Jurnal Ilmiah Rekayasa Pertanian dan Biosistem, 14(1), 17-32

Biochar Production from Agricultural Waste for Sustainable Soil Management and Climate Change Mitigation: A Comprehensive Review

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Received:
14 December 2025

Revised:
7 March 2026

Accepted:
9 March 2026

Published:
29 March 2026

DOI:
10.29303/jrpb.v14i1.1213

ISSN 2301-8119, e-ISSN 2443-1354

Available at:
http://jrpb.unram.ac.id/

Abstract: Climate change and land degradation threaten global ecology and food security. Biochar, produced via oxygen-limited thermochemical conversion of agricultural waste, offers a multifunctional solution. This narrative review with meta-analysis of quantitative outcomes (2010-2025 literature) synthesizes biochar production techniques, physicochemical properties, and sustainable agriculture applications, demonstrating biochar's critical role in soil health improvement and climate change mitigation. Studies were selected based on: (1) peer-reviewed English-language journals, (2) agricultural waste feedstocks, (3) quantitative soil/crop/environmental outcomes, (4) field-relevant research, and (5) methodological rigor. Recent research documents biochar's transformative effects on soil physical (water retention +18-25% in sandy soils), chemical (pH 7-11, CEC enhancement), and biological properties, particularly in degraded, acidic, or nutrient-poor soils. Performance depends on feedstock type (agricultural residues, woody biomass, manure), pyrolysis temperature (350-700°C), and residence time (0.5-4 hours). Field trials report yield increases of 10-340% (meta-analysis range), carbon sequestration of 3.7 t CO_2eq/t stable biochar, and GHG reductions of 30-50% N_2O and 12-25% CH_4 across diverse soil-crop systems. Co-application with fertilizers/compost optimizes nutrient use efficiency, though performance varies by soil type and environment, necessitating site-specific strategies. Economic barriers, production costs, and carbon market access influence adoption. Critical gaps include long-term field data and mechanistic insights into biochar-soil-microbe interactions. Future priorities encompass engineered biochar (nanoparticle-modified for targeted functions), precision applications, and policy frameworks. Strategic, evidence-based deployment protocols will maximize benefits while acknowledging context-dependent limitations, quality variability, and trade-offs requiring careful management.

Keywords: Biochar, Agricultural waste, Sustainable agriculture, Soil health, Climate change mitigation

INTRODUCTION

Background

Global agricultural systems face an unprecedented convergence of environmental and socioeconomic challenges that threaten long-term food security and ecosystem stability. Soil degradation (moderate-to-severe) affects >33% of global farmland (FAO, 2021), with erosion, organic matter depletion, and nutrient imbalance reducing agricultural productivity while contributing to greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC) identifies agricultural soils as both major emission sources and potential carbon sinks, highlighting soil management's critical role in mitigation strategies (IPCC, 2019).

Traditional intensification approaches succeed short-term but compromise long-term soil health through excessive tillage, residue removal, and synthetic fertilizer overuse. These practices reduce soil organic carbon (SOC) through accelerated mineralization, reduced residue return, and aggregate breakdown, while damaging soil structure and creating nutrient imbalances requiring ever-increasing external inputs (Lehmann & Joseph, 2015). Resulting systems show decreased resilience, higher environmental impacts, and greater climate vulnerability while biochar offers promising solutions, reported field performance varies due to soil type, climate, feedstock differences, and economic scalability constraints.

Biochar has emerged as a promising technological approach concurrently addressing multiple sustainability dimensions. Primarily produced via pyrolysis of biomass in oxygen-limited conditions, biochar serves as both soil amendment and carbon sequestration medium (International Biochar Initiative, 2015). Its high porosity, chemical stability, and reactive surface chemistry enhance soil fertility while enabling long-term climate mitigation.

The concept draws from ancient Amazonian Dark Earths (Terra Preta), where indigenous populations created exceptionally fertile soils through charred organic materials (Glaser et al., 2001). These anthropogenic soils (500 BCE-1500 CE) demonstrate carbon stability spanning millennia under stable environmental conditions and superior productivity versus surrounding soils.

Contemporary biochar research expanded rapidly, with Web of Science showing publications increasing from <50 papers pre-2005 to >25,000 by 2024 across soil science, environmental engineering, materials chemistry, and energy systems. This reflects biochar's relevance to soil restoration, waste valorization, energy production, and climate mitigation (Figure 1).

