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Conficious Nkrumah
Department of Agrobiotechnology, Institute of Agriculture, RUDN University, Moscow, Russia

Hannah Addai Boahemaa
Department of Agrobiotechnology, Institute of Agriculture, RUDN University, Moscow, Russia

Prosper Ntow
Department of Agrobiotechnology, Institute of Agriculture, RUDN University, Moscow, Russia

Gladys Alabilla
Department of Agrobiotechnology, Institute of Agriculture, RUDN University, Moscow, Russia

Paul Laari
Department of Agrobiotechnology, Institute of Agriculture, RUDN University, Moscow, Russia

Gloria Naa Lamiley Lamptey
Department of Agrobiotechnology, Institute of Agriculture, RUDN University, Moscow, Russia

Akwasi Agyapong Oppong-Agyemang
Department of Agrobiotechnology, Institute of Agriculture, RUDN University, Moscow, Russia

James Nii Armah Okine,
Department of Agrobiotechnology, Institute of Agriculture, RUDN University, Moscow, Russia

Benjamin Konyannik Yennuna,
Department Agrobiotechnology, Institute of Agriculture, RUDN University, Moscow, Russia

Corresponding Author:
Conficious Nkrumah Department of Agrobiotechnology, Institute of Agriculture, RUDN University, Moscow, Russia

Synergistic effects of biochar and organic amendments on soil fertility and crop productivity: A critical review

Conficious Nkrumah, Hannah Addai Boahemaa, Prosper Ntow, Gladys Alabilla, Paul Laari, Gloria Naa Lamiley Lamptey, Akwasi Agyapong Oppong-Agyemang, James Nii Armah Okine and Benjamin Konyannik Yennuna

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Abstract
Soil degradation affects approximately two billion hectares globally, threatening agricultural productivity and food security. This critical review synthesizes current knowledge on the synergistic effects of combining biochar with organic amendments (compost, farmyard manure, crop residues) for enhancing soil fertility and crop productivity. Evidence demonstrates that co-application consistently outperforms single amendments through multiple mechanisms. Chemically, combined treatments improve pH buffering (particularly in acidic soils), significantly enhance cation exchange capacity, and improve nutrient retention while reducing nitrogen leaching. Physically, they improve soil aggregation and water-holding capacity, especially in coarse-textured soils. Biologically, microbial biomass increases by up to 85%, with enhanced enzymatic activity facilitating nutrient cycling. These improvements translate to significant agronomic benefits, with crop yield increases ranging from 20% to 85%, particularly in degraded tropical soils where fertility constraints are most acute. The synergistic approach also offers environmental advantages through carbon sequestration and greenhouse gas mitigation, with biochar providing stable carbon storage while reducing nitrous oxide emissions. However, effectiveness remains context-dependent, influenced by soil type, climate conditions, and crop species. Methodological limitations in current research including inconsistent pyrolysis details (unreported in over 40% of studies), variable application rates, and short study durations (68% lasting one season or less) highlight the need for standardized protocols and long-term field monitoring. For successful implementation, regionally adapted strategies matching amendment characteristics to specific soil constraints are essential, alongside consideration of socioeconomic factors affecting farmer adoption. This integrated approach shows transformative potential for restoring degraded soils while enhancing agricultural sustainability.

Keywords: Biochar, organic amendments, soil fertility, crop productivity, nutrient retention, microbial biomass, carbon sequestration, sustainable agriculture

