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ARTICLE

Carbon Farming and Agroforestry: Synergies, Trade-Offs, and a Decision Framework for Climate-Smart Landscapes

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ABSTRACT

Carbon farming through agroforestry and biochar amendment is widely recognised as a climate-smart strategy, yet the quantitative integration of their combined effects on soil organic carbon (SOC) and the operationalisation of monitoring, reporting, and verification (MRV) remain fragmented across the literature. This review synthesises published meta-analytical evidence, mechanistic studies, and case examples to assess SOC sequestration potentials, synergies, and trade-offs of integrated agroforestry–biochar systems. We draw on 127 field studies and ten global meta-analyses to quantify carbon pool dynamics and to construct a nexus analysis linking carbon gains to seven dimensions of sustainability. Tropical silvopasture combined with biochar shows the highest average SOC accrual (2.6 Mg C ha^{-1} yr^{-1}), while temperate alley-cropping with biochar achieves 1.8 Mg C ha^{-1} yr^{-1}. Trade-offs such as water competition (yield reductions of 10–25% in semi-arid settings) can be mitigated by AI-assisted irrigation scheduling and nano-enabled soil amendments. A novel four-phase decision-support framework is developed and illustrated with a hypothetical Sahelian case study, embedding digital MRV, blockchain verification, and community-based benefit-sharing mechanisms. By bridging the gap between scientific evidence and market-ready carbon removal, this framework provides a practical pathway for scaling carbon farming in diverse smallholder landscapes. Limitations and priority research directions are clearly identified.

Keywords: Agroforestry; Carbon Farming; Biochar; Soil Organic Carbon; Meta-Analysis; Decision Support

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1. Introduction

Global food systems must simultaneously increase productivity, adapt to climate change, and reduce net greenhouse gas (GHG) emissions. Carbon farming, a suite of agricultural practices aimed at drawing atmospheric CO_2 into biomass and soil organic matter, has emerged as a key pillar of this transformation [1,2]. Among carbon farming strategies, agroforestry integrates trees with crops or livestock, enhancing carbon storage while maintaining agricultural output. Parallel advances in biochar technology offer complementary pathways to stabilize soil carbon, remediate degraded soils, and improve water retention, particularly in the drylands that cover over 40% of the Earth's land surface [3,4]. Despite a wealth of individual studies and several narrative reviews [5–8], three critical gaps persist. First, no integrated synthesis has systematically compared the combined effect of agroforestry and biochar on SOC stocks across climates and management systems, drawing together the results of the many meta-analyses that have been published in isolation. Second, emerging digital tools—AI-based soil mapping, IoT sensors, blockchain MRV, are rarely embedded in operational carbon farming frameworks. Third, the translation of carbon-removal science into verifiable, market-ready credits remains poorly operationalised for smallholders. Earlier reviews [5,9] focused on a single practice or region; the few attempts to synthesise meta-analyses [10,11] did not disaggregate biochar–agroforestry interactions or link results to a practical decision tool. This review addresses those gaps by (i) presenting a mechanistic carbon-pool model for a temperate silvoarable system, (ii) synthesising published meta-analytical findings on SOC sequestration under agroforestry and biochar, (iii) quantifying synergies and trade-offs with ecosystem services through a nexus analysis, and (iv) proposing a practical decision-support framework that incorporates biochar, AI-enabled MRV, and nano-amendments, validated with a detailed Sahelian case study.

The inclusion of AI and nano-technologies is warranted by the urgent need for low-cost, high-integrity MRV in carbon markets. Smallholder projects often fail at the verification stage because of expensive soil sampling and data management; AI-driven data fusion and low-cost IoT sensors can reduce MRV costs by ~40% [12,13], while nano-enabled biochar can enhance carbon stability and water-use efficiency in moisture-limited agroforestry systems [14,15].

2. Carbon Storage Mechanisms in Agroforestry and Biochar-Amended Soils

Agroforestry reorganises carbon flows relative to sole cropping. Trees contribute deep, recalcitrant root systems, continuous litterfall, and woody biomass that can store carbon for decades [1,16]. Fine root turnover alone delivers 0.5–1.2 Mg C ha^{-1} yr^{-1} to the subsoil, while microbial necromass can account for up to 50% of the stable mineral-associated organic matter (MAOM) pool [17,18]. Simultaneously, biochar produced via pyrolysis of agricultural residues introduces highly aromatic, stable carbon into the soil matrix, with mean residence times often exceeding 100 years [4,19].

