70% of farmers	
	Soil Moisture	66% observed improved soil moisture	
	Fertilizer Use	62% reduced > 70% fertilizer use (≈ USD 200 ha^{-1} saved)	
	Soil Structure	71% reported improved soil structure	
Tamale, Ghana	Lettuce Yield	Increased by 93%	High productivity gains and rapid return on investment.
	Rocket Stove Efficiency	Improved 15–33%	
	Payback Period	1–2 months	
Brazil (Sugarcane bagasse)	Break-even Time	7.5 years	Economically feasible mainly for large-scale farms with C credit support.
	IRR	18%	
	Viability Conditions	Viable if C credit > USD 120 tCO$_2$eq and > 60% bagasse availability	
Tropical AFS (Global meta-analysis)	Average Yield Increase	15% at 5–10 Mg ha^{-1}	Even modest biochar application benefits smallholders.
	Yield Response (Kenya)	Significant gains even at 1 Mg ha^{-1}	
Sub-Saharan Africa (Baseline context)	Fertilizer Use	20–50 kg ha^{-1}	Highlights biochar's potential to offset nutrient depletion.
	Nutrient Depletion	10–70 kg N, 2–10 kg P, 8–50 kg K ha^{-1} yr^{-1}	

application rates exceeding 40 Mg ha^{-1} [94]. Studies demonstrate that biochar application—such as 40 Mg ha^{-1} of wheat straw biochar (raising pH from 6.5 to 6.9), 12 Mg ha^{-1} of rice husk biochar (5.27 to 6.73), 20 Mg ha^{-1} of cow manure biochar (6.4 to 8.0), or even 2% of peanut hull biochar in sandy soils (5.6 to 7.1)—can elevate soil pH well beyond the agricultural target of 6.5 [95]. Crop residues and yard waste provide significant negative emissions (– 864 to – 885 kg CO$_2$eq t^{-1}), mainly through C sequestration, while forestry waste and manure offer moderate benefits (– 0.85 to – 0.7 ton CO$_2$) but with partial waste utilization (70–85%). Crop residues are only partially utilized—about 35% is used for fertilizer or feed, while the rest is often burned or left unused, contributing to missed C sequestration opportunities [96]. In contrast, forestry waste and manure are more moderately reused: forestry byproducts are frequently employed as up to 75–85% of mushroom cultivation substrates, later becoming composted fertilizer, while manure may be diverted to livestock feed, energy conversion (e.g., biogas or fuel), or soil amendments—thus contributing to carbon-benefiting utilization schemes [97–98]. Dedicated biomass such as switchgrass provides high net energy (4899 MJ t^{-1}) but can be a net GHG emitter (+ 36 kg CO$_2$eq t^{-1}) depending on land-use impacts. Specialized systems like CharBoss demonstrate strong removal potential (– 2.70 MT CO$_2$eq t^{-1} biochar), while large-scale estimates suggest global mitigation potential of up to 1.8 Pg CO$_{22}$-Ceq annually (Table 2).

Table 2 Quantitative performance of different Biochar feedstocks and systems in terms of GHG impact, energy, and utilization.
Source: [99–103]

Feedstock Type	Net GHG Impact	Waste Utilization	Net Energy	Other Notes
Forestry Waste	−0.85 to − 0.7 ton CO_2	70–85%	–	Moderate GHG benefits, trade-offs with biodiversity
Manure	−0.85 to − 0.7 ton CO_2	70–85%	–	Similar to forestry waste
Crop Residues (Corn Stover)	−864 kg CO_2eq per ton dry feedstock (emissions reduction)	–	–	62–66% of reduction from C sequestration
Yard Waste	−885 kg CO_2eq per ton dry feedstock (emissions reduction)	–	–	High economic potential (+\$69 t^{-1} if CO_2eq offset = \$80)
Dedicated Biomass (Switchgrass)	+ 36 kg CO_2eq t^{-1} dry feedstock (possible net emitter)	–	4899 MJ t^{-1} dry feedstock	High energy yield but risk of being emitter depending on land-use accounting
CharBoss (Forest Fire Waste)	−2.70 MT CO_2eq per MT biochar produced	–	–	2,403.81 MT CO_2eq CORC certificates (12 months)
Global Biochar Potential	1.8 Pg CO_2-Ceq per year (12% of anthropogenic emissions)	–	–	130 Pg CO_2-Ceq reduction over 100 years
Urban Applications (Uppsala)	−1.4 to − 0.11 ton CO_2-eq per ton biochar	–	–	Demand: 1700 m^3 $year^{-1}$; 23% ends in landfill by 2100