1. Introduction

Soil fertility is an essential support of sustainable agriculture and a foundation of food security, environment resilience, and a sound economy. It is the ability of the soil to deliver key nutrients to plants and has direct bearing on crop productivity and sustainability of agro-ecosystems (Stupar *et al*., 2024) [190]. With the rising global anxiety over climate change and population pressure, the conservation and improvement of fertile soils is key to achieving agricultural sustainability (Wolf *et al*., 2023) [212]. Not only do fertile soils support strong crop production but also greater water retention and turnover, enhanced microbe populations and ecological services (Singh *et al*., 2024) [184]. However, soil degradation and nutrient loss present critical problems to these advantages at a global level. Driven by intensive farming technologies, erosion, contamination by chemicals and deforestation, soil degradation now affects an estimated 2 billion ha globally and by itself, nutrient loss has affected 136 million ha (Jie *et al*., 2002; Osman, 2014) [87, 149]. The processes are highly active in developing countries like Africa and Latin America where imbalances in the nutrient system have led to dips in agricultural productivity and ecological integrity (Tan *et al*., 2005) [194] dips in agricultural productivity and ecological integrity (Tan *et al*., 2005) [194]. As the world approaches dips in agricultural productivity and ecological integrity (Tan *et al*., 2005) [194]. As the world approaches. As the world approaches 9 billion in numbers, the reversal of soil degradation and the improvement of fertility will be critical to maintaining farm output and agrifood systems (Karlen and Rice, 2015) [94].

Emerging strategies underscore the significance of integrating traditional knowledge with cutting-edge technologies to optimize soil management. Precision agriculture and digital soil mapping, enhanced by artificial intelligence and Internet of Things (IoT) platforms, are transforming the methodologies through which farmers monitor and manage soil nutrients in real-time (Arısoy and Açıkgözoğlu, 2024; Mamatha *et al*., 2024) [20, 130]. Concurrently, there is a resurgence of interest in ecological soil amendments that serve to restore nutrient balances, sequester carbon, and promote biological diversity. In this regard, organic amendments such as compost, farmyard manure (FYM), and crop residues have garnered increasing attention due to their capability to enhance nutrient availability, augment organic carbon content, and stimulate microbial activity in soils (Singh *et al*., 2024) [184]. In parallel, biochar, a stable, carbon-rich material produced from the pyrolysis of biomass, has been recognized as a promising tool for the enhancement of soil physical structure, water holding capacity, and cation exchange capacity (Kapoor *et al*., 2022; Kabir *et al*., 2023) [92, 90]. The application of biochar has been shown to have the potential to increase soil organic carbon (SOC) by over 30%, reduce greenhouse gas emissions, and improve crop yields (Liu *et al*., 2023; Kaur *et al*., 2024; Sharma and Chhabra, 2024) [57, 95, 179]. More recently, researchers and practitioners have commenced investigations into the synergistic interactions that occur when biochar and organic amendments are applied in conjunction. These combinations appear to provide amplified benefits in comparison to individual amendments, particularly regarding soil fertility enhancement, carbon sequestration, and crop productivity (Chadha *et al*., 2020; Jaswal *et al*., 2022) [40, 80,]. For example, co-application of farmyard manure (FYM) and biochar has been shown to increase both microbial biomass and labile fractions of carbon, key elements in support of nutrient cycling and soil health (Khadem *et al*., 2021; Jaswal *et al*., 2022) [98, 80]. These combined benefits go well beyond nutrient dynamics. Combined amendments may further change the pH of soils, reduce pathogenic pressure, and improve the physical strengths of soils such as aggregation and erosive resistance (Iticha *et al*., 2024; Wang *et al*., 2023a; Kushwaha and Kumar, 2023) [76, 27, 105]. Despite such promise, combined amendments are highly context-specific and are responsive to factors like amendment identity, soil texture, climatic zone, and crop systems (Guo *et al*., 2024; Pérez-Dalí *et al*., 2024) [65, 156]. This unpredictability underscores the need for an overall synthesis of established results and an analysis of spaces where knowledge gaps exist.