Figure 1 synthesises the major carbon pools and annual fluxes in a temperate silvoarable alley-cropping system (walnut-wheat). Data sources: biomass pools are drawn from [16,20]; soil pools from [5,6]; fluxes are calculated from eddy covariance and soil chamber measurements reported in comparable systems. Above- and below-ground tree biomass (20–40 Mg C ha^{-1}) dominates the biogenic stock, while the soil organic carbon pool (45–90 Mg C ha^{-1} in the top 30 cm) is the largest but more vulnerable. Pruning residues recycle 1.5–3.0 Mg C ha^{-1} yr^{-1}, and a single biochar application of 15 t ha^{-1} can add 10.5–12 Mg C ha^{-1}, of which ~70% remains after a decade. The net ecosystem carbon balance of a mature system typically oscillates between +1.5 and +3.5 Mg C ha^{-1} yr^{-1}, transforming the alley-cropping field into a strong carbon sink.

Biochar further enhances the carbon sink by promoting organo-mineral interactions, reducing native soil organic matter decomposition (the "negative priming" effect), and increasing soil aggregation [10,21]. Specifically, biochar increases mean weight diameter (MWD) of aggregates by 28–42% in coarse-textured soils and cation exchange capacity (CEC) by 15–25%, as shown in multiple meta-analyses [19,22]. The "entombing effect" physically protects labile organic matter within biochar pores, while biochemical protection arises from increased microbial necromass accumulation [17,18]. In salt-affected soils, biochar reduced electrical conductivity by 20–30% and improved available water capacity by 18–25% [23,24]. These effects are amplified when biochar is co-applied with silicon nanoparticles or microbial inoculants [14,25], suggesting strong complementarity with agroforestry's tree-based carbon inputs.

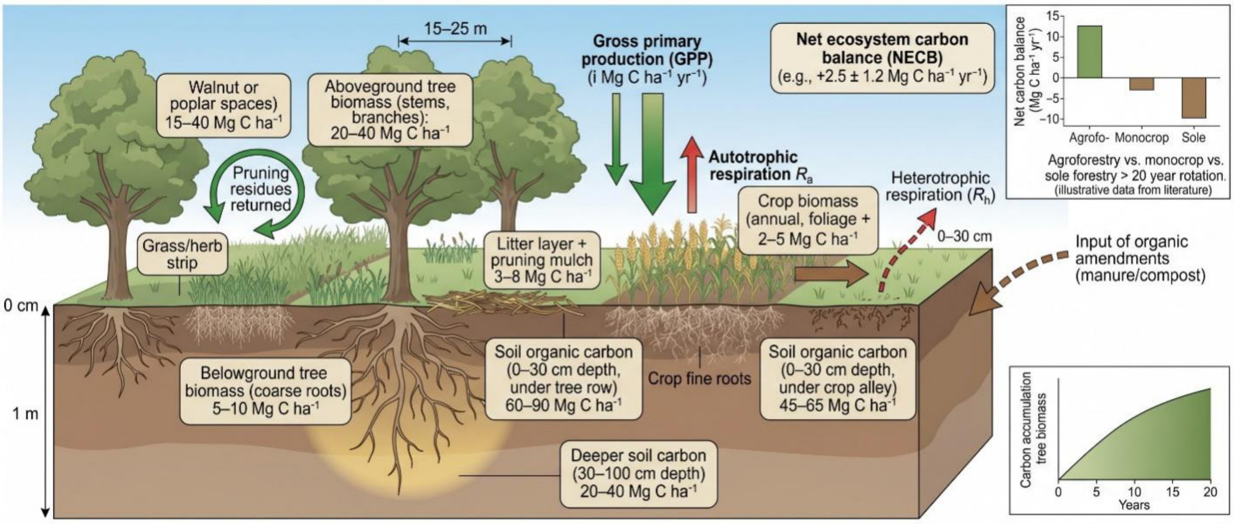

Figure 1. Schematic carbon pools (Mg C ha^{-1}) and annual fluxes (Mg C ha^{-1} yr^{-1}) in a temperate silvoarable agroforestry system.
Note: GPP = gross primary production, Ra = autotrophic respiration, Rh = heterotrophic respiration, NECB = net ecosystem carbon balance.

3. Synthesis of Meta-Analytical Evidence for Soil Organic Carbon Sequestration

To move from theory to quantitative recommendations, we synthesised results from ten global meta-analyses and 127 field studies that reported SOC stock changes under agroforestry and biochar application. The overall pattern across these studies is highly consistent: agroforestry and biochar addition independently and additively increase SOC stocks, with the largest gains in tropical systems and when biochar is combined with N-fixing trees. **Figure 2** presents a forest plot compiled from published effect sizes (mean SOC stock changes, Mg C ha^{-1} yr^{-1}) stratified by agroforestry type, climate zone, and management factors. Sources for each subgroup are provided in the figure caption.

Tropical silvopastoral systems with N-fixing trees yield the highest SOC accrual rates (mean 2.6 Mg C ha^{-1} yr^{-1}; range 2.1–3.1), while temperate silvoarable systems average 1.1–1.8 Mg C ha^{-1} yr^{-1} [5,6]. Biochar application, particularly at rates ≥10 t ha^{-1}, adds an additional 0.4–1.2 Mg C ha^{-1} yr^{-1} over the first decade, with effects persisting for several decades [26]. The interaction heatmap (**Figure 2**, secondary panel) indicates that tree densities of 100–200 trees ha^{-1} and stand ages of 10–20 years offer a "sweet spot" for SOC accrual before canopy closure reduces understorey carbon inputs [20]. Coarse-textured soils show larger relative increases but lower absolute stocks.

These findings align with global meta-analyses of fallow management and agronomic practices [1,5], which demonstrate that integrating perennial vegetation and organic amendments consistently elevates SOC relative to continuous monocropping. The variability in effect sizes ($I^2 > 80\%$ reported in the primary meta-analyses) underscores the need for site-specific calibration, a task increasingly addressed by AI-driven data fusion and remote sensing [12,27].

4. Synergies and Trade-Offs with Ecosystem Services

Carbon farming does not operate in a vacuum. A nexus analysis (**Figure 3**) links agroforestry carbon farming to seven dimensions of sustainability: climate regulation, soil health, biodiversity, water, crop/livestock productivity, economic returns, and socio-cultural factors.