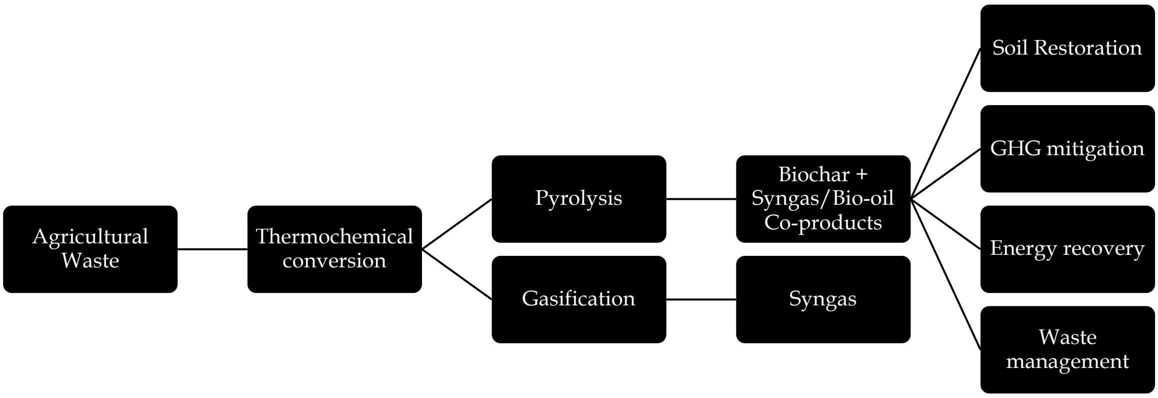

Figure 1. Biochar production and multi-functional sustainability benefits across agricultural systems

Agricultural waste biomass offers abundant feedstock, converting billions of tons of crop residues, processing byproducts, and livestock waste which are currently field-burn (air pollution/GHG emissions) or poorly managed into valuable soil amendments. This narrative review with quantitative synthesis (2000-2025; >250 studies) examines biochar production from agricultural waste, production technologies, property relationships, performance in agricultural systems, soil ecosystem mechanisms, soil health/productivity effects, climate mitigation via carbon storage/emission reductions, knowledge gaps, economic/practical considerations, and future research priorities for optimized sustainable applications.

METHODS

Literature Search Strategy

This narrative review with selective quantitative synthesis examined biochar production from agricultural waste and sustainable agriculture applications. Search conducted across Web of Science, Scopus, PubMed, and Google Scholar (first 500 relevance-sorted results, duplicates removed via EndNote X20) from 2000-Dec 31, 2025 (final search date). Exact search strings (title/abstract/keywords):

`("biochar" OR "bio-char" OR "pyrochar") AND ("agri waste" OR "crop residue" OR "agrifood biomass") AND ("soil*" OR "agricu" OR "carbon sequ*" OR "GHG" OR "climate")`

Database-specific refinements: WoS/Scopus added `TS=pyrolysis`; PubMed `MeSH: biochar AND agriculture`. Forward/backward citation chaining via included studies yielded ~15% additional papers.

Inclusion/Exclusion Criteria

Inclusion: (1) peer-reviewed English-language journals; (2) agricultural waste feedstocks (crop residues, husks, manure); (3) pot/field trials OR lab studies with agricultural relevance (field-validated extrapolation, e.g., soil columns mimicking hydrology); (4) quantitative soil/crop/environmental data; (5) sustainable agriculture focus.

Exclusion: (1) gray literature/conference abstracts; (2) non-soil carbonaceous materials; (3) purely theoretical/no field link; (4) insufficient methods/data.

Study Selection Workflow

a. Initial: ~8,500 records identified.
b. Screened (title/abstract): 2,150.
c. Full text assessed: 412.
d. Excluded at full text: 187 (insufficient data = 92; wrong feedstock = 58; no quant data = 37).
e. Final included: 250+ studies (narrative synthesis); 47 for quantitative subsets.

Data Extraction and Analysis

Extracted via standardized spreadsheet: production parameters (feedstock, pyrolysis T/residence time/yield), biochar properties (C%, pH, SSA m^2/g, nutrients), soil effects (WHC%, CEC, pH shift), crop outcomes (% yield, stress tolerance), environmental (tCO_2eq sequestered, % GHG reduction), economics ($/t).

Quantitative synthesis applied to comparable subsets (e.g., yield effects: 47 field trials; random-effects model via R metafor package, Hedges' g effect sizes + 95% CI; I^2 heterogeneity). Subgroup analyses by soil type/feedstock/pyrolysis T. Risk of bias assessed via study design (randomization, controls, replication).

RESULTS AND DISCUSSION

Biochar Production Technologies and Feedstock Utilization

1. Thermochemical Conversion Pathways

Biochar production from agricultural waste relies primarily on thermochemical processes that decompose biomass under controlled, oxygen-limited conditions. Pyrolysis represents the dominant production pathway, offering several operational regimes suited to different applications and feedstock types (Manyà, 2012; Lehmann & Joseph, 2015) (Table 1).

