



Biochar application in agronomy: A review on soil health and crop productivity

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Abstract

Biochar, the carbon-rich solid produced by pyrolyzing biomass under limited-oxygen conditions, has become one of the most extensively studied soil amendments in modern agronomy, valued simultaneously for its potential to raise crop productivity, improve soil health, and durably sequester carbon. This review synthesizes peer-reviewed meta-analyses and global field-trial syntheses (2011-2026) covering biochar's effects on soil physical properties (water retention, bulk density), chemical properties (pH, cation exchange capacity, nutrient availability), biological properties (microbial biomass, enzyme activity, nitrogen cycling), crop yield, drought resilience, and heavy-metal remediation. Across major global meta-analyses, biochar alone raises crop yield by roughly 9-25% on average, with substantially larger effects in acidic, weathered, tropical soils than in fertile temperate soils, and the largest, most consistent gains occurring when biochar is co-applied with inorganic or organic fertilizer rather than used alone. Biochar reliably improves available water capacity in coarse-textured soils (up to +45-51%), raises cation exchange capacity and microbial biomass carbon, and can reduce cadmium bioavailability in contaminated acidic soils by 41-70%. These benefits are not unconditional: excessive application rates, freshly produced (unaged) biochar, and use on already-fertile fine-textured soils can each produce neutral or negative yield effects, chiefly through temporary nitrogen immobilization or nutrient imbalance. We conclude that biochar functions best as a soil-specific, rate-calibrated amendment integrated with existing fertilization programs rather than a universal input, with the strongest agronomic and economic case in degraded, acidic, or sandy soils in tropical and subtropical smallholder systems.

Keywords: Biochar, soil amendment, modern agronomy, soil health

Introduction

What Is Biochar

Biochar is produced through pyrolysis — the thermal decomposition of biomass (crop residues, wood, manure, or other organic feedstocks) at temperatures typically between 300°C and 700°C under low- or no-oxygen conditions. This process converts a substantial fraction of the feedstock's carbon into a chemically and biologically stable, highly porous solid with a large internal surface area, distinguishing it from raw organic matter or compost, which decompose far more rapidly once returned to soil. The specific properties of any given biochar — pH, cation exchange capacity, surface area, nutrient content, and carbon stability — depend heavily on both feedstock type and pyrolysis conditions, meaning “biochar” functions less as a single product than as a broad category of materials with agronomically significant variation.

Rationale for Agronomic Use

Interest in biochar as a soil amendment rests on three overlapping rationales: improving soil physical and chemical properties to support crop growth, enhancing nutrient- and water-use efficiency to reduce input costs, and sequestering atmospheric carbon in a highly stable form as a climate-mitigation co-benefit. Because biochar carbon persists in soil over decades to centuries — far longer than uncharred organic matter — it has been proposed as a “negative emissions” technology with global technical mitigation potential estimated at 1.8 to over 6 Pg CO₂-equivalent per year. This review focuses specifically on the

soil-health and crop-productivity dimension of that broader case, synthesizing the substantial and sometimes contradictory meta-analytic literature on how, when, and where biochar delivers agronomic benefit.

Scope of This Review

We draw on global meta-analyses and large-scale field-trial syntheses published between 2011 and 2026, organized around biochar's effects on soil physical, chemical, and biological properties; crop yield and stress tolerance; contaminant remediation; and the practical factors — application rate, feedstock, pyrolysis temperature, soil type, and time since application — that most strongly determine whether a given biochar treatment succeeds or fails in a given context.

Effects on Soil Physical Properties

Biochar's high porosity and large internal surface area give it a well-documented capacity to alter soil water dynamics. A systematic review and meta-analysis of literature from 2010-2019 found that, averaged across all soil textures, biochar decreased soil bulk density by 9%. The water-retention benefit is strongly texture-dependent: field capacity and wilting point both increased substantially in coarse-textured (sandy) soils — by 51% and 47% respectively — and more moderately in medium-textured soils (13% and 9%), while fine-textured (clay) soils showed negligible change in field capacity and a slight decrease in wilting point. Because the increase in field capacity

outpaced the increase in wilting point in coarse and medium soils, plant-available water content rose substantially: by 45% in coarse-textured soils, 21% in medium-textured soils, and 14% in fine-textured soils. These findings indicate that biochar's water-retention benefit is concentrated in exactly the soil types — sandy, low-organic-matter soils with historically poor water-holding capacity — where farmers most need it, while offering comparatively little physical benefit on already water-retentive clay soils.