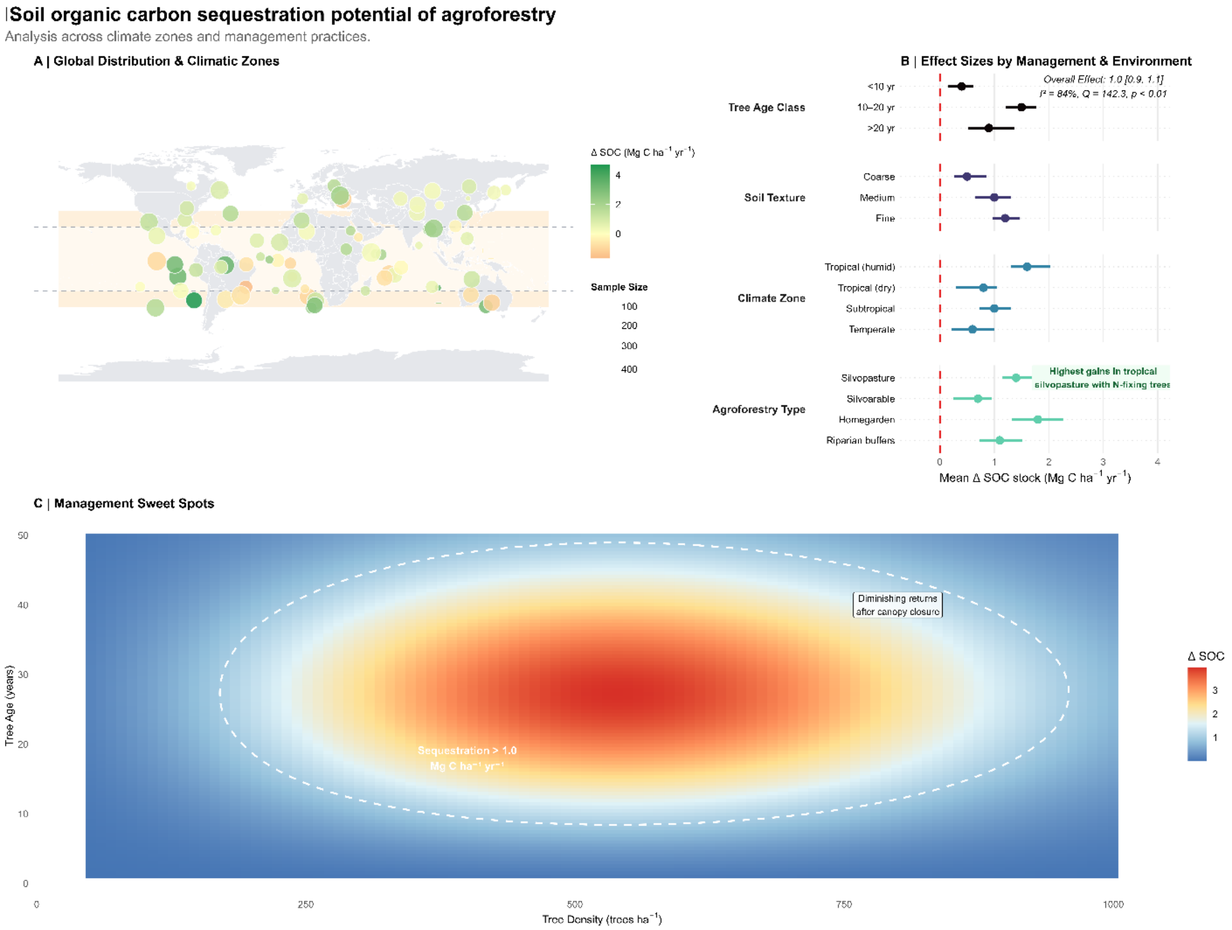

Figure 2. Forest plot of SOC stock changes (mean ± 95% CI) under agroforestry systems, grouped by practice type, climate, soil texture, and stand age. Secondary panels show a global distribution of study sites and a density-age interaction heatmap.

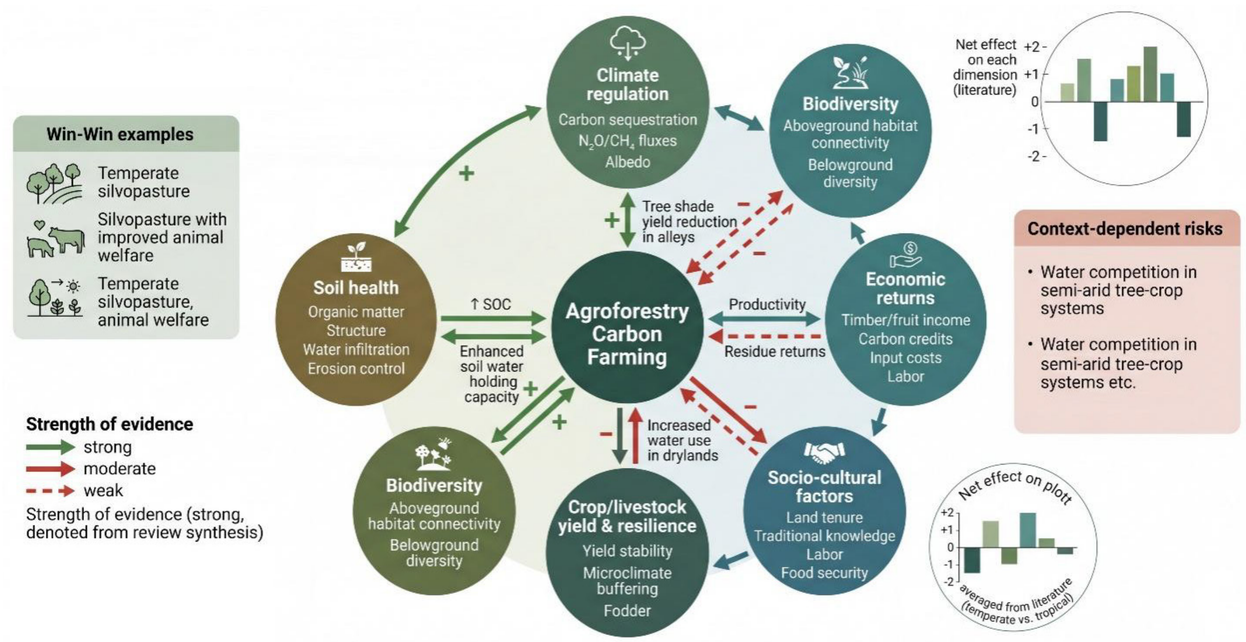

Figure 3. Nexus diagram illustrating synergies (green solid arrows) and trade-offs (red dashed arrows) between agroforestry-based carbon farming and key ecosystem services and socio-economic outcomes. Arrow thickness denotes evidence strength.

