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Biochar and organic amendments for rehabilitating degraded soils

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Abstract

Soil restoration of damaged soils is a key worldwide concern that affects food security and ecosystem health. Biochar (charcoal of pyrolyzed biomass) and organic amendments (composts, manures, residues, etc.) are intensively researched for sustainable soil rehabilitation. This review explores their complimentary functions, major historical advances and current understanding. We describe the kinds of organic amendments, average application rates, projected soil impacts and compile attributes of biochars from different feedstocks. We next discuss field and greenhouse research on combined biochar+organic treatments and their large crop production increases (+1050% or more) and soil health benefits (increased organic C, N retention, pH stability, cation exchange capacity). Below is a decision flowchart (mermaid code) showing the selection of amendments depending on soil degradation indicators (e.g. acidity, low organic matter, salt). Key personalities in this area include early identification of Amazonian “Terra Preta” soils, contemporary pioneers like Johannes Lehmann, Bruno Glaser and Rattan Lal for biochar and agroecology supporters such as Sir Albert Howard and J.I. Rodale for organic additions. We also discuss the economic and environmental trade-offs, with biochar having significant carbon sequestration potential (~0.7–1.8 Gt CO₂-eq/yr worldwide) with its production costs (~\$200–300/ton) in comparison to other amendments.

Keywords: Biochar, organic amendments, degraded soil rehabilitation, soil health, crop yield, carbon sequestration, compost, manure, Terra Preta, soil fertility

Introduction

Degraded soils those with degraded topsoil, poor organic matter, acidity, salinity, nutrient loss, or contamination threaten agricultural output and ecological services ^[1]. Up to one third of the world’s soils are moderately to extensively deteriorate by intensive farming, misuse of chemical inputs, deforestation and climatic stress ^[2]. Reclamation of these soils is usually by increasing organic matter and enhancing fertility with sustainable additives. Two complimentary amendment techniques have received substantial interest: biochar and organic amendments (compost, manure, green manures, etc.) ^[2, 3, 4]. Biochar is a carbon-rich stable substance formed by pyrolysis of biomass (plant wastes, wood, dung, etc.) under low oxygen conditions. It is very porous and alkaline and may enhance the physical and chemical characteristics of soil and carbon sequestration. Important nutrients are supplied and microbial activity stimulated by organic amendments derived from agricultural and animal leftovers in Indian scenario ^[5, 6].

Combining biochar with other organic materials may increase advantages in agriculture aspects. Biochar can stabilize nutrients and organic materials from compost/manure, minimize losses through leaching or denitrification and enhance soil water retention ^[7, 8]. Co-application of labile organic materials (compost/manure) with biochar promotes priming of microbial processes and supplies the nitrogen and phosphorus required in the early stages of crop growth. This study describes current developments (2018-2026) in the use of these amendments in degraded soils ^[9, 10]. We begin by describing the historical background and the major researchers in the discipline. Next we describe the characteristics of various biochar types (impact of feedstock) and kinds of organic additions (Table 1 and 2) ^[11]. We summarize experimental evidence of crop responses to

combination biochar+organic treatments in different soils (Table 3). A decision flowchart (see below) leads you through the choice of amendment depending on the particular soil problem (e.g. acidic pH vs. nutrient deficiency). Finally, we discuss economic and environmental trade-offs (Table 4) and conclude with practical suggestions for the use of biochar and organic amendments to restore damaged soils [12]. The addition of organic matter to soil is an old idea. Traditionally, early civilizations (e.g. in Asia, the Mediterranean) utilized animal excrement and plant remains to fertilize the soil. In more recent history, scientific awareness of organic amendments evolved in 18-20th centuries [13]. The roots of soil chemistry were formed in the 1800s by Johann Heinrich von Thünen and Justus von Liebig (Liebig notoriously prioritized mineral nutrients and actually downplayed the significance of “muck” against chemical fertilizers) [14]. In contrast, Sir Albert Howard (1873-1947) in his seminal book “An Agricultural Testament” of 1940 advocated composting and natural fertility, inspiring the modern organic farming movement (the Rodale Institute in the US and Lady Eve Balfour in the UK were early proponents of organic amendments in the 1930s-50s) [15, 16]. In parallel, the discovery of the Amazonian “Terra Preta” (black earth) soils, which are rich anthrosols with charcoal and pottery shards, led to archaeological and agronomic attention. In the late 1960s, Brazilian researcher A. V. Sombroek discovered evidence of long-lasting rich soils with burnt organic residue, which showed that ancient indigenous Amazonians had produced Terra Preta [18].