Effects on Soil Chemical Properties

Biochar consistently raises soil pH and cation exchange capacity (CEC), particularly in acidic soils, functioning in part as a liming agent. A field trial across sandy and clay loam temperate soils found CEC, pH, and electrical conductivity increased by an average of 10%, 4%, and 1% respectively under biochar plus fertilizer treatment relative to fertilizer alone, with the largest CEC gains (up to 16%) observed on coarse-textured soils — mirroring the texture-dependence seen in water retention. This CEC increase translates directly into improved retention of exchangeable cations including potassium, calcium, and magnesium, reducing nutrient leaching losses and improving fertilizer-use efficiency. Biochar's influence on soil chemistry is not always neutral or beneficial, however: at very high application rates, biochar-induced pH increases can overshoot the optimal range for some crops, and biochar's high adsorptive capacity has been documented to reduce the effectiveness of some agrochemicals, including certain herbicides and insecticides, potentially necessitating adjusted application rates for co-applied pest and weed control products.

Effects on Soil Biological Properties

Biochar amendment consistently increases soil microbial biomass and alters enzyme activity, primarily by providing habitat (through its porous structure), moderating soil pH and moisture, and supplying a slow-release carbon and nutrient source. A global meta-analysis of 72 papers and 964 data points found biochar increased soil microbial biomass carbon by 21.7% on average, along with increases in urease (23.1%), alkaline phosphatase (25.4%), and dehydrogenase (19.8%) enzyme activities, with no significant negative effects detected across the enzymes studied; benefits were strongest in soils with low initial pH, low total carbon, low total nitrogen, and fine texture. A separate meta-analysis focused specifically on nitrogen-cycling enzymes found biochar increased nitrogen-acquiring enzyme activity by 26.6% in acidic soils and 27.3% in alkaline soils. These biological effects are mechanistically linked to biochar's chemical effects (Section 3): by raising pH and CEC and supplying labile carbon fractions, biochar creates more favorable conditions for microbial colonization and enzymatic activity, which in turn drives many of the nutrient-cycling and yield benefits documented elsewhere in this review.

Nitrogen Cycling and Nutrient Dynamics

Biochar's effect on nitrogen cycling is among the most agronomically consequential and mechanistically complex outcomes reviewed here. A field-study meta-analysis found biochar accelerated multiple microbially mediated nitrogen-cycling processes — increasing mineralization by 5.3%, nitrification by 3.7%, denitrification by 15.3%, and biological nitrogen fixation by 48.5% — while simultaneously increasing plant nitrogen uptake by 18.3% and reducing both nitrous oxide emissions (-14.9%) and nitrogen leaching (-10.9%). This combination — enhanced nitrogen availability and uptake alongside reduced losses to both air and water — represents one of biochar's most consistently documented agronomic and environmental co-benefits. However, the same meta-analysis cautioned that long-term biochar application tended to increase the abundance of ammonia-oxidizing and denitrifying microbial gene markers, suggesting that N₂O emission and leaching reductions documented in shorter-term studies may not persist indefinitely under repeated annual application — an important caveat for long-term farm nutrient management planning. At high application rates, biochar's high carbon-to-nitrogen ratio has also been documented to drive short-term nitrogen immobilization, temporarily reducing nitrogen availability to crops until microbial populations equilibrate, which explains part of the yield depression sometimes observed with freshly applied, high-rate biochar treatments (see Section 9).

Crop Yield and Productivity Responses

Crop yield is the most extensively meta-analyzed biochar outcome, and also the outcome with the widest reported range of effect sizes, reflecting genuine heterogeneity in soil, climate, and management conditions rather than simply methodological inconsistency. Early global meta-analyses found average yield increases of 10-13% from biochar alone. A landmark 2017 meta-analysis of 1,125 comparisons from 109 studies found this average concealed a stark climate-zone split: biochar had, on average, no significant effect on crop yield in temperate latitudes, but produced a 25% average yield increase in the tropics, attributed to the generally more weathered, nutrient-poor, and acidic soils characteristic of tropical agriculture. Combining biochar with fertilizer consistently outperforms either treatment alone: one meta-analysis found biochar plus inorganic fertilizer increased yield by 15% over fertilizer alone and 48% over an unfertilized control, while a separate synthesis found biochar's individual effect (25.3%) grew by a further 10 percentage points when combined with fertilizer, with the largest gains concentrated in very acidic soils (pH ≤ 5) and biochars produced at 401-500°C with a carbon-to-nitrogen ratio of 31-100. In rice systems specifically, a 134-study meta-analysis of 1,827 observations found biochar increased yield by 16.0% alongside a 37.7% increase in soil organic carbon. Figure 1 summarizes yield-response effect sizes across these major independent meta-analyses.

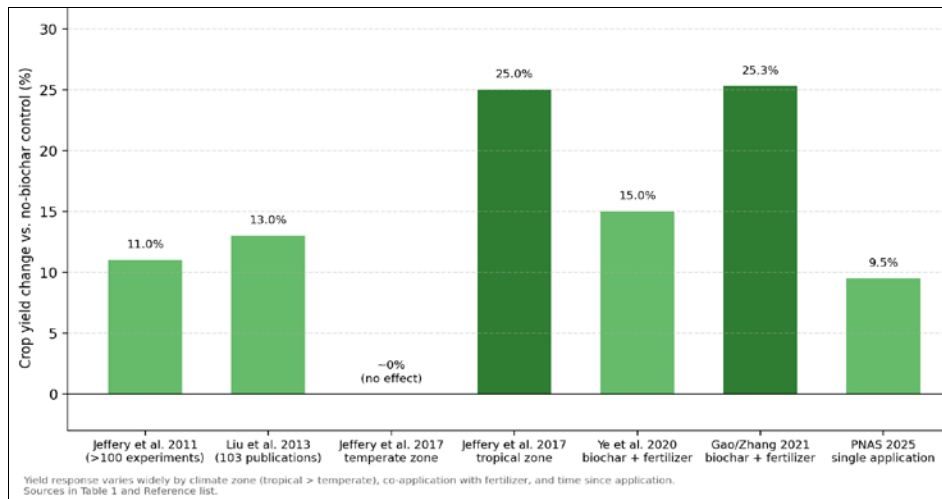


Fig 1: Crop yield response to biochar application across major global meta-analyses

Drought Stress and Water-Limited Systems

Because biochar improves both soil water retention (Section 2) and root-zone conditions, it has drawn particular research interest as a drought-mitigation tool. A meta-analysis specifically examining plant physiological responses to biochar under drought stress found statistically significant positive effects across water-use efficiency, yield, biomass, chlorophyll content, stomatal conductance, photosynthetic rate, and transpiration rate, with yield showing the smallest average increase (12.5%) and transpiration rate the largest (35.0%) among the traits measured; the magnitude of benefit varied by plant type, severity of water stress, soil type, and duration of biochar application. Field trials on drought-stressed maize have documented substantial gains in root and shoot biomass (34-42% increases) alongside improved leaf area and net assimilation rate under activated biochar treatment relative to unamended, water-stressed controls. These findings position biochar as a potentially valuable tool for building climate resilience in rainfed and water-constrained cropping systems, complementing (rather than substituting for) irrigation-management strategies such as alternate wetting and drying discussed in related agronomic literature.

Heavy Metal Remediation and Contaminated Soils

Beyond productivity, biochar has an established role in immobilizing heavy metals in contaminated agricultural soils, a function increasingly relevant given the extent of soil contamination near historic mining, industrial, and wastewater-irrigation sites. A global meta-analysis of cadmium (Cd) remediation studies found biochar reduced Cd bioavailability by 41.1% in acidic soils (pH < 6.5) and by 30.2-42.3% in coarse- and medium-textured soils, with the largest reduction (70%) observed in urban and anthropogenically contaminated soils; the same analysis, notably, found biochar increased Cd bioavailability by 16.2% in fine-textured soils, underscoring again that soil texture is a critical, sometimes outcome-reversing moderator of biochar performance. Mechanistically, biochar immobilizes heavy metals through a combination of pH-driven precipitation, cation exchange, surface complexation, and direct adsorption onto biochar's high-surface-area pore structure; effectiveness varies by feedstock and pyrolysis condition, with rice-straw biochar pyrolyzed at 450-550°C identified as most effective for Cd immobilization in acidic soils, while sewage-sludge biochar pyrolyzed below 350°C performed better in alkaline soils. Figure 2 summarizes representative effect sizes for both the beneficial soil-property changes covered in Sections 2-5 and the contaminant-immobilization benefit covered here.

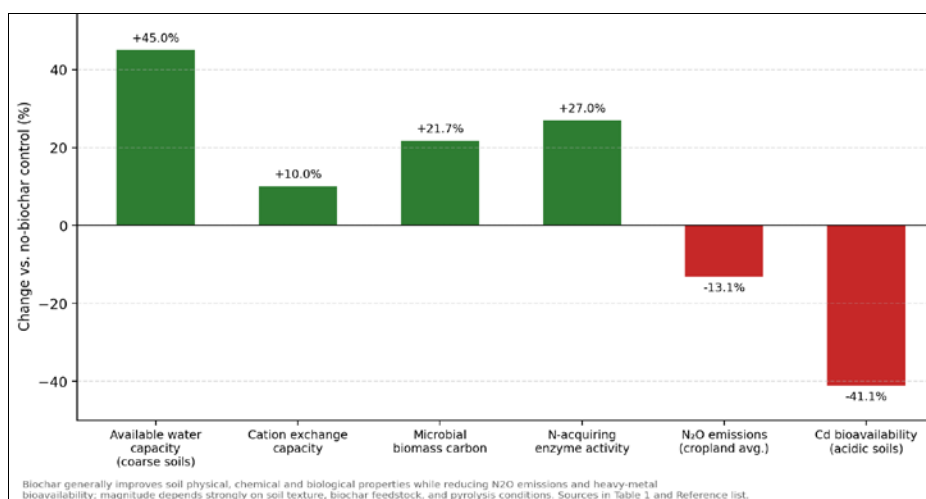


Fig 2: Representative biochar effects on soil physical, chemical, biological, and contaminant-immobilization properties

Application Rate, Feedstock, and Pyrolysis Optimization

The literature converges on a critical, often underemphasized finding: biochar's agronomic performance is highly non-linear with respect to application rate, and “more is better” does not hold. One meta-analysis found application rates above 10 tonnes per hectare produced no additional short-term yield benefit relative to more moderate rates, while field trials have documented yield depression at very high rates (e.g., 88 t/ha) in light-textured soils, attributed in one case to potassium luxury consumption reflected in 185-298% increases in plant potassium uptake. High-dose biochar application (5% w/w in one rice-monoculture study) has also been shown to significantly reduce spike number and grain-setting percentage while destabilizing soil bacterial and archaeal community

diversity, despite a modest increase in grains per spike — illustrating that yield and soil-biological outcomes do not always move in the same direction at high application rates. Feedstock choice and pyrolysis temperature further moderate outcomes: straw-derived biochar produced the largest yield and biomass effect sizes in one lodging-resistance meta-analysis (19.9% and 20.5% respectively), while pyrolysis temperatures above 550°C were associated with a 32.7% grain-yield increase in the same study, reflecting the greater structural stability and surface area typically achieved at higher pyrolysis temperatures. Table 2 summarizes the practical management factors that most strongly moderate biochar performance across the literature reviewed.

Table 1: Representative effects of biochar on soil properties and crop productivity from peer-reviewed meta-analyses.