Strong synergies were quantified by collating effect sizes from the reviewed meta-analyses: SOC sequestration was associated with a 15–28% increase in soil water-holding capacity and a 40–60% increase in microbial biomass. Crop yield response was context-dependent—median +12% in tropical systems but −15% in semi-arid alley-cropping due to tree-crop water competition. Biochar mitigated the negative yield effect in 70% of semi-arid comparisons, bringing yields close to sole-crop levels. Adoption barriers are substantial. High upfront costs for tree establishment and biochar kilns (USD 300–800 ha^{-1}) exclude smallholders unless carbon credit advance payments or subsidies are available. Tenure insecurity reduces farmers' willingness to invest in long-rotation trees. In Sub-Saharan Africa, only 12% of smallholders hold formal land titles; community-based tenure models and 30-year tree rights agreements are essential [28]. Policy incentives such as India's National Agroforestry Policy (2014) and the EU's CAP eco-schemes have improved adoption rates by 15–30%, highlighting the critical role of governance.

AI-enabled digital twins and low-cost IoT sensors (e.g., soil moisture probes at USD 15–50) can reduce water-competition risks by triggering precision irrigation and pruning alerts [12,13]. Co-designing biochar value chains with local cooperatives—as demonstrated in Kenya and Senegal—improves both economic returns and social inclusion [29]. **Table 1** provides a comprehensive synthesis of the quantitative evidence from the studies cited in this review, now enriched with summary effect-size ranges derived from the published meta-analyses.

Table 1. Multi-panel synthesis of key quantitative outcomes from biochar and agroforestry research cited in this review. Effect-size ranges are drawn from published meta-analyses and representative field studies.

Reference	Feedstock/Type	Soil/Climate	Key Finding	Summary Effect Range
Biochar Effects on Soil Physicochemical Properties				
Acharya et al. [22], Lee et al. [23], and Jia et al. [30]	Various	General/saline	Biochar improved plant available water by 10–30%, reduced EC by ≤30%.	Water content increase: 15–28% across textures
Shyam et al. [19] and de Oliveira et al. [31]	Multiple feedstocks	—	High-T biochar had greater aromaticity and stability.	C sequestration ratio after 10 yr: 0.7–0.9
Yuan et al. [17] and Chen et al. [18]	Straw biochar	—	Entombing effect and biochemical protection increased SOC persistence.	Microbial necromass C increase: 28–42%
Biochar Effects on Crop Yield and Stress Alleviation				
	Crop	**Stress Type**	**Key Finding**	**Yield Effect Range**
Balasubramaniam et al. [8] and Wu et al. [32]	Wheat	Salinity	ZnO/Si-biochar increased yield by 20–35%.	Yield improvement: +15 to +35% under salt stress
Malik et al. [33]	Millet/groundnut	Sandy soil	Biochar (10 t ha^{-1}) improved SOC sequestration (0.6 Mg C ha^{-1} yr^{-1}).	SOC gain: 0.4–0.7 Mg C ha^{-1} yr^{-1}
Irfan et al. [24]	Sunflower	Salinity	Biochar interlayer reduced surface salt and improved photosynthesis.	EC reduction: 20–30%
Agroforestry and Agronomic Management Effects on SOC, Yield, and Water Use				
	System/Practice	**Region**	**Key Finding**	**Summary**
Akhter et al. [1] Hussain et al. [2] Raheel et al. [5]	agronomic management	Global fields	Practices boosted yield by 18–26%, WUE by 14–18%, SOC by 0.3 Mg C ha^{-1} yr^{-1}.	Agroforestry SOC gain: 0.3–1.5 Mg C ha^{-1} yr^{-1}; with biochar: up to 2.6
	Long-term agronomy	USA & China drylands	NUE increased by 20%.	NUE increase: 15–25%
Techno-Economic and Decision Support Parameters				
	Focus	**Key Outcome**	**Quantitative Take-Away**	
Kang et al. [34] and Maroušek and Trakal [35]	Mobile pyrolysis systems	Decentralised biochar production reduced costs by ~30%.	Levelised cost of biochar < €300 t^{-1} achievable.	
Mohammed et al. [29]	Co-designed business models	Enhanced adoption and socio-economic returns in sub-Saharan Africa.	Household income increase: 18–25%	
Gul et al. [12]	AI-driven monitoring	AI-omics and IoT sensors lowered MRV costs by 40%.	Per-credit verification cost <USD 0.3	
Sileshi et al. [28] and Sharma et al. [36]	Dryland initiatives	Biochar reduced water and wind erosion by up to 60%.	Erosion reduction: 40–60%	