Recent studies show that biochar enhances microbial interactions and nutrient cycling in AFS by stimulating beneficial microbial activity, improving nutrient availability, moderating soil pH toward optimal levels for plant growth, increasing moisture retention, and reducing soil contamination. Additionally, biochar's interaction with soil microorganisms boosts soil fertility and plant growth by increasing organic matter, increasing the availability of phosphate, and potassium, and enhancing soil enzyme activities [104–106]. Lifecycle assessments (process-based LCAs focusing on cradle-to-grave biochar systems) highlight biochar's potential to reduce agricultural emissions, particularly nitrous oxide (N_2O) and carbon dioxide (CO_2) from soils and manure management, with estimates suggesting its use could offset 13–40% of Norway's agricultural greenhouse gases [107].

Circular economy describes a systemthat reduces resource use, waste, emissions, and energy loss by maintaining, reusing, and recycling materials within a closed-loop process. A circular economy approach can optimize sustainability by using AFS waste (e.g., pruned branches, crop residues) as biochar feedstock, reducing waste while supporting soil health [108]. Ultimately, maximizing biochar's benefits requires balancing production methods, application rates, and feedstock sources to minimize trade-offs (Table 3).

According to published studies, the potential of AFS to mitigate GHG emissions can be estimated based on standardized biochar application rates. For example, applying 1 Mg ha^{-1} of biochar in AFS may sequester roughly 0.1–0.4 Mg CO_2 eq ha^{-1} yr^{-1}, whereas 2.5 Mg ha^{-1} could achieve 0.3–1.0 Mg CO_2 eq ha^{-1} yr^{-1}. A rate of 5 Mg ha^{-1} may result in 0.6–2.0 Mg CO_2 eq ha^{-1} yr^{-1}, and 10 Mg ha^{-1} could sequester 1.2–4.0 Mg CO_2 eq ha^{-1} yr^{-1}. These values are calculated by integrating reported soil organic carbon (SOC) accumulation rates in agroforestry systems (0.1–4.2 Mg C ha^{-1} yr^{-1-1}) with GHG mitigation efficiencies derived from global biochar meta-analyses in cropland soils [114–115].

Table 3 Environmental Trade-offs of different Biochar feedstocks in terms of sustainability and soil pH impact.
Source: [13, 95, 104], 109–113]

Feedstock Type	Sustainability Considerations	Soil pH Impact
Wood Residues	Naturally moderate sustainability; watch sourcing	Typically increases soil pH—meta-analysis shows ~ 58% rise; e.g., pecan-shell biochar at 2% raised pH from 4.8 to 6.3 (+ 1.5 pH units)
Agricultural Waste (e.g., rice husks, corn stover)	High sustainability, valorizes residues	Can increase pH—~26% average rise (meta-analysis); cassava biochar pH ≈ 10.40, rice husk ≈ 7.48
Manure-Based Biochar	Good waste solution, but watch nutrients	Often increases pH—~64% average rise (meta-analysis)
Urban Green Waste	Promotes recycling; contamination potential	Variable pH effects; likely moderate increases depending on composition

8 Policy and practical implications

Biochar-AFS can qualify for C credits by sequestering C and reducing greenhouse gas emissions, provided they meet specific eligibility criteria. Projects must utilize approved biogenic feedstocks (e.g., forestry residues, agricultural waste) and avoid non-biogenic materials like plastics [116]. Sustainable production practices, including monitoring air emissions and pyrolysis temperatures, are essential, along with verifiable C sequestration data. Certification standards such as Verra's VM0044 and Puro.Earth's Biochar Methodology provides frameworks for quantifying emissions reductions and ensuring compliance [116]. Kenya's subsidies for biochar production have improved fuel efficiency, reduced indoor smoke exposure, and mitigated soil degradation [117]. Similarly, Verra's Verified Carbon Standard (VCS) has enhanced the credibility of C offset projects, increasing buyer confidence [118]. However, challenges like market complexity and the difficulty of small-scale projects meeting stringent requirements persist, necessitating streamlined processes to enhance accessibility.

Governments and NGOs play a pivotal role in promoting biochar-AFS adoption. Governments can accelerate implementation through financial incentives (e.g., subsidies, tax benefits), policy support (e.g., consumer education, market expansion), and funding for research and development [119]. NGOs contribute by raising awareness, providing training, and fostering partnerships among stakeholders, including farmers, researchers, and industry players [14]. Collaborative efforts between policymakers and NGOs are crucial to overcoming barriers, as seen in initiatives that combine policy frameworks with grassroots engagement [120].