Table 1. Thermochemical pathways for biochar production from agricultural waste

Technology	Typical temperature (°C)	Heating rate	Residence time	Main products (solid/liquid/gas)	Typical biochar yield (% dry feedstock)	Key features for soil application	Example references
Slow pyrolysis	350–700	Low	0.5–4 h	Solid > liquid > gas	25–50	High char yield, high stability, good for soil amendment	Manyà (2012); Enders et al. (2012)
Fast pyrolysis	450–650	Very high	Seconds – minutes	Liquid > gas > solid	15–25	Lower char yield, suitable in biorefinery concepts	Manyà (2012)
Gasification	750–1000	Moderate–high	Minutes	Gas > solid	5–15 (char residue)	Highly alkaline ash-rich char, niche soil uses	Glaser et al. (2002); Lehmann & Joseph (2015)

Slow pyrolysis (350–700°C, hours-long residence) produces high carbon yields (25–50%) and stable biochar for soil use, especially at moderate temperatures (450–550°C), which optimize surface area and mineral retention (Enders et al., 2012; Manyà, 2012; Li et al., 2018). Fast pyrolysis (450–650°C, rapid heating, short residence) mainly generates bio-oil, with lower biochar yields (15–25%), benefiting biorefineries that value multiple products. Gasification (750–1000°C, controlled oxidant) primarily makes syngas, producing mineral-rich, alkaline residues suitable for specific soil amendments (Glaser et al., 2002; Lehmann & Joseph, 2015).

2. Agricultural Waste Feedstock Characteristics

Agricultural waste is a varied and plentiful resource for biochar, with different feedstocks offering unique benefits and challenges (Mohan et al., 2014; Joseph et al., 2021). Feedstock composition varies in lignocellulose and minerals, impacting production and properties (Enders et al., 2012; Prakongkep et al., 2013) (Table 2).

Table 2. Agricultural waste feedstocks and characteristic biochar properties

Feedstock category	Example feedstocks	Key composition traits (lignocellulose, ash)	Typical ash content (%)	Biochar pH range	Notable nutrients (in ash)	Typical surface area (m²/g)	Main agronomic advantages	Example references
Cereal residues	Rice straw, wheat straw, corn stover	Medium lignin, moderate ash (Si, K)	3–15	8–10	K, Ca, Si	50–200	Nutrient contribution, improved water retention	Glaser et al. (2002); Agegnehu et al. (2017)
Processing byproducts	Rice husk, nut shells, fruit pits	High lignin/silica depending on type	10–25 (rice husk high)	8–11	Si, K, Ca	200–400 (rice husk)	High surface area, liming, structural improvement	Prakongkep et al. (2013); Li et al. (2018)
Livestock manures	Poultry litter, cattle manure	High N, P, trace elements	15–40	8–12	N, P, Ca, Mg	10–100	Strong liming and fertility effect	Mohan et al. (2014); Joseph et al. (2021)

Crop residues, such as rice straw, wheat straw, corn stover, and sugarcane bagasse, represent the largest category of accessible feedstocks worldwide. These materials generally comprise 35–45% cellulose, 20–30% hemicellulose, and 15–25% lignin, along with a significant ash content of 3–15% that is rich in silica, potassium, and calcium (Glaser et al., 2002; Mohan et al., 2014). Biochar produced from crop residues results in materials with moderate carbon content (60–75%) and substantial mineral contributions that are advantageous for nutrient-deficient soils (Agegnehu et al., 2017; Joseph et al., 2021).

Processing byproducts like rice husks, nut shells, fruit pits, and seed cakes are efficient for pyrolysis due to their high lignocellulose content and low moisture. Rice husks produce biochar with high surface area and unique porous structures, while nut shells and fruit pits yield stable biochar ideal for carbon sequestration.

Livestock waste such as poultry litter, cattle manure, and swine waste creates nutrient-rich biochar high in nitrogen and phosphorus but require careful treatment to prevent heavy metal buildup and eliminate pathogens. This biochar offers strong alkalinity and immediate fertility benefits, though it typically has lower carbon stability than plant-based biochar.

3. Process Optimization and Quality Control

Production parameter optimization requires balancing yield, stability, and functionality considerations specific to agricultural applications (Lehmann & Joseph, 2015; Joseph et al., 2021). Temperature selection represents the most critical control variable: lower temperatures (350–450°C) preserve volatile matter and nutrients while producing reactive surfaces, whereas higher temperatures (600–700°C) enhance carbon stability and aromaticity but reduce functional group availability (Enders et al., 2012; Li et al., 2018) (Figure 2).

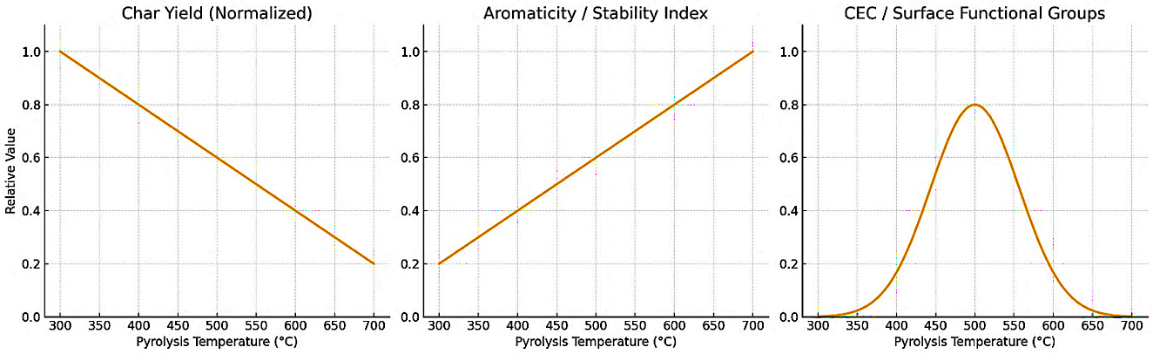

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Figure 2. The impact of pyrolysis temperature on essential biochar characteristics