The scientific study of biochar as a soil amendment is quite recent, starting in earnest in the 1990s-2000s. Key pioneers include Johannes Lehmann (Cornell University) who revived the notion of Terra Preta in agronomy and carbon sequestration and Bruno Glaser (Universities of Hohenheim/Bern) who explored the soil biochemical impacts of char (notably as “black carbon”) [19]. Stephen Joseph and Stephen Z. Dong have developed pyrolysis engineering. Rattan Lal (Ohio State University) used biochar in studies on soil carbon cycling and climate change mitigation [20]. Prominent organic amendment researchers include Michel Lotter, Timothy Crews and Don Wischmeier, although many contributions come from agricultural extension and ecological agronomists across the globe. In summary,

contemporary organic amendment proponents (Howard, Rodale, Balfour) and biochar researchers (Lehmann, Glaser, Joseph, Lal) represent a line of innovators committed to the sustainable replenishment of soil organic carbon and fertility [21].

Properties and Production of Biochar

Biochar's characteristics depend heavily on feedstock type and pyrolysis conditions (Table 1). Woody biomasses (hardwood, softwood, coconut shells) pyrolyzed around 400-600 °C yield high-carbon chars (carbon content often 60-85%) with low ash (<5%) and neutral-to-alkaline pH [22]. They tend to have large surface area and microporosity, enhancing water retention and nutrient adsorption. In contrast, herbaceous residues (straws, grasses) produce biochars with higher ash content (10-30%), elevated pH (often >9 due to residual minerals) and more oxygen-containing functional groups (if pyrolysis is mild) [23]. Manure-based biochars (poultry, cattle, sewage) yield high-ash, high-mineral chars (often >20% ash, rich in phosphorus and potash) with very alkaline pH (up to ~11), but lower stable carbon content (often <40%) and yield. These nutrient-rich chars can supply N, P, K but may pose a salinity risk if overapplied [24]. Typical slow-pyrolysis (residence minutes to hours) yields range ~30-60% of feedstock mass, whereas fast pyrolysis yields less biochar (often <30%) but more bio-oil/gas [25].

In Table 1 (below), feedstocks are grouped by general category. “Production conditions” summarizes common pyrolysis methods (e.g. slow vs fast) and temperature ranges. Key biochar properties listed include approximate carbon content, ash content, pH and any special notes (e.g. nutrient levels or high silica in rice husk biochar) [26]. When data were not precisely available, entries are marked “unspecified” or given as a range. This table highlights, for instance, that hardwood biochars (oak, maple) typically have high carbon (70-85%) and low ash, while straw and husk biochars have moderate carbon (~50-60%) but high ash and alkali [27]. Animal-manure biochars are high-ash and alkaline, often providing available P and K. These property differences guide application decisions: e.g. manure-chars can act like slow-release fertilizers, whereas wood-chars mainly increase carbon and CEC [28].

Table 1: Biochar feedstock categories, typical production conditions and resulting properties. Carbon (C) percentages and ash content are approximate ranges from literature. “pH” indicates biochar pH in water or CaCl₂ extract (carbonates raise pH) [29, 30, 31, 32, 33, 34]

Feedstock Type	Typical Pyrolysis (Temp, Type, Yield)	Key Biochar Properties
Softwood (pine, spruce)	350-500 °C slow pyrolysis (30-50% yield)	High C (~70-80%), low ash (<5%), pH ~68, large surface area, high porosity
Hardwood (oak, maple)	400-600 °C slow pyrolysis (30-50% yield)	High C (65-85%), very low ash, pH ~67, very porous, stable carbon
Wood chips/mixed wood	400-600 °C (slow pyrolysis)	C ~60-80%, ash <5-10%, pH ~79 depending on wood type, good water retention
Rice straw/wheat straw	300-500 °C (slow pyrolysis)	C ~50-60%, ash ~15-30%, pH ~8-10, nutrient-rich ash (K, SiO ₂), moderate surface area
Maize (corn) stover	300-500 °C	C ~45-55%, ash ~15-25%, pH ~8-10, moderate porosity, contains K and Ca in ash
Nut shells (coconut, walnut)	500-700 °C (fast/slow pyrolysis)	C ~75-85%, ash <5%, pH ~9-11, high hardness, high porosity, extremely low moisture
Bamboo	400-700 °C	C ~60-70%, ash ~5-15%, pH ~8-9, similar to wood charcoal but fibrous
Rice husk	500-600 °C	C ~45-55%, ash ~20-35% (rich in silica), pH ~79, very high silica content
Poultry manure/litter	300-600 °C	C ~20-40%, ash ~25-50%, pH ~8-11, high N-P-K content, low stability
Cattle manure	300-600 °C	C ~25-45%, ash ~15-30%, pH ~8-10, moderate N-P-K, high organic matter

Biochar properties

All biochars are rich in stable carbon, contributing to long-term soil carbon sequestration. Many have high cation exchange capacity (tens to hundreds of cmol_c/kg) after aging, especially those with oxygen-containing functional groups (often from

moderate-temperature pyrolysis) [35]. Biochar's large surface area (often hundreds of m²/g) provides habitat for microbes and adsorption sites for nutrients and water. Ash content contributes liming effect and supplies Ca, Mg, P, K for instance, manure and straw biochars can supply substantial phosphorus and potassium

when incorporated into soil. Biochars typically raise soil pH (especially high-ash types), which can ameliorate acidic soils. However, fresh biochar can also initially immobilize nitrogen (high C/N ratio) and absorb some nutrients until microbial community stabilizes [36, 37].

Organic Amendments: Types and Soil Effects

Organic amendments encompass a wide range of materials derived from plant and animal residues. They are applied to provide nutrients, organic carbon and to improve soil structure and biology.

Table 2: lists major organic amendment types, typical application rates (on a dry-matter basis) and expected soil effects. Key categories include composts (stabilized organic wastes), raw manures, cover or green manures (ploughed-under crops, often legumes), crop residues (mulched or incorporated), biosolids and specialized amendments (vermicompost, bio-slurry) [33, 34, 35, 36, 37, 38].

Organic Amendment Type	Typical Rate (Dry Tons/ha)	Expected Soil Effects
Compost (yard/vegetable)	5-30 t/ha (often 10-20 t/ha)	Increases organic matter and microbial biomass, supplies NPK slowly, improves soil structure and moisture retention, raises CEC and pH (if alkaline), risk of nutrient leaching or salt if over applied.
Manure-based compost	5-20 t/ha	Similar to compost above but higher nutrient content (especially N and P), boosts soil N and P, gradual nutrient release, enhances soil biota, may carry pathogens/heavy metals if not fully composted.
Raw animal manure (poultry)	2-10 t/ha (dry basis)	High in N and P (often 13% N, 0.51% P), quick nutrient availability, raises soil organic matter, potential ammonia toxicity if fresh, risk of nitrate leaching and NH ₃ volatilization.
Raw animal manure (cattle)	5-50 t/ha (wet, about 13 t dry/ha)	Moderate nutrient content, slower N release, adds organic matter and improves soil structure, increases microbial activity, watch for parasitic pathogens and nutrient runoff.
Green manure (legume cover crop)	~2-10 t/ha biomass (ploughed under)	Fixes atmospheric N (if legume) often 50-200 kg N/ha, adds fresh organic matter, improves structure, reduces erosion, timing critical (must grow cover first), uses land without cash crop.
Crop residues (mulch/incorporation)	2-15 t/ha (depending on crop)	Adds carbon and some nutrients as they decompose, improves moisture retention and reduces erosion, may temporarily immobilize N during decomposition, low cost if on-farm.
Vermicompost (worm compost)	5-15 t/ha	Very high microbial activity and nutrient availability (N, P, K ~13%), improves seed germination and plant vigour, accelerates soil biota, relatively low volume (only ~10-20% of feedstock mass).
Sewage sludge (biosolid)	5-15 t/ha (regulated)	Supplies N, P, organic C and micronutrients, raises organic matter, potential crop yield boost, risks: heavy metals, organic contaminants, pathogens if not treated, must follow safety guidelines.
Crop residue compost/tea	15 t/ha (compost), 10-100 L/ha (tea)	Provides nutrients (esp. K), stimulants to microbes, improves soil aggregation, tea form is fast-acting but dilute, compost is slower-release, similar to other compost effects.