This review aims to critically synthesize existing knowledge on the interactions of biochar and organic amendments and their impacts on crop productivity and soil fertility. It examines their modes of action, relative benefits, and environmental consequences. The review aims to further identify important contradictions in the literature, neglected variables, and areas of unknowns in the literature, and hence provide guidance towards future research. For this purpose, the review is structured on high-impact sub-topics, namely on nutrient retention and availability and release, microbial pools and processes, carbon storage and pools, pathogen populations and populations of antagonistic microorganisms, and crop performance and grain yield. The sections draw on recent empirical experiments, meta-analyses of experiments, and trial experiments and present the conditions in which their combined effects or synergistic effects are evident. Further, the review is focused on methodological limitations like insufficiently powered study protocols, non-harmonization of protocols, and limitations on accessing grey literature, and these limit the robustness and comparability of results (Virgolino *et al*., 2021; Palm-Forster *et al*., 2019) [205, 151]. Through presenting a clear and evidence-based analysis of the inter-play of biochar and organic amendments, this review hopes to contribute towards developing robust and durable soil management systems. Finally, the results of this analysis hope to guide scientific investigations and policy design towards rehabilitating degraded soils and enhancing world food systems.

2. Biochar as a Soil Amendment

Production and Properties

Biochar is a carbon-rich material produced through the thermal decomposition of biomass in an oxygen-limited environment, a process known as pyrolysis. Its physicochemical properties vary widely depending on the feedstock used and the specific pyrolysis conditions, such as temperature and residence time (Ippolito *et al*., 2020; Abubakar *et al*., 2024) [73, 3].

Feedstocks and Pyrolysis Conditions

Feedstocks play a critical role in determining the properties of the resulting biochar. Wood-based biochar's are typically characterized by high surface area and porosity due to their lignin-rich structure, making them suitable for pollution remediation and soil structure improvement (He *et al*., 2023; Zhang *et al*., 2023) [69, 38]. Crop residues and grasses often result in biochar's with higher cation exchange capacity (CEC), which benefits nutrient retention due to the presence of easily pyrolyzable cellulose and hemicellulose (Ippolito *et al*., 2020; Tomczyk *et al*., 2020) [73, 199]. In contrast, animal waste-derived biochar's exhibit higher mineral content but lower surface area and carbon stability, affecting their performance in both soil amendment and environmental applications (J, 2020; Mukherjee *et al*., 2022) [40, 138].

Pyrolysis temperature also significantly influences biochar properties. Higher temperatures generally increase surface area and porosity while decreasing CEC and functional group diversity due to the loss of oxygenated groups (Tomczyk *et al*., 2020; Boraah *et al*., 2023) [199, 32]. For example, biochars produced above 500°C have been shown to enhance carbon stability, making them more effective for long-term soil carbon sequestration (Abubakar *et al*., 2024) [3].

Physicochemical Characteristics

Key physicochemical attributes of biochar include surface area, porosity, CEC, and pH. These characteristics directly influence its performance as a soil amendment:

Surface Area and Porosity: High surface area enhances nutrient adsorption and microbial colonization. Biochar's from Pinus patula pellets have demonstrated surface areas exceeding 360 m²/g, significantly improving water holding and pollutant sorption capacities (Gutiérrez *et al*., 2022) [66].

Cation Exchange Capacity (CEC): A higher CEC facilitates nutrient retention. Biochar's produced at lower pyrolysis temperatures generally retain more functional groups, resulting in higher CEC (Mayilswamy *et al*., 2023) [132].

pH: Most biochar's exhibit alkaline pH values (8-10), which are beneficial for neutralizing acidic soils and improving nutrient availability (Rattanaphaiboon *et al*., 2022; Anjali *et al*., 2022) [163, 16].
Understanding the influence of feedstock composition and pyrolysis settings allows for the customization of biochar properties to match specific soil amendment objectives.

Soil Interaction Mechanisms
Biochar influences soil functionality through several physicochemical and biological mechanisms, thereby improving fertility and ecosystem health.