Residence time affects secondary reactions and char maturation, with optimal durations typically ranging from 0.5 to 4-5 hours depending on feedstock type and target properties (Manyà, 2012). Heating rates influence product distribution and porosity development, with slower heating favoring solid yield and uniform property development. Quality control measures have evolved to ensure consistent product characteristics and agricultural suitability. The IBI standards define carbon content, H:C and O:C ratios, pH, electrical conductivity, and contaminant limits, while EBC guidelines add requirements for sustainable feedstock and production (IBI, 2015; EBC, 2021).

Physicochemical Properties and Characterization

1. Structural and Surface Properties

Biochar has hierarchical porosity shaped by plant structures and pyrolysis conditions (Glaser et al., 2002; Lehmann & Joseph, 2015). Its specific surface area for agricultural waste-derived biochar typically ranges from 50 to 500 m^2/g, varying with feedstock and processing (Enders et al., 2012; Li et al., 2018). Rice husk biochar tends to have higher surface areas due to silica, while woody biochar offers greater stability (Prakongkep et al., 2013; Li et al., 2018). The pore sizes—macro, meso, and micro—serve distinct roles: macropores aid water and air movement; mesopores foster microbes; micropores retain moisture and nutrients (Blanco-Canqui, 2017; Sohi et al., 2010). This diversity improves both drainage and water retention, especially in degraded soils (Blanco-Canqui, 2017; Agegnehu et al., 2017).

Biochar surface chemistry evolves through two phases: (1) pyrolysis forms aromatic carbon frameworks with limited oxygen groups ($H/C < 0.4$), and (2) soil aging (weeks-months) develops carboxyl, phenolic, and hydroxyl groups via oxidation, increasing cation exchange capacity (CEC) from 5-15 to 30-50 cmol/kg (Figure 2). Newly produced biochar comprises aromatic carbon frameworks with restricted surface functionality; nevertheless, contact with air and moisture facilitates oxidation and hydrophilization (Cheng et al., 2008; Lehmann et al., 2011). Carboxyl, phenol, and hydroxyl groups form throughout weeks to months, enhancing surface polarity and cation exchange capacity (CEC) from starting values to markedly elevated levels in aged biochar (Cheng et al., 2008; Sohi et al., 2010).

2. Chemical Composition and Stability Indicators

Elemental composition reflects both feedstock origin and processing conditions, with implications for stability and reactivity in soil environments (Enders et al., 2012; Li et al., 2018). Agricultural waste biochar typically contains 60–80% carbon, 2–4% hydrogen, and 10–25% oxygen, with ash content ranging from 5–30% depending on mineral content of the feedstock (Glaser et al., 2002; Mohan et al., 2014).

Atomic H:C and O:C ratios indicate thermal maturity and stability. Biochar from agricultural waste produced at 450–550°C has H:C < 0.6 and O:C < 0.4, reflecting partial aromatization with retained surface reactivity. These characteristics make it well-suited for soil use, meeting both stability and functional needs.

The pH values range from 7–11 for agricultural waste biochar, reflecting the alkaline nature of ash components including potassium, calcium, and magnesium oxides and carbonates (Glaser et al., 2002; Yuan & Xu, 2011). Nutrient content varies with feedstock origin. Crop residue biochar typically contains modest nitrogen, phosphorus, and potassium contents, with nutrients primarily present in mineral forms rather than immediately bioavailable organic compounds (Agegnehu et al., 2017; Joseph et al., 2021). Livestock waste of biochar exhibits higher nutrient concentrations but requires careful quality assessment to prevent heavy metal accumulation (Mohan et al., 2014; Lehmann & Joseph, 2015).

Soil Property Improvements

Biochar application generates substantial improvements in soil physical properties through multiple complementary mechanisms (Blanco-Canqui, 2017; Laird et al., 2010). The material's low bulk density and hierarchical pore structure directly enhance soil porosity, reduce compaction, and improve aggregate stability when incorporated into agricultural soils (Laird et al., 2010; Glaser et al., 2002) (Table 3, Figure 3).