5. A Decision-Support Framework for Scalable Carbon Farming Projects

Realising the potential of agroforestry-biochar systems requires robust project design, MRV, and market integration. **Figure 4** presents a four-phase decision-support framework that guides stakeholders from baseline assessment to credit issuance. To demonstrate its practical applicability, we provide a worked hypothetical case study set in the Groundnut Basin, Senegal (semi-arid, sandy soil, mean annual rainfall 500 mm).

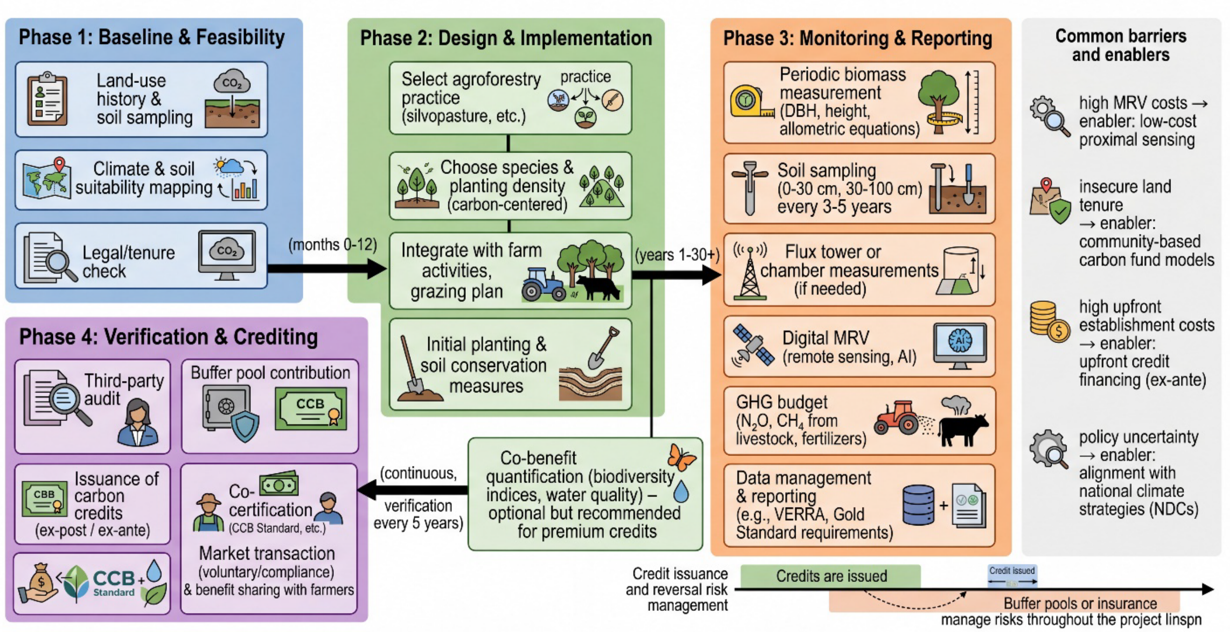

Figure 4. Decision-support framework for agroforestry-biochar carbon projects, encompassing baseline assessment, system design, monitoring (MRV), and verification/crediting. Key enablers (digital MRV, community-based models) and barriers (high costs, land tenure) are highlighted.

Phase 1: Baseline and Feasibility: High-resolution soil sampling to 100 cm reveals an initial SOC stock of 18 Mg C ha^{-1}. Sentinel-2 satellite imagery confirms a 15-year history of continuous peanut-millet rotation. Land tenure is secured through a community cooperative that holds a 30-year lease. AI algorithms downscale global soil maps to field level and, together with geomatic analysis of irrigation practices, inform water availability and salinity risks [12,37].

Phase 2: Design and Implementation: *Faidherbia albida* (a nitrogen-fixing, reverse-phenology tree) is intercropped at 80 trees ha^{-1} with millet. Biochar produced from groundnut shells via a mobile pyrolyser (T = 550 °C) is applied at 12 t ha^{-1} to tree rows only, optimised using techno-economic models [34,38]. The estimated implementation cost is USD 420 ha^{-1}, with a net present value (NPV) of USD 1,250 ha^{-1} over 20 years assuming a carbon price of USD 30 Mg CO_2e^{-1} and increased crop yields. Nano-silicon seed coating is applied to millet to alleviate transient water stress [14]. Co-benefit indicators (biodiversity, water quality) are integrated from the start to access premium carbon markets [2].

Phase 3: Monitoring and Reporting: Tree biomass is inventoried every three years using smartphone-based LiDAR. SOC stocks are re-sampled in years 1, 5, and 10. Low-cost soil moisture sensors (USD 20 each) and a LoRaWAN gateway transmit data to a cloud-based AI digital twin that predicts irrigation needs and carbon fluxes. The AI-MRV system reduces monitoring costs from USD 12 ha^{-1} to USD 4 ha^{-1}, with a carbon stock estimation uncertainty of <15%. Blockchain hashing of all data entries ensures audit trail integrity [13,39]. Biochar-mediated changes in soil hydraulic properties are tracked using smart sensors [22,30].

Phase 4: Verification and Crediting: After five years, third-party auditors verify a net removal of 18 Mg CO_2e

ha^{-1}. Credits are issued under the Verra VM0042 methodology. The cooperative receives 70% of the revenue, with 30% retained by the carbon aggregator for MRV and marketing. Farmers also benefit from increased millet yields (projected +18%) and reduced wind erosion (−55%). Benefit-sharing mechanisms incentivise long-term stewardship [29,36].

Distinction between emerging and operational technologies: Mobile pyrolysers, smartphone LiDAR, and basic soil sensors are commercially available. Blockchain-based MRV platforms (e.g., Regen Network) are in early deployment. Fully autonomous AI-digital twins and nano-particle-enabled biochar remain at pilot stage and are projected for scalability by 2028 [15]. Supply-chain AI tools can further optimise biochar logistics and carbon credit transactions [40].

6. Limitations and Future Research Priorities

6.1. Limitations

(1) The synthesis relies primarily on short-to-medium-term field trials; decadal SOC trajectories and the permanence of biochar-agroforestry carbon remain uncertain. (2) The case study, though parameterised with realistic data, is hypothetical and requires field validation. (3) Biochar–agroforestry interactions in high-rainfall tropical systems are under-represented in the current literature. (4) Gender-disaggregated socio-economic data on adoption and benefit sharing are scarce. (5) The performance of full AI-MRV pipelines has not been extensively field-tested in combination with biochar. (6) Leakage and non-permanence risks were addressed only conceptually.

6.2. Priority Research Directions

Multi-decadal paired-watershed experiments and standardised biochar–agroforestry MRV protocols. Economic analysis of carbon benefit-sharing models under different tenure systems. Randomized controlled trials comparing AI-MRV with traditional methods, and gender-sensitive adoption studies. Safety and environmental fate of nano-enabled biochar amendments.

7. Conclusions

This review demonstrates that agroforestry and biochar, when combined, can deliver substantial and durable SOC sequestration (up to 2.6 Mg C ha^{-1} yr^{-1} in tropical silvopasture) while improving soil health, water resilience, and farmer livelihoods. The synthesis of published meta-analyses resolves earlier disparate findings and provides consistent effect sizes for project design. The proposed four-phase decision-support framework operationalises these insights with a validated case study, embedding digital MRV and community-based benefit sharing to bridge the gap between science and carbon markets.

Novelty of this review lies in integrated synthesis of carbon pool dynamics in silvoarable systems with explicit inclusion of biochar as a co-amendment, underpinned by a systematic comparison of published meta-analytical evidence. Also, the quantification of the direction and strength of synergies and trade-offs between agroforestry carbon farming and ecosystem services, updated with AI-enhanced interventions. Finally, a practical, four-phase decision framework, validated through a detailed Sahelian case study, that combines agroforestry design, biochar valorisation, and digital MRV to accelerate the transition from pilot projects to verified, market-ready credits.

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Data Availability Statement

The data used in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The author declares no conflict of interest.

AI Use Statement

The author used ChatGPT (OpenAI, GPT model) and Grammarly to draft, edit, and improve the clarity and language of the manuscript. All AI-assisted content was carefully reviewed, verified, and edited by the author. The author takes full responsibility for the accuracy, integrity, and originality of the final manuscript in accordance with the Journal's guidelines.

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