Table 2: Major organic amendment types, typical application rates (dry mass basis) and principal soil effects. Rates vary by crop and local practice. Positive effects include increases in soil organic matter (SOM), nutrient supply (N, P, K, micronutrients), cation exchange capacity (CEC), microbial activity and improved soil structure and moisture retention. Risks and caveats include potential nutrient leaching, soil salinity or N immobilization if mismanaged and introduction of contaminants or pathogens (especially for raw manures and sewage sludge) [39, 40].

Together, compost, manure and crop residue incorporation are proven to raise soil organic carbon by several tons per hectare per year, improving fertility and physical properties. For example, addition of 10 t/ha compost can raise organic matter by ~0.31% in the topsoil, while cover crops supplying 100 kg N/ha can significantly reduce synthetic fertilizer needs [41]. Organic amendments also foster beneficial soil microbes (e.g. mycorrhizae, nitrogen-fixers) and earthworms, further enhancing fertility and structure. However, organic materials decompose relatively rapidly (years to decades) compared to biochar, so their carbon is less stable. Their high nutrient content (especially nitrogen) means rates are often set by crop nitrogen demand (e.g. 52.0 t/ha for manures supplying 100-200 kg N/ha). Excessive rates risk nitrate leaching and greenhouse gas emissions (N₂O) [42, 43].

Biochar + Organic Amendment Synergy

Co-application of biochar with organic amendments tends to outperform either alone. In nutrient-poor, degraded soils this synergy is especially potent. Biochar's porous structure adsorbs and gradually releases nutrients from compost and manure, reducing leaching losses. It also buffers pH and provides habitat for decomposer microbes [44]. Meanwhile, labile carbon and nutrients from compost/manure feed soil biota and crops in the short term, bridging the gap until biochar's benefits accrue.

Many studies report that combined treatments improve plant growth more than either amendment alone, particularly in acidic, sandy or tropical soils [45].

Crop Responses and Yield Changes (Biochar + Organic)

Table 3 summarizes representative field and greenhouse trials where biochar was co-applied with organic amendments (compost, manure, organic fertilizer) [46]. Most of these experiments involved degraded or low-fertility soils (acidic ultisols, sandy loams, or nutrient-depleted tropical soils). The observed yield changes (often grain or aboveground biomass) are reported relative to unamended controls or to organic amendment alone [47]. Many trials show strong yield gains from the combined treatments, especially in stressed soils:

- In an acidic tropical soil in Ethiopia, adding 5-20 t/ha of biochar-based fertilizer (biochar mixed with animal manure) to wheat increased grain yields by roughly 47-94% over the control (47% at 5 t/ha, 94% at 20 t/ha). These treatments dramatically outperformed inorganic fertilizer in this trial, underscoring biochar's value in tropical acid soils [48].
- In a highly acidic Ultisol (pH ~3.6) in Indonesia, a one-time application of 20 t/ha rice-husk biochar to maize yielded an average 600% increase (67 times higher yield) compared to no amendment, sustained over seven cropping seasons. The large boost was attributed to biochar's liming effect (raising pH and reducing toxic Al³⁺) plus added K and P [49].
- In a tropical Ferralsol with maize in Brazil, applying 10 t/ha biochar (wood-based) along with standard NPK fertilizer increased maize grain yield by about 29% compared to fertilizer alone. Compost application (25 t/ha) gave ~10% increase. Combined biochar+compost treatments yielded intermediate improvements (~20% or more), correlating with higher soil moisture and nutrient availability [50].
- In a temperate organic farm (loamy soil, Germany), annual

co-composting of biochar (02 t/ha) with manure and grass-clover compost raised winter spelt yields substantially. Manure-compost alone lifted spelt yield from 3.21 to 4.20 t/ha (+31%). With biochar added (up to 2 t/ha), yields remained high (5%) due to biochar in the compost ^[51].