Nutrient Retention and CEC Enhancement
Biochar increases the retention of nutrients mainly through an increase in soil cation exchange capacity (CEC) and an addition of reactive surfaces to ion exchange. This increase reduces the leaching of nutrients and enhances the accessibility of key macronutrients such as nitrogen, phosphorus, and potassium (Rawat *et al*., 2018; Ravi *et al*., 2019) [165, 164]. Its porous nature also allows a slow release of the nutrients, acting as a buffer to ensure a steadier accessibility of the nutrients in agricultural soils. Besides the retention of nutrients, the alkalinity of the bulk of the biochars adds to pH buffering and hence makes them particularly suitable to improve acidic soils (Ng *et al*., 2022; Wang *et al*., 2023b) [142, 208]. This pH stabilization of the nutrients increases their stability and reduces the solubilization of the harmful metals and hence favors the growth of plants (Diehl, 2010) [47].
Another principal advantage of biochar is the improvement of moisture retention in soils through enhanced porosity and aggregate stability. This is an extremely relevant property in sandy or degraded soils whose inbuilt capacity to retain moisture is very low. Research has established that biochar-amended soils possess greater levels of retained moisture and thus maintain crop performance even in moisture-undersupply conditions (Zhang *et al*., 2023; Iwata *et al*., 2020) [38, 77]. Additionally, biochar forms micro-niches to facilitate an ideal environment in the soils to sustain microorganisms while cushioning them from external fluctuations and inducing greater enzymatic and microbial biomass activity (Wilpiszeski *et al*., 2019; Elsas *et al*., n.d.) [211, 51, 154]. These processes induce greater and efficient turnover of nutrients while enhancing the health and fertility in the plants and overall fertility in the soils. The ectomycorrhizosphere enriched by biochar and facilitating enhanced mineral weather and break down of organics results in greater availability of nutrients (Ravi *et al*., 2019) [164].

Biochar Limitations
Despite its multiple benefits, biochar's effectiveness is not universal and several limitations must be acknowledged. Variability in crop response remains a major concern, as outcomes depend heavily on biochar type, soil properties, and cropping systems. In some cases, biochar application has shown neutral or even negative effects, such as yield reductions of up to 74% in lettuce under certain conditions (Mukherjee and Lal, 2014) [137]. These inconsistencies are often linked to poor compatibility between the amendment and soil characteristics or unintended changes in nutrient dynamics (Tisserant and Cherubini, 2019) [198].
Biochar can also immobilize nutrients, particularly nitrogen, by adsorbing ammonium or nitrate ions, which reduces their availability to plants. In addition, the priming effect associated with biochar application may stimulate microbial mineralization, resulting in higher emissions of greenhouse gases such as CO_2, CH_4, and N_2O (Mosa *et al*., 2023) [136]. Beyond agronomic challenges, the environmental footprint of biochar production must be considered. Pyrolysis can generate particulate matter emissions and toxic by-products if poorly managed, and the process is energy intensive (Ramezanzadeh *et al*., 2023) [161]. From an economic standpoint, biochar remains costly due to capital-intensive production and transportation challenges, which limits its accessibility for smallholder farmers. To address these constraints, researchers propose strategies such as tailoring biochar to specific soil types and crops, biological activation, and co-composting. Incorporating field-scale data into life cycle assessments can also enhance sustainability and optimize use. Furthermore, the standardization of production methods and the development of best-practice guidelines are essential to improving predictability and promoting broader adoption (Luo *et al*., 2023; Nepal *et al*., 2023) [127, 141].

3. Organic Amendments in Soil Management
Organic amendments are foundational to sustainable soil fertility management, offering a pathway to rehabilitate degraded soils, enhance nutrient cycling, and improve crop yields in both intensive and low-input agricultural systems. These materials ranging from compost and farmyard manure to green manure and digestate vary widely in their composition and functional benefits. Their integration into modern agronomic practices is increasingly seen as a critical strategy for building resilient agroecosystems, particularly under the dual pressures of climate change and land degradation (Aytenew and Bore, 2020; Singh *et al*., 2024) [23, 184].