Effective training is essential to maximize biochar's benefits for soil health and crop productivity. Farmers need education on biochar properties, production techniques, and optimal application methods [121]. Programs like the International Biochar Initiative (IBI) Biochar Academy, the Biochar Learning Center, and Warm Heart Worldwide offer courses and resources to build practical knowledge [121]. Participatory approaches, such as involving farmers in field trials (e.g., the Tamale, Ghana study, which saw a 93% yield increase in lettuce), enhance adoption by addressing local challenges [122] (Fig. 3).

9 Conclusion

This review demonstrates that integrating biochar into AFS can offer ecological and socioeconomic benefits, including improved soil fertility, enhanced crop yields, and increased C sequestration. The evidence highlights biochar's potential as a climate-smart

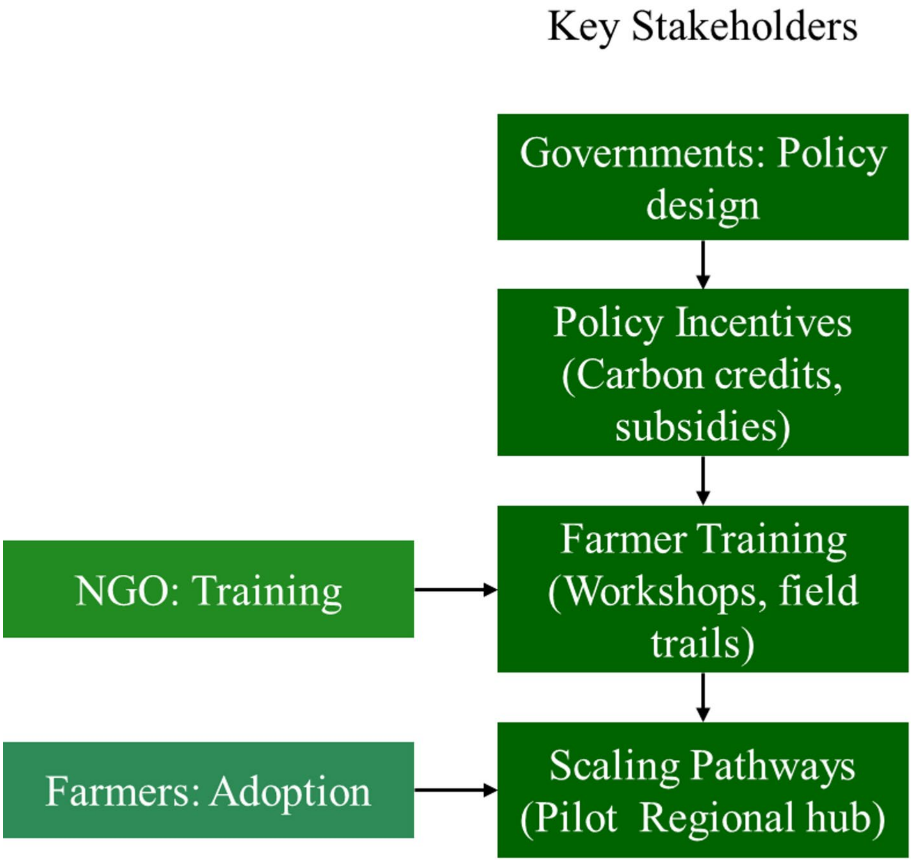

Fig. 3 Three-phase policy adoption framework for scaling biochar-enhanced AFS

strategy that supports both tropical and dryland regions while contributing to sustainable land management.

From a practical perspective, the findings suggest, scaling biochar-based AFS can restore degraded lands, reduce dependency on chemical fertilizers, and improve food security. International bodies such as FAO, CIFOR-ICRAF, and the Global Biochar Initiative should work with national institutions like ICIMOD in the Himalayan region to promote adoption through policy integration, farmer training, and incentive mechanisms. Governments and NGOs can play a vital role by supporting local biochar production from agricultural residues, creating community-based extension services, and linking biochar practices to C credit schemes.

Future efforts should focus on participatory research, capacity building, and farmer-led demonstrations to unlock the full potential of biochar-based AFS in fostering climate resilience and sustainable rural development.

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Author contributions
S. M. Kamran Ashraf conceptualized the study and prepared the first draft of the manuscript. Saleha Khatun Ripta collected data and contributed to editing and reviewing sections of the article. Md. Tanbheer Rana reviewed and edited the manuscript. Kazi Kamrul Islam also reviewed and edited the manuscript.

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