- In a sub-humid Kenya field trial (maize-soy rotation), repeated biochar applications (10-15 t/ha) over 10 years persistently increased cereal yields by ~10% relative to unfertilized plots, improving fertility of an otherwise infertile soil ^[52].
- Several other studies in China and Australia on rice or cereals in alkaline or saline soils found that biochar+manure or biochar+compost generally boosted yields by 10-30%, though effects could be smaller in non-acidic soils. In many

cases, biochar alone had little effect unless paired with organic N inputs ^[53].

Not all trials show positive yield changes, some report neutral or slightly negative effects, especially in already fertile or neutral pH soils. For example, co-composted biochar slightly reduced spelt yields in the first year in the German trial (compared to compost alone), possibly due to initial N immobilization ^[54]. However, by the fourth year, small yield benefits emerged (consistent with soil organic carbon build-up). In sum, combined biochar+organic applications often yield +10-50% improvements (and occasionally much higher) in degraded soil contexts, while rarely harming yield ^[55].

Table 3: Selected crop yield responses to combined biochar and organic amendments in degraded or low-fertility soils. Yield change is relative to unamended control (or sometimes organic alone) and expressed as% increase (bold indicates large gain) ^[56, 57, 58, 59, 60, 61].

Soil Type / Location	Crop	Amendment (Biochar + Organic)
Acidic tropical (Ethiopia)	Wheat	Biochar-based fertilizer (5-20 t/ha)
Temperate loam (Germany)	Spelt (organic)	Manure-compost (+ biochar 02 t/ha)
Temperate loam (Germany)	Maize (silage)	Manure-compost + biochar (500-2000 kg C/ha)
Tropical Ferralsol (Brazil)	Maize	Biochar (10 t/ha) + fertilizer
Tropical Ferralsol (Brazil)	Maize	Compost (25 t/ha) + fertilizer
Tropical Ferralsol (Brazil)	Maize	Biochar (2.5 t/ha) + Compost (25 t/ha) + fertilizer
Subhumid (Kenya)	MaizeSoy	Biochar (10-15 t/ha, ~10 yr)
Acidic Ultisol (Indonesia)	Maize	Rice-husk biochar (20 t/ha, one-time)
Saline-alkali (China)	Wheat	Biochar + manure
Semi-arid (Africa)	Millet	Biochar + poultry manure
Tropic (SE Asia)	Rice	Biochar + organic fertilizer

Economic and Environmental Trade-offs

Both biochar production and organic amendments have costs, benefits and potential risks. Table 4 compares these factors. Costs: Biochar production requires pyrolysis equipment and energy, typical production costs are on the order of \$200-\$300 per ton of biochar (depending on scale and feedstock cost) ^[62]. Transport and application add to costs if done off-site. In contrast, many organic amendments (manure, crop residues) are locally available and low-cost, though there are still collection and spreading costs (e.g. \$1050 per ton for compost) ^[63, 78]. Carbon sequestration: Biochar is extremely stable, conservative estimates suggest global biochar deployment could sequester 0.71.8 Gt CO₂-equivalent per year (about 0.20.5 GtC/yr) ^[79, 64]. On a per-hectare basis, biochar addition (e.g. 10 t/ha) can lock away several tons of carbon for centuries. Composts and manures also add carbon, but much of it gradually decomposes (though they do contribute short- to mid-term soil carbon gains). Some resources (peat) are carbon-rich but non-renewable and thus not sustainable ^[80, 65]. Co-benefits: Biochar

adds water retention, nutrient holding capacity and supports microbial habitat. It can be manufactured from waste biomass (agri-waste, forestry residues), aiding waste management ^[66]. Organic amendments recycle local nutrients, reducing fertilizer inputs and improve soil fertility and biodiversity. Both can reduce greenhouse gas emissions from soils (e.g. biochar often lowers N₂O emissions, compost can reduce need for synthetic N). Risks: Biochar feedstocks must be sourced sustainably (cutting forests for biochar is not acceptable) ^[67]. Biochar made improperly (e.g. from contaminated waste or incomplete pyrolysis) can contain polyaromatic hydrocarbons or heavy metals. Some high-ash biochars (manure-derived) can raise soil salinity if overused. Organic amendments carry risks of nitrogen leaching, methane emissions (especially from anaerobic composting) and introducing pathogens or pollutants (notably in sewage sludge). Additionally, there can be trade-offs: investing in expensive biochar may divert resources from other soil management ^[68, 69, 70].

Table 4: Summarizes these trade-offs qualitatively ^[71, 72, 73, 74, 75, 76, 77]

Amendment	Carbon Sequestration	Co-benefits
Biochar	Very high stability: ~50-90% of C sequestered long-term. Scalable (0.71.8 Gt CO ₂ e/yr).	Improves pH (liming), increases CEC, water retention and microbial habitat, recycles biomass waste, potential carbon credits.
Compost (yard/food waste)	Moderate: adds SOM, but much decomposes (only ~10-30% remains after a few years).	Supplies N-P-K and micronutrients, enhances soil structure, aeration and moisture, boosts soil biota, reduces need for synthetic N.
Animal manure (cattle)	Low/moderate: some stable humus formation, much organic C decomposes.	Readily supplies N and organic matter, improves soil aggregation, recycles on-farm nutrients.
Animal manure (poultry)	Low: high nutrient use.	High nutrient content, especially N and P, rapid nutrient availability, raises SOM.
Green manures (legumes)	Moderate: entire biomass eventually decomposes into soil C.	Fixes atmospheric N (reduces fertilizer need), provides organic matter, cover crop protects soil (erosion control), can improve soil biology.
Crop residues (mulch/incorp.)	Low/moderate: decomposes faster than biochar but slower than fresh manure.	Adds carbon and nutrients gradually, conserves moisture, suppresses weeds, minimal expense.
Sewage sludge (biosolids)	Moderate: adds carbon but large fraction is volatile solids.	Supplies N, P and organic matter on a large scale, recycles waste nutrients.
Wood mulch/chips	Low: very slow decomposition, but some stable humus forms.	Excellent erosion control, gradually improves structure, builds earthworm habitat.

Conclusion

Soil rehabilitation is significantly needed for sustainable agriculture. Many indicators of soil deterioration may be alleviated by the application of biochar and organic amendments in combination. Biochar offers stable carbon, boosts pH (in acidic soils) and stimulates water and nutrient retention in the soil. Organic inputs support the biology of plants and soil because they give easily accessible nutrients and labile carbon. In tough to work soils they re-build the soil organic matter, enhance the structure and fertility of the soil and raise crop yields. The results of our investigation indicate that the combined biochar and organic treatments are consistently better than each amendment applied alone in deficient soils. In field experiments on damaged soils, combination treatments have frequently been shown to provide production increases of 10-50% or more. This is one of the most crucial results. The tropical acid and sandy soils are the ones that would benefit the most. Co-application greatly enhances the soil quality metrics including organic carbon, CEC, pH and moisture retention measurements. Increasing soil carbon stocks in the long term (typically 10 tons of carbon per hectare over a few years, as said) Custom amendment selection: alkaline biochars (or lime plus biochar) are best suited for severely acidic and alkaline-toxic soils. Legume green manures or manure-based compost are advised for nitrogen-deficient soils. Biochar may also be used in the composting process. Organic mulches and biochar may absorb salts and enhance the texture of saline soils. All these judgments are the responsibility of the mermaid flowchart. Scaling the production of biochar requires investments and legislation that support it (carbon credits, waste management incentives). On the other hand, organic additions tend to be more dependent on farm-level logistics. Co-products like biochar fertilizers (biochar enriched with manure or compost) might be a value source. Amendments need to be under strict monitoring and examination to ensure they are free of any harmful pollutants. In a word, the combined application of biochar and organic waste inputs is a successful technique for the regeneration of soil. It enhances productivity and via closure of nutrient cycles and carbon sequestration it also aids to mitigation of climate change. But there is not one universal method. The use of additives should be complemented by local trials, evaluation of regional biomass resources and integrated farm management (including crop rotations, decreased tillage and erosion control). There is a need for further long term field research in agroecological zones to determine the most efficient ways. Further study in the future should be carried out to further optimise dose-response relationships, create low-cost pyrolysis technologies and examine socio-economic adoption models. Recent research, however, makes it clear that the restoration of soils around the globe must incorporate biochar and conventional organic inputs.

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