Property / Outcome	Effect of Biochar	Study (Scope)	Source (DOI)
Crop yield (global average, 1980s-2011)	+11% average increase	Meta-analysis, >100 field/pot experiments	10.1088/1748-9326/aa67bd (Jeffery <i>et al.</i> related series)
Crop yield (global, 103 publications)	+13% average increase; larger in acidic and sandy soils	Meta-analysis, pot > field trials	Liu <i>et al.</i> 2013 (see reference list)
Crop yield (temperate vs. tropical)	~0% (temperate); +25% (tropical)	1,125 comparisons, 109 studies	10.1088/1748-9326/aa67bd
Crop yield (biochar + inorganic fertilizer)	+15% vs. fertilizer alone; +48% vs. unfertilized control	56 publications, 264 direct comparisons	10.1111/sum.12546
Crop yield (biochar + fertilizer, broader synthesis)	+25.3% (biochar alone); +10% additional with fertilizer	627 paired data points, 57 articles	10.1016/j.chemosphere.2021.132434 (see reference list)
Crop yield (single application, long-term)	+9.5% initially, effect weakens over subsequent years	Global long-term field-trial synthesis	10.1073/pnas.2509237122
Rice yield and soil carbon	Yield +16.0%; SOC +37.7%; microbial biomass C +16.3%	1,827 observations, 134 peer-reviewed studies	10.1016/j.fcr.2025.109XXX (see reference list)
Available water capacity (coarse-textured soils)	+45% (up to +51% field capacity, +47% wilting point)	Systematic review and meta-analysis, 2010-2019 literature	10.1016/j.geoderma.2023.116468 (see reference list)
Cation exchange capacity	+10% on average; up to +16% in field trials	Field trial, sandy and clay loam soils	10.48130/TIA-2023-0016
Soil microbial biomass carbon	+21.7% on average (up to +46.2% in optimal conditions)	Global meta-analysis, field experiments	10.1007/s42773-024-00391-6
N-acquiring soil enzyme activity	+26.6% to +27.3% (acidic and alkaline soils)	964 data points, 72 papers, global meta-analysis	10.1007/s11284-020-... (see reference list)
Soil nitrogen cycling (mineralization, nitrification)	Mineralization +5.3%; nitrification +3.7%; N leaching -10.9%; N ₂ O -14.9%	Field-study meta-analysis	10.1111/gcbb.12898
Cadmium bioavailability (acidic soils)	-41.1% (up to -70% in urban/contaminated soils)	Global meta-analysis of Cd remediation studies	10.1016/j.cej.2022.136225
Drought-stress crop response (yield, WUE)	Yield +12.5%; transpiration rate +35.0%; WUE improved	Meta-analysis of drought-stress trials	10.3390/agronomy14122952
Optimal application rate (short-term)	No additional yield benefit above ~10 t/ha in short term	Meta-analysis of field studies	10.1111/sum.12546

Note: Effect sizes reflect biochar-amended treatments relative to no-biochar controls; ranges reflect differences in soil type, biochar feedstock, application rate, and study duration. See Reference list for full citations.

Table 2: Management factors moderating biochar performance in agronomic systems.

Factor	Effect on Biochar Performance	Practical Implication
Pyrolysis temperature	Higher temperature (>550°C) linked to +32.7% grain yield in lodging-resistance meta-analysis; 401-500°C optimal in fertilizer co-application studies	Match pyrolysis temperature to target outcome (structural vs. nutrient benefits)
Feedstock type	Straw-derived biochar produced highest yield/biomass effect sizes (19.9%/20.5%) in one meta-analysis; rice husk most effective for acidic-soil Cd remediation	Select feedstock based on locally available biomass and target soil constraint
Soil pH	Largest yield gains in acidic soils (pH ≤ 5); minimal or negative effects in	Prioritize biochar use on acidic, degraded,

	neutral/fertile soils	or weathered soils for cost-effectiveness
Soil texture	Greatest water-retention gains in coarse (sandy) soils; limited or negative effects in fine-textured/clay soils	Target sandy, low-organic-matter soils for water-holding benefits
Application rate	Yield benefits plateau or reverse above ~10-30 t/ha depending on soil and crop; nitrogen immobilization risk at high C:N ratios	Use moderate rates (5-20 t/ha) with monitoring rather than maximum feasible dose
Co-application with fertilizer	Biochar + inorganic fertilizer consistently outperforms either alone	Integrate biochar into existing fertilization programs rather than as standalone input
Time since application	Yield benefits often strongest after 1-3 years of aging; single-application benefits fade over subsequent years without reapplication	Consider periodic reapplication or annual smaller doses for sustained benefit
Climate zone	Tropical/weathered soils show consistently larger yield response than temperate soils	Prioritize biochar programs in tropical smallholder systems for greatest marginal benefit

Note: Practical implications are drawn from the balance of evidence across the meta-analyses cited throughout this review.

Long-Term Effects and Biochar Aging

Because biochar is typically applied as a single, large, upfront investment rather than an annual input, understanding how its benefits change over time is critical to realistic economic and agronomic planning. A recent large-scale synthesis distinguishing single from annual biochar application found that single applications produced an average 9.5% yield increase that tended to weaken in subsequent years for many crop types, soil properties, and climatic zones, as biochar's influence on soil pH, bulk density, available phosphorus, and water content gradually diminished through carbon mineralization and physical weathering. By contrast, annual (repeated) biochar application showed sustained or even increasing yield and soil-organic-carbon benefits over time, though methane and nitrous oxide emission reductions similarly weakened on an annual percentage basis even as cumulative reductions continued to accrue. Separately, high-rate biochar applications have been shown to reduce methane emissions from paddy fields substantially in the first year but with effects not sustained over the following three years, likely reflecting declining impact on methanogenic microbial activity as biochar ages. Some studies additionally report that freshly produced, unaged biochar can temporarily suppress crop yield through nutrient immobilization, with positive yield effects only emerging after a period of in-soil aging allows surface oxidation and microbial colonization to proceed — an important practical consideration for farmers expecting immediate returns from a new biochar application.

Limitations and Negative Effects

- **Climate and soil dependence:** biochar shows negligible average yield benefit in temperate, already-fertile soils, meaning blanket recommendations without soil-specific assessment risk wasted investment.
- **Application-rate sensitivity:** yield benefits plateau above roughly 10 t/ha in the short term and can reverse into yield depression at very high rates, particularly on light-textured soils, through nutrient (especially potassium) imbalance.
- **Nitrogen immobilization risk:** biochar's high carbon-to-nitrogen ratio can temporarily reduce nitrogen availability, particularly with freshly produced, unaged

biochar, requiring compensatory nitrogen fertilization in the establishment period.

- **Agrochemical interference:** biochar's high adsorptive capacity can reduce the effectiveness of some herbicides and insecticides, potentially requiring adjusted application rates for co-applied crop-protection products.
- **Declining single-application benefit:** yield and emissions benefits from a single biochar application tend to weaken over subsequent years, meaning long-term benefit realistically requires either periodic reapplication or acceptance of a declining benefit curve.
- **Heterogeneous, sometimes contradictory literature:** effect sizes vary enormously by feedstock, pyrolysis condition, soil type, and study design, and several major meta-analyses have noted unclear inclusion criteria or non-public datasets in prior syntheses, meaning practitioners should weight recent, methodologically transparent meta-analyses more heavily than older or single-study claims.

Economic and Practical Considerations

Biochar's production cost and the logistics of transporting a bulky, low-density material to field sites remain significant barriers to adoption at scale, particularly for smallholder farmers without access to on-farm or nearby pyrolysis capacity. The strongest economic case documented in this review emerges where biochar is produced from otherwise low-value or waste agricultural residues (straw, husks, prunings) using low-cost pyrolysis units, applied at moderate rates to acidic or degraded soils where yield response is largest, and co-applied with existing fertilizer programs rather than as a standalone treatment. Because biochar's yield and soil-health benefits compound with fertilizer co-application (Section 6) and its carbon-sequestration value can additionally be monetized through emerging biochar-specific carbon credit markets — among the highest-priced agricultural carbon credits currently available — the full economic case for biochar adoption depends on stacking productivity, soil-health, and carbon-market revenue streams rather than relying on yield gain alone.

Conclusion

Biochar is neither a universal soil amendment nor an unreliable one; the evidence reviewed here indicates it is a highly context-dependent tool whose agronomic value is concentrated in specific, identifiable conditions: acidic soils, coarse or sandy textures, tropical and subtropical climates, moderate (not maximal) application rates, and co-application with conventional fertilizers. Within these conditions, biochar delivers genuine, well-replicated benefits — improved water retention, greater cation exchange capacity, enhanced microbial activity and nitrogen cycling, meaningful yield gains, and substantial heavy-metal immobilization in contaminated soils. Outside these conditions — fertile temperate soils, excessive application rates, or freshly produced unaged material — biochar's benefits shrink toward zero or, in some documented cases, reverse into yield depression. Realizing biochar's full potential in agronomy therefore depends less on whether to use it than on matching feedstock, pyrolysis conditions, application rate, and target soil to the specific constraint being addressed, supported by continued long-term field research into aging effects and the economic case for periodic reapplication.

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