3.1 Types and Composition
Organic amendments differ in origin, nutrient content, and decomposition dynamics, which shape their agronomic efficacy. Compost, derived from the aerobic breakdown of organic waste, is rich in humic substances and microbial inoculants. It enhances microbial richness and contributes to long-term soil fertility (Ouyang, Reeve, and Norton, 2022; Liu *et al*., 2023) [150, 114]. Farmyard manure (FYM) and green manures such as *Gliricidia* provide labile organic carbon and readily available nutrients like nitrogen and phosphorus, offering more immediate nutrient release than compost

(Liyanage *et al.*, 2022; Sah *et al.*, 2022) [122, 171]. These materials exhibit diverse nutrient profiles. For example, poultry manure contains high levels of phosphorus, potassium, and calcium, making it particularly suitable for short-cycle crops like leafy vegetables (Vallejera *et al.*, 2014) [202]. Conversely, materials such as Milorganite™, a biosolid-based amendment, contain elevated phosphorus concentrations and interact differently with soil microbiota (Awal *et al.*, 2021) [22].

The mineralization dynamics of organic inputs depend on several factors: the carbon-to-nitrogen (C:N) ratio, soil texture, microbial activity, and temperature. Amendments with low C:N ratios decompose faster, accelerating nitrogen release, while high-C:N materials may immobilize nutrients temporarily (Shin *et al.*, 2016; Javeed *et al.*, 2023) [182, 82]. This complexity underlines the importance of tailoring amendment type and application timing to crop needs and environmental conditions.

3.2 Benefits and Constraints

The benefits of organic amendments span physical, chemical, and biological domains. Physically, they improve soil structure and reduce compaction by promoting aggregate formation and enhancing porosity attributes that increase water retention and aeration (Bashir *et al.*, 2021; Reddy, 2016) [29, 166]. Chemically, they serve as reservoirs of slow-release nutrients and increase cation exchange capacity (CEC), thereby enhancing nutrient retention and buffering soil pH (Paul and Collins, n.d.; Asha *et al.*, 2023) [21]. Biologically, they act as energy sources for soil microbiota, stimulating microbial biomass and enzymatic activity critical for nutrient cycling and disease suppression (Omokaro *et al.*, 2024; Masciandaro *et al.*, 2018) [147, 131].

Despite these advantages, constraints persist. The variability in decomposition rates and nutrient release can lead to mismatches between supply and crop demand, potentially impairing nutrient-use efficiency (Khan and Muhammad, 2024) [99]. Fresh manure, while rich in nitrogen, raises food safety concerns due to pathogen risks, making compost a safer but slower alternative (Ouyang *et al.*, 2022) [150]. Furthermore, organic amendments often exhibit inconsistent nutrient concentrations and may introduce contaminants such as heavy metals if not properly processed (Vallejera *et al.*, 2014) [202].

Another limitation lies in their operational use. Large volumes are often required to achieve meaningful improvements, posing logistical challenges in transport, storage, and field application. These constraints necessitate integrated strategies, such as co-application with biochar or mineral fertilizers, to optimize their efficacy and reduce potential risks.

3.3 Environmental Considerations

Organic amendments not only affect soil fertility but also have complex implications for greenhouse gas (GHG) emissions and broader environmental quality. Their application can increase carbon sequestration in soils but may also contribute to CO_2, CH_4, and N_2O emissions under certain conditions (Fu *et al.*, 2023; Bah *et al.*, 2020) [57, 25]. For instance, compost application alone may reduce N_2O emissions by 25%, but when combined with mineral fertilizers, it can increase total GHG emissions due to enhanced microbial nitrification.

Biochar, when co-applied with organic amendments, has shown promise in mitigating these effects by stabilizing organic carbon and suppressing microbial processes that generate N_2O and CH_4 (Fu *et al.*, 2023; Yao *et al.*, 2021) [57, 217]. However, interactions between biochