Biochar-Mediated Greenhouse Gas Mitigation: A Pathway towards Climate-Resilient Agriculture

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ABSTRACT

Agriculture, forestry and other land use contribute roughly one-fifth to one-quarter of global anthropogenic greenhouse gas (GHG) emissions and agriculture alone is the dominant source of anthropogenic nitrous oxide and methane. Biochar, the carbon-rich solid produced by pyrolyzing biomass under oxygen-limited conditions, has emerged as a dual-purpose intervention: a negative-emission technology that sequesters carbon in soil on centennial timescales and a soil amendment that can raise productivity and buffer crops against drought. This review synthesizes current evidence on biochar-mediated GHG mitigation, covering production chemistry, mechanisms of carbon sequestration and effects on nitrous oxide and methane fluxes and links these to co-benefits for soil fertility, water retention and climate resilience. Meta-analytic evidence indicates average reductions of roughly 30 to 40% in soil nitrous oxide emissions, with variable and context-dependent effects on methane, alongside soil organic carbon accrual on the order of 13 Mg C ha^{-1} in field settings. Life cycle assessments place the net mitigation potential of residue-based biochar systems between 0.04 and 1.67 t CO_2-equivalent per ton of feedstock and global technical potential in the range of 0.5 to 2 Gt CO_2 per year. Outcomes hinge on feedstock, pyrolysis temperature, application rate, soil type and system boundaries; realizing the climate-resilience promise therefore requires site-specific design, long-term field validation and credible carbon accounting.

INTRODUCTION:

Anthropogenic climate change and food security are tightly coupled challenges. The land sector both suffers and contributes to climate disruption: Agriculture, Forestry and Other Land Use (AFOLU) accounted for about 23% of total net anthropogenic GHG emissions during 2007 to 2016, contributing around 13% of anthropogenic CO_2, 44% of CH_4, and 81% of N_2O (IPCC SRCCL). The IPCC Sixth Assessment Report places AFOLU at 13 to 21% of global anthropogenic emissions over 2010 to 2019, with agricultural methane and nitrous oxide averaging 157 ± 47 Mt CH_4 yr^{-1} and 6.6 ± 4.0 Mt N_2O yr^{-1}, equivalent to 4.2 ± 1.3 and 1.8 ± 1.1 Gt CO_2eq yr^{-1} under AR6 GWP100 metrics. Once pre- and post-production activities are included, agri-food systems generate up to one-third of all anthropogenic emissions, with farm-gate agriculture alone responsible for roughly half of global methane and three-quarters of nitrous oxide from human activity. The potency of these gases compounds their volume: on a 100-year basis, biogenic methane carries a global warming potential of 27.0 and nitrous oxide of 273 relative to CO_2.

Biochar entered this debate through two converging lines of evidence. Archaeological soils of the Amazon basin, the so-called dark earths containing biomass-derived black carbon aged between 600 and 8,700 years, exhibit elevated cation exchange capacity and fertility relative to adjacent soils, suggesting that fire-derived carbon can persist and improve soil function over millennia.

Climate-smart agriculture explicitly targets three outcomes: sustainably increasing productivity, building adaptive capacity and resilience and reducing or removing GHG emissions. Biochar is unusual among interventions in contributing to all three pillars simultaneously, which is why it has been framed as a pathway towards climate-resilient agriculture. This article examines how biochar is produced and why its properties vary; the mechanisms by which it sequesters carbon and alters N_2O and CH_4 fluxes, with quantitative meta-analytic evidence; its effects on soil fertility, yield and water relations under climatic stress; the factors that govern efficacy and the principal knowledge gaps that must be closed before biochar can be deployed responsibly at scale.

Why biochar matters for climate mitigation?

Biochar mitigate climate change through two complementary pathways. First, it helps to sequester carbon: the aromatic, recalcitrant carbon in biochar persists in soil for centuries to millennia, locking away carbon that would otherwise return to the atmosphere as CO_2 during biomass decomposition or combustion. Second, they reduce on-farm GHG emissions: meta-analysis of field experiments had shown that biochar significantly lowers soil N_2O emissions (by ~23%) and CH_4 emissions (by ~15%), while increasing soil organic carbon (SOC) stocks (~27%) and crop yields (~16%).

Global assessments estimate that biochar could deliver 3.4-6.3 Pg CO_2 e yr^{-1} of mitigation, roughly half of which is durable CO_2 removal, without compromising food security or habitat conservation. In practical terms, one ton of biochar can permanently remove ~2.68 Mg CO_2 emissions from the atmosphere, while also curbing CO_2 via syngas/bio-oil co-products that displace fossil fuels.

Biochar production and physicochemical properties

Biochar is produced by thermochemical conversion of biomass in an oxygen-limited environment, most commonly slow pyrolysis at temperatures of roughly 350 to 650 °C,

which partitions biomass carbon among solid biochar, condensable bio-oil and non-condensable syngas10. Production conditions determine the fraction of feedstock carbon retained in the solid phase, its chemical recalcitrance and the energy available in co-products, a balance with direct consequences for both carbon sequestration and system economics.

Pyrolysis temperature is the master variable for most properties. Higher temperatures increase fixed carbon, total carbon, pH, ash content, specific surface area and porosity, while decreasing biochar yield, volatile matter and cation exchange capacity. Elevated temperatures also enhance aromaticity and reduce O: C and H: C ratios, indicators of greater biological and chemical stability. Stability determination matters because unstable biochar would return carbon to the atmosphere rapidly, potentially aggravating rather than alleviating climate change. A widely used operational threshold holds that biochar with a molar O: C ratio below 0.2 has a half-life of at least 1,000 years. In a comprehensive analysis of roughly 5,400 articles and more than 50,000 data points, feedstock selection emerged as the single largest influence on final biochar properties, with pyrolysis temperatures above 500 °C generally conferring half-lives exceeding 1,000 years. Wood-based biochars tend to have the highest specific surface areas; crop and grass biochars tend to have higher cation exchange capacities and manure-based biochars are richer in nutrients but less effective as carbon sinks. Feedstock chemistry also introduces silicon in rice residues and varying ash loads that drive the liming effect so often observed in acidic soils.

The carbon content of commercial-grade biochars ranges from as low as 7% for gasified biosolids to 79% for wood pyrolyzed above 600 °C of this initial carbon, 63 to 82% is expected to remain unmineralized after 100 years at the global mean annual cropland temperature of 14.9 °C. These ranges illustrate why 'biochar' is not a single material but a family of products whose agronomic and climatic performance must be specified rather than assumed. Table 1 summarizes the principal production-property relationships.

Table 2. Pyrolysis conditions and resulting biochar properties

Property	Effect of increasing pyrolysis temperature	Effect of feedstock choice
Carbon content and aromaticity	Increases; O:C and H:C ratios decrease	Wood > crop residue > manure; manure biochars lowest C content
Stability and half-life	Increases; >500 °C generally yields >1,000-yr half-lives15; O:C < 0.2 indicates ≥1,000-yr half-life14	Lower stability for manure-derived biochars
Specific surface area and porosity	Increases strongly	Highest for wood-based biochars
pH and ash content	Increase (liming potential rises)	High-ash feedstocks (manure, crop residues) yield higher pH
Cation exchange capacity	Decreases with temperature	Crop and grass biochars > wood biochars
Biochar yield and volatile matter	Decrease; more carbon partitioned to gas and oil	Rice-residue feedstocks retain high yield and silica content

Mechanisms of greenhouse gas mitigation

1. Carbon sequestration and SOC stabilization

Biochar's climate value relies on its stability. Pyrolysis at 500-700 °C produces highly condensed aromatic structures with low H or organic C ratios, yielding mean residence times of centuries to >1,000 years for the recalcitrant carbon pool. Meta-analytic evidence indicates ~97% of biochar carbon is recalcitrant, with only a small labile fraction mineralized rapidly.

Beyond direct storage, biochar stabilizes native SOC through:

- Physical protection via enhanced aggregation and organic-mineral complex formation.
- Chemical interactions where oxidized biochar surfaces sorbed labile organic compounds, reducing their decomposition.
- Microbial effects that can suppress priming (i.e., biochar slightly retards SOM mineralization on average, -3.8%), though responses vary by soil texture and biochar type.

Long-term field data (e.g., 2-year pure biochar additions) confirm increased aggregate stability and SOC accrual, especially when pyrolysis conditions and feedstock are optimized.

2. Nitrous oxide (N_2O) suppression

N_2O has 273 times more global warming potential to that of CO_2 over 100 years, making its mitigation critical. Biochar reduces N_2O emissions through multiple, often interacting mechanisms:

- Improved soil aeration and moisture regulation, which limit anaerobic micro-sites where denitrification produces N_2O.
- pH buffering (liming effect), which can shift denitrification end-products from N_2O toward N_2 and reduce the N_2O:(N_2O + N_2) ratio.
- Altered nitrogen dynamics: enhanced N retention, reduced inorganic N leaching (-23.2%), and lower NH_3 volatilization (-24.9%) decrease substrate availability for nitrification/denitrification.
- Microbial community shifts: reductions in denitrifier abundance and changes in functional gene expression further suppress N_2O production.

Kaur *et al*. (2023) in a field syntheses reported average N_2O reductions of ~23%, with stronger effects in acidic soils and when high-temperature, lignin-rich biochars are used.

3. Methane (CH_4) dynamics

Biochar's effect on CH_4 is context-dependent. In well-drained uplands, biochar typically reduces CH_4 emissions or has neutral effects by improving aeration and stimulating methanotrophs. In flooded rice paddies, however, biochar can initially increase CH_4 by supplying labile dissolved organic carbon that fuels methanogens.

Net outcomes depend on:

- Biochar properties: high-temperature biochar with larger pore surfaces can facilitate electron transfer to iron-reducing bacteria, which compete with methanogens and dampen CH_4 spikes.
- Management: pairing biochar with improved water management (e.g., alternate wetting and drying) and N optimization can flip the balance toward net CH_4 reduction.

Overall, global field syntheses find a net CH_4 reduction of ~15% across diverse systems, contributing to lower GHG intensity per unit yield.

Biochar, soil fertility and crop productivity

Biochar's agronomic effects operate through measurable changes in soil properties. A meta-analysis of 59 studies found that biochar application increased soil pH by 46%, cation exchange capacity by 20%, and organic carbon by 27%, while reducing bulk density by 29% and increasing porosity by 59%, with the greatest physical effects in coarse and fine-textured soils and from biochars produced

above 500°C. The cation exchange capacity result echoes the Amazonian dark earths, where black carbon sustains high surface charge and nutrient retention. Plant-available phosphorus increases by a factor of 4.6 on average, though the effect is significant only for application rates above 10 Mg ha^{-1} and pyrolysis temperatures below 600°C, and it is strongest in acidic and neutral soils. Biochar also reduces plant tissue concentrations of heavy metals by 17 to 39%, a co-benefit for food safety on contaminated land.

Syntheses of field studies report mean crop yield increases in the range of 10 to 42%, with the largest gains in low-nutrient, phosphorus-sorbing acidic soils typical of the tropics and in sandy soils of drylands. In the 10-year Kenyan trials, biochar increased maize yield by about 1.2 Mg ha^{-1} and soybean by 0.4 Mg ha^{-1} per season, additively with mineral fertilizer and undiminished across a decade. A global meta-analysis reported an average yield increase of 21% alongside the GHG reductions described above. Even in fertile calcareous soils, biochar caused no yield loss over four growing seasons and improved water-holding capacity. Field-trial reviews consistently find greater benefits on degraded tropical soils than in temperate regions.

Biochar and climate resilience: water, drought and extremes

Climate-resilient agriculture must perform under water stress, and the hydrological effects of biochar are among its most policy-relevant co-benefits. A meta-analysis of hydrological literature established that biochar generally improves soil hydrological properties through increased porosity, field capacity and plant-available water. Mechanistically, biochar increases water-holding capacity via its internal porosity, high specific surface area and promotion of aggregation, while effects on infiltration are inconsistent; water repellency can occur depending on feedstock and pyrolysis temperature. The benefits are largest in coarse-textured soils, where biochar raised readily available water by 165 to 191% at 10% by volume for woodchip and waterweed biochars, with 5% by volume emerging as the broadly optimal rate. Wheat-straw biochar pyrolyzed at 550°C increased available water content by 166% and reduced bulk density by 13% relative to control and 5 t ha^{-1} biochar improved available water content by 76% in another trial. In sand-enriched soils, date-palm biochar raised available water capacity by up to 80% compared with unamended soil, outperforming compost.

Crucially for a changing climate, several lines of evidence indicate that biochar's hydrological value grows under stress. In a coarse-textured California soil subjected to drying, biochar maintained higher soil moisture and sustained microbial respiration relative to unamended controls. It has been reported that aged biochar improved soil water regime and microbial carbon-use efficiency under drought more than fresh biochar. Field trials conducted across drought and wet years in South Korea demonstrated that corn-waste biochar enhanced soil water retention during drought conditions and sustained maize productivity under contrasting hydrological conditions. Under deficit irrigation in Pakistan, activated biochar at 5 t ha^{-1} improved membrane stability, antioxidant activity and yield-related traits, increasing grain and stover yield by 26% and apparent water productivity by 33%. Biochar's ability to increase surface area, microporosity and nutrient retention translates into better crop water use efficiency and drought tolerance. These properties align biochar with the resilience pillar of climate-smart agriculture, for which adoption reviews show improved farm productivity, income stability and reduced production risk under variable climate.

Co-benefits for climate-resilient agriculture

Biochar's value extends beyond GHG metrics. By improving soil physical and chemical properties, it strengthens agronomic resilience to climate stressors:

- Soil structure and water: reduced bulk density, enhanced porosity, and better moisture retention improve drought tolerance and infiltration.
- Nutrient retention: higher cation exchange capacity and sorption capacity reduce leaching of N, P, and base cations, supporting more efficient fertilizer use.
- Yield and nutrition: The yield gains of ~15-19% and improvements in crop nutritional quality, with larger benefits in low-fertility, sandy, or degraded soils.
- Contaminant immobilization: biochar can adsorb heavy metals and organic pollutants, reducing phytotoxicity and food-chain transfer.

These co-benefits align biochar with climate-smart agriculture goals: sustainably increasing productivity, enhancing resilience and reducing emissions.

Net climate benefit: life cycle assessment and mitigation potential

The climate case for biochar rests on the full system, not just the field. A quantitative review of life cycle studies found total climate-change impacts ranging from a net emission of 0.04 to a net reduction of 1.67 t CO_2 e per ton of feedstock, driven by assumptions about feedstock, stability, soil emissions and substitution effects. A comparative review of negative emission technologies estimated biochar's net removal at 1,173 kg CO_2 e per ton of CO_2 removed, the lowest global warming potential per ton removed among the technologies assessed, though with a wide range across studies (from a net positive impact of 1,710 to a net negative of 3,300 kg CO_2eq t^{-1}) and with trade-offs in particulate matter, acidification and eutrophication where energy or dedicated feedstocks are involved.

A spatially explicit national analysis for China estimated negative emission potential up to 0.92 Gt CO_2 per year at an average net cost of US$90 per ton CO_2, sufficient to satisfy the negative-emission demand of most scenarios compatible with carbon neutrality by 2060. Pyrolytic carbon capture and storage extends the concept by retaining carbon in bio-oil and permanent pyrogas oxidation products, aspiring to sequestration efficiencies above 70%, a threshold identified as critical for relevance as a negative emission technology. Standardized greenhouse-gas inventory methodologies now exist for biochar additions to mineral soils, applicable from farm to national scales and to voluntary carbon markets. The central caveats remain those flagged since the earliest syntheses: system boundaries, feedstock opportunity costs, biochar stability in situ and the absence of whole-system field budgets.

Quantified mitigation potential and trade-offs

Life-cycle and systems analyses converge on substantial but conditional mitigation:

- Global technical potential: 3.4-6.3 Pg CO_2e yr^{-1}, ~50% as durable CO_2 removal, without endangering food security or habitats.
- Soil carbon accrual: biochar can sequester ~0.7-1.8 Gt CO_2(C eq.) yr^{-1} globally; region-specific estimates (e.g., China) suggest +1.9 Pg C in SOC with concurrent N_2O and CH_4 reductions of 20-25 Mt CO_2e yr^{-1} each and +19% yields.

- Emission intensity: field experiments show reduced global warming potential and GHG intensity per unit yield, even when CO_2 fluxes are unchanged, due to lower N_2O/CH_4 and higher yields.

Trade-offs hinge on energy displacement assumptions: relative to bioenergy, biochar systems can increase emissions by ~3% if replacing coal but decrease by ~95% if replacing renewable energy, highlighting the importance of system boundaries and local energy mixes.

Implementation pathways for research and practice

For climate-resilient agriculture programs, biochar is best deployed as part of an integrated package:

- Targeted placement: prioritize low-fertility, acidic, or sandy fields where co-benefits and GHG reductions are largest.
- Quality control: specify H/Corg, ash, pH, and surface area thresholds aligned with intended function (stability vs. nutrient supply).
- Monitoring: track SOC stocks, N_2O/CH_4 fluxes and yield over multiple seasons to capture time-dependent effects and avoid overreliance on short-term lab data.
- Policy and markets: leverage carbon removal credits for the durable C pool while accounting for non-CO_2 reductions and yield gains in farm-level GHG inventories.

Challenges, knowledge gaps and future directions

Five gaps currently limit confident scaling of biochar for climate-resilient agriculture. First, long-term field data remain scarce. Most evidence derives from laboratory incubations and short trials and field results do not always reproduce them; multi-decade trials are needed to constrain biochar carbon persistence, re-application intervals and legacy effects on nitrogen cycling, which may include increasing nitrogen losses in the long term. Second, meta-analytic disagreement itself needs resolution: 18 meta-analyses of N_2O span a fivefold range of effect sizes, reflecting differences in weighting, publication pools and moderator treatment. Third, life cycle assessments diverge widely and methodological conventions for feedstock accounting, stability, co-product credits and land-use effects must be harmonized. Fourth, environmental risks are incompletely characterized, including contaminant content of feedstocks (heavy metals, polycyclic aromatic hydrocarbons), freshwater transport of fine particles, and effects of black carbon aerosol emissions; the mitigation co-benefit of reduced plant heavy-metal uptake partly offsets feedstock quality concerns. Fifth, adoption is an economic and institutional problem as much as a technical one: feedstock logistics dominate system costs, carbon pricing determines profitability and extension services, subsidies and trust in co-product quality govern farmer uptake. Standardized protocols for biochar characterization, stability testing and GHG accounting, together with agronomic-economic assessment at local scales are prerequisites for mainstream deployment. Addressing these will refine deployment rules and ensure biochar delivers on its promise as a scalable, climate-resilient agriculture tool.

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