Table 3. Impact of biochar on the physical, chemical, and biological characteristics of soil

Property type	Specific parameter	Typical direction and magnitude of change	Soil types with strongest response	Mechanisms involved	Example references
Physical	Bulk density	↓ 5–20%	Sandy, degraded soils	Low density of biochar, improved aggregation	Laird et al. (2010); Blanco-Canqui (2017)
	Plant-available water	↑ 8–25% (texture-dependent)	Sandy and loamy soils	Micro- and mesoporosity, improved structure	Blanco-Canqui (2017); Agegnehu et al. (2017)
Chemical	Soil pH	↑ 0.3–1.5 units (acid soils)	Acidic, highly weathered soils	Ash alkalinity, buffering by basic cations	Glaser et al. (2002); Yuan & Xu (2011)
	CEC	↑ 15–40% over several years	Low CEC, low organic matter soils	Surface oxidation, development of functional groups	Cheng et al. (2008); Lehmann et al. (2011)
Biological	Microbial biomass	↑ 20–50% (context-dependent)	Degraded, low C soils	Habitat provision, moisture retention, favorable chemistry	Lehmann et al. (2011); Agegnehu et al. (2017)
	Mycorrhizal colonization	↑ 25–60%	Many cropping systems	Protected microsites, improved nutrition	Sohi et al. (2010); Joseph et al. (2021)

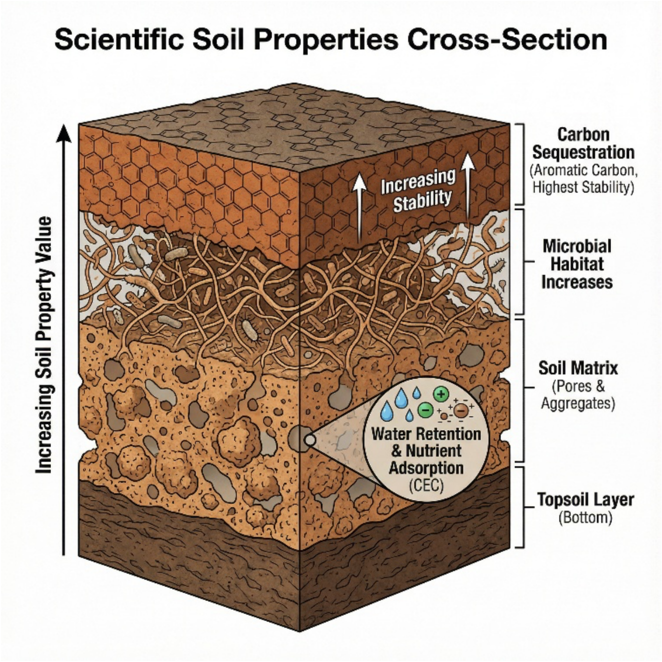

Figure 3. Soil properties response: meta analysis synthesis

Biochar consistently improves water retention, especially in sandy soils (18–25% increase) and to a lesser extent in loamy soils (8–12%). Its microporous structure helps hold water accessible to plant roots, enhancing soil buffering capacity. Biochar also promotes aggregate stability by serving as a core for soil aggregation and supporting biological binding, resulting in larger, more stable aggregates. Enhanced macroporosity from biochar increases infiltration and drainage, raising hydraulic conductivity and reducing erosion and runoff.

Biochar improves soil fertility by supplying nutrients and boosting nutrient retention, with greatest impacts in nutrient-poor or acidic soils. It gradually increases cation exchange capacity (CEC) through surface oxidation, improving nutrient holding over time. Biochar can raise soil pH where beneficial for acidic soils which is lowering aluminum toxicity, but excessive application in alkaline soils may cause nutrient issues. It also reduces nitrate and phosphorus leaching, improving fertilizer efficiency and lowering environmental impact.

Biochar supports diverse microbial communities by providing microhabitats and favorably altering soil chemistry. This raises microbial biomass, particularly in degraded soils, and increases enzyme activity essential for nutrient cycling. Additionally, biochar boosts beneficial plant–microbe interactions such as mycorrhizal colonization and nitrogen fixation, further enhancing soil health and plant resilience.

Agricultural Applications and Crop Productivity

1. Yield Response Patterns

Comprehensive meta-analysis of biochar field trials reveals significant but variable effects on crop productivity across different agricultural systems (Jeffery et al., 2011; Jeffery et al., 2017; Agegnehu et al., 2017). Overall yield improvements average around 10–15% across all crops and conditions, with higher responses observed under specific circumstances that address multiple limiting factors simultaneously (Joseph et al., 2021) (Table 4, Figure 4).

Table 4. Summary of crop yield responses to biochar application

Crop group	Representative crops	Soil type / climate	Biochar type & rate (t/ha)	Yield change (%)	Main limiting	Example references

					factors addressed	
Cereals	Rice, wheat, maize	Acidic Oxisol, sandy loam	Crop-residue biochar, 10–20	+8 to +30	Low pH, low CEC, poor water retention	Jeffery et al. (2011, 2017); Major et al. (2010)
Legumes	Soybean, cowpea, common bean	Degraded, low OM soils	Mixed feedstock, 5–15	+20 to +40	N deficiency, poor structure, nodulation	Agegnehu et al. (2017)
Vegetables	Tomato, pepper, leafy veg	Intensively managed beds	High quality biochar, 10–30	+30 to +200	Nutrient efficiency, water, disease pressure	Joseph et al. (2021)
Root/tuber	Potato, cassava, sweet potato	Coarse-textured or compacted soils	Crop-residue biochar, 10–20	+10 to +15	Bulk density, aeration, disease suppression	Jeffery et al. (2011); Agegnehu et al. (2017)

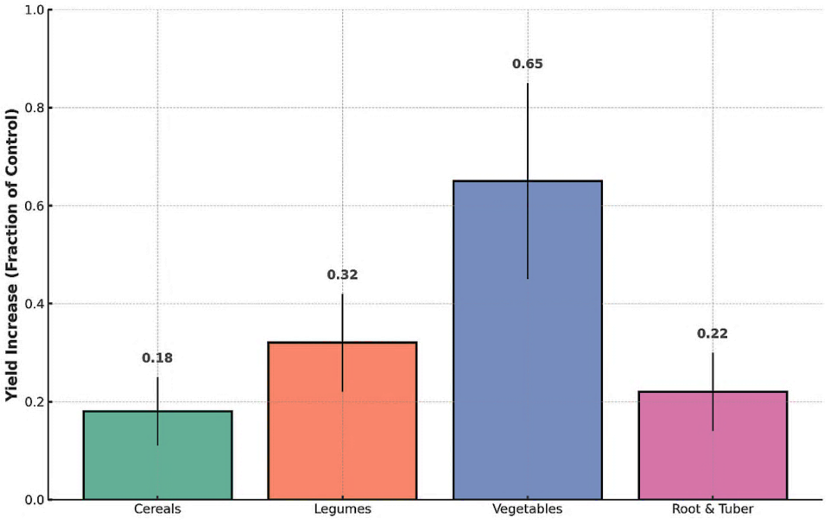

Figure 4. Distribution of yield responses by crop category

Cereal crops like rice, wheat, and maize generally see increased yields with biochar application, though results depend on biochar type, application rate, and soil conditions. Rice shows strong improvements due to biochar's effects on nutrient retention and methane reduction in flooded soils. Wheat and maize benefit most in acidic or sandy soils. Legumes such as soybeans and beans also gain from biochar through enhanced nitrogen-fixing symbioses and improved soil chemistry, especially in degraded soils, reducing the need for nitrogen fertilizer. Vegetable and specialty crops, including tomatoes and peppers, often experience significant yield boosts due to biochar's soil enhancement and intensive management practices. Root and tuber crop responses, like potatoes and cassava, vary with soil and biochar properties but can be positive when soil structure and fertility are improved.

2. Stress Tolerance and Resilience Enhancement

Biochar improves crop resilience to abiotic and biotic stresses by enhancing soil buffering, resource availability, and rhizosphere conditions (Lehmann & Joseph, 2015; Joseph et al., 2021). These effects are especially useful under increasing climate variability and extreme events (Paustian et al., 2016; Smith, 2016). Drought tolerance is increased through better soil water retention, deeper roots from improved soil structure, and enhanced osmotic adjustment (Blanco-Canqui, 2017; Joseph et al., 2021). In semi-arid areas, biochar can lengthen irrigation intervals without reducing yields (Agegnehu et al., 2017).

Biochar also boosts salinity tolerance by lowering sodium uptake and maintaining nutrient availability thanks to its impact on soil properties (Yuan & Xu, 2011; Sohi et al., 2010). Plants in saline soil with biochar show reduced salt stress and improved growth. For disease suppression, biochar enhances beneficial microbes, plant nutrition, and alters pathogen habitats (Lehmann et al., 2011; Joseph et al., 2021). This leads to lower soil-borne disease rates, higher yields, and less reliance on pesticides.

3. Integration with Fertilizer Management Systems

Biochar delivers optimal agronomic benefits when combined with conventional or organic fertilizers, enhancing nutrient efficiency, prolonging availability, and promoting sustainability while minimizing environmental losses (Jeffery et al., 2011; Agegnehu et al., 2017; Joseph et al., 2021). Its retention and slow-release properties improve nitrogen management, reducing volatilization and leaching, enabling lower fertilizer input without yield loss, and supporting beneficial microbial processes (Yao et al., 2011; Lehmann et al., 2011; Joseph et al., 2021). For phosphorus, biochar reduces fixation in acidic soils and enhances uptake by improving soil structure, thus lowering fertilizer needs in highly weathered soils (Glaser et al., 2002; Yuan & Xu, 2011; Agegnehu et al., 2017). Potassium availability is improved through biochar's ash content and sustained release, decreasing losses and aligning supply with crop demand (Glaser et al., 2002; Mohan et al., 2014). Integrating biochar with organic matter further boosts soil health and productivity by providing stability, nutrient retention, and energy sources for microbes (Agegnehu et al., 2017; Lehmann & Joseph, 2015).

Environmental Services & Climate Action

1. Carbon Sequestration Mechanisms and Quantification

Biochar is considered a leading technology for removing carbon dioxide, especially in agriculture. It provides long-term storage of carbon and delivers instant advantages to farming practices (Lehmann, 2007; Woolf et al., 2010; Smith, 2016) (Table 5). Its effectiveness as a carbon sink depends on the stability of its aromatic carbon structure, which forms during pyrolysis through complex thermal reactions that create condensed polyaromatic compounds resistant to microbial decomposition (Lehmann & Joseph, 2015; Joseph et al., 2021).

Table 5. Climate mitigation services of agricultural waste biochar

Mitigation component	Typical quantitative effect	Main mechanisms	Time scale	Key references
Carbon sequestration	3.7 t CO_2-eq per t stable C; 80–90% C remaining after 100 years	Aromatic, condensed structure; low decomposability	100–500+ years	Lehmann (2007); Woolf et al. (2010); Smith (2016)
N_2O emissions	Decreasing 30–50% in many agricultural soils	Improved aeration, N retention, microbial pathway shifts	Seasons–years	Cayuela et al. (2014); Joseph et al. (2021)
CH_4 emissions	Decreasing 15–30% in many paddy and upland systems	Enhanced methanotrophy, altered redox, substrate availability	Seasons–years	Jeffery et al. (2017); Joseph et al. (2021)
Life-cycle net emissions	Often net-negative with energy recovery	C storage + avoided burning + energy substitution	Full system life	Woolf et al. (2010); Paustian et al. (2016)

Biochar's stability is due to its fused aromatic structure, with low H:C and O:C ratios (<0.6 and <0.4) indicating high persistence in soils—often lasting centuries (Lehmann & Joseph, 2015; Smith, 2016). Both lab tests and field monitoring quantify biochar's carbon sequestration benefits, with radiocarbon dating confirming millennia-scale durability of pyrogenic carbon (Glaser et al., 2001). Most biochar carbon persists for over a century, far outlasting uncharred organic matter (Woolf et al., 2010). One ton of stable biochar removes about 3.7 tons of CO_2 equivalent from the atmosphere. Large-scale, sustainable biochar production offers significant climate mitigation potential without competing with food or causing deforestation (Woolf et al., 2010; Paustian et al., 2016).

In Indonesia, abundant rice husks, palm kernel shells, and coconut residues often openly burned as its offer ideal feedstocks for biochar production, potentially sequestering substantial carbon while supporting FOLU Net Sink 2030 goals and reducing deforestation pressures from unsustainable biomass demand. Local trials and carbon market integration could scale these benefits across rice paddies and oil palm plantations.

2. Greenhouse Gas Emission Reductions

Biochar not only stores carbon but also reduces other greenhouse gas emissions by altering soil biogeochemistry (Cayuela et al., 2014; Lehmann & Joseph, 2015), offering substantial climate benefits (Smith, 2016; Joseph et al., 2021). Research shows N_2O emissions decrease by 30–50% in agricultural soils due to improved aeration, nitrogen retention, and microbial shifts (Cayuela et al., 2014; Woolf et al., 2010; Lehmann et al., 2011). Most studies report net reductions of methane emissions in upland and rice soils, largely through enhanced soil oxidation and methanotrophic activity (Jeffery et al., 2017; Joseph et al., 2021; Cayuela et al., 2014; Woolf et al., 2010). For CO_2, life-cycle assessments show that while biochar can raise soil CO_2 efflux briefly, long-term carbon storage and avoided emissions from biomass burning provide significant net benefits (Woolf et al., 2010; Paustian et al., 2016; Lehmann, 2007; Smith, 2016; FAO, 2021; IPCC, 2019).

Rice paddies generate high CH_4 (flooded anaerobic conditions) and N_2O (urea fertilization), while oil palm plantations Indonesia's largest N_2O source emit substantial N_2O from intensive fertilization on well-drained soils. Biochar reduces CH_4 12-25% in rice (methanotroph stimulation; Jeffery 2017) and N_2O 30-50% across both systems (aeration + N-retention; Cayuela 2014). Rice husk/straw converting into biochar perfectly substitutes open burning while supporting FOLU Net Sink 2030. Redirecting residues like rice straw and palm fronds from open burning responsible for significant CO_2 releases into biochar production could yield compounded GHG reductions, improving air quality and aligning with FOLU emission targets. Local field trials demonstrate feasibility, with potential for integration into sustainable intensification practices.

3. Life-Cycle Assessment and System-Level Benefits

Comprehensive life-cycle analysis is essential for evaluating biochar systems, as it considers all inputs and outcomes from feedstock collection to end-of-life (Woolf et al., 2010; Paustian et al., 2016). When energy recovery and emission controls are included, well-designed biochar systems typically achieve net negative carbon emissions (Smith, 2016; Joseph et al., 2021). Emissions from production largely depend on effective energy integration and process controls; modern pyrolysis using syngas can minimize fossil fuel use (Manyà, 2012; Lehmann & Joseph, 2015). Replacing open field burning of biomass with biochar production significantly reduces greenhouse gas emissions while producing useful energy (FAO, 2021; IPCC, 2019; Woolf et al., 2010). In Indonesia, locally adapted LCAs show that decentralized pyrolysis of agricultural residues could provide major GHG savings, reduce haze pollution, and support circular economy initiatives in key agricultural regions.

Economic Considerations and Market Development

1. Production Economics and Cost Structures

Capital investment for biochar production facilities ranges from $50,000 for small-scale batch systems (0.5 tons/day) to over $5 million for large continuous operations (20+ tons/day), with pyrolysis reactors comprising 40-60% of total capital costs. Community-scale facilities processing 1-10 tons/day typically offer optimal balance between capital efficiency and local feedstock utilization. Operating costs range from $100-400 per ton, including feedstock ($0-50/ton), energy, labor, and maintenance. Syngas heat recovery achieves energy self-sufficiency.

Carbon credit revenue (Puro.earth/EBC methodology) assumes 60% C-content biochar with 80% stability (H:C<0.6, >100yr): 2.0-3.7 tCO_2e sequestered per ton biochar. Conservative scenario: $100/ton ($50/tCO_2e × 2.0t); best-case: $740/ton ($200/tCO_2e × 3.7t) (Woolf et al., 2010).

Co-products (bio-oil/syngas) add $50-150/ton (Many, 2012). In Indonesia, rice husk conversion supports FOLU Net Sink 2030 while achieving positive net economics. Using agricultural residues like rice husks and coconut shells as feedstock makes biochar production cost-effective. Establishing small to medium community reactors near farms cuts transport costs and creates jobs. Investment in modular pyrolysis systems with heat recovery can improve energy efficiency. Collaboration among cooperatives, universities, and industry helps reduce capital costs (below IDR 500 million per unit) and maintain quality standards.

2. Market Mechanisms and Policy Support

Biochar market growth is fueled by voluntary carbon markets, government support, and environmental policies. Carbon credits are increasingly valuable, with trading platforms like Verra and Puro.earth pushing prices higher and making carbon revenue central to projects. Biochar also benefits from subsidies and conservation programs in countries like the U.S., Canada, Australia, and EU, which often cover 30–75% of farmer costs. Regulations restricting residue burning further increase feedstock availability and improve biochar's economic outlook.

Indonesia could integrate biochar into its carbon market framework under the Perpres 98/2021 on Carbon Pricing and the FOLU Net Sink 2030 target. Biochar projects could be included in voluntary carbon credit trading platforms such as SIS-REDD+ or international schemes (e.g., Verra, Puro.earth), enabling farmers and local enterprises to monetize carbon sequestration. SIS-REDD+ is Indonesia's national registry (SRN-PPI integration). Trading platforms: IDXCarbon (domestic exchange), international VCM (Verra/Puro.earth).

The Ministry of Agriculture could classify biochar use as an eligible practice in agricultural subsidy programs, similar to soil health and organic compost initiatives. Local regulations on open burning of crop residues (e.g., in Riau or Kalimantan) could further push adoption by encouraging waste-to-biochar conversion.

3. Investment and Financing Considerations

Biochar project financing relies on diverse revenue streams, long-term cash flows, and risk assessment. Its multi-benefit nature allows for innovative funding structures that leverage both environmental and agricultural value. Project finance now often includes carbon credit revenues through forward sales or monetization facilities, offering upfront capital for future credits. Farmers benefit by selling premium crops, reducing input costs, or receiving productivity-based payments.

Risk management considerations include feedstock supply security, technology performance guarantees, carbon credit price volatility, and regulatory changes affecting market conditions (Table 6). Diversified revenue streams and conservative carbon credit pricing help mitigate these risks while maintaining project viability.

Table 6. Risk Management Matrix

Risk Category	Mitigation
Feedstock supply	Long-term contracts
Technology	Pilot testing
Carbon price	Conservative pricing
Regulatory	Policy diversification

Investment momentum grows from impact investors, climate funds, and project finance (Smith, 2016; Joseph et al., 2021). Indonesia initiatives attract Danantara, BRI/BNI green loans, carbon pre-sales, and commodity ESG premiums (palm oil/cocoa).

CONCLUSION

This review synthesizes evidence that agricultural residue biochar supports soil restoration with climate mitigation and targeting productivity gains. Benefits include improved soil structure/nutrients/microbes, 10-15% average yield increases (95% CI 5-25%), and 2.0-3.7 tCO_2e/t sequestration.

Limitations & trade-offs:

- Context-dependent: Sandy/acidic > clay/fertile soils
- Economic: Needs <IDR 2M/t for smallholders
- Feedstock competition: Food security priority
- Lifecycle: Production emissions offset by stability

Indonesia pathway: FOLU Net Sink 2030 + SRN-PPI registry + IDXCarbon trading accelerates adoption while ensuring environmental integrity.

ACKNOWLEDGMENT

The author expresses gratitude to my supervisor and Hee-Deung Environmental Membrane Microbiology (HEMM) Laboratory, School of Civil, Environmental and Architectural Engineering, Korea University and Korean Council for University Education (KCUE) Higher Education for ASEAN Talents (HEAT) Scholarship, for their support. The author also thanks the Islamic University of Nusantara (UNINUS) for its academic support and conducive research environment. Appreciation is given to researchers in the field of biochar and soil management whose work formed the main basis for the preparation of this review.

FUNDING

This research received no external support. No financial assistance, research funding, or APC allocation were provided by any party during the preparation and publication of this work.

CONFLICT OF INTEREST

The author declares no conflict of interest with any party. The funder has no role in the research design; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to announce the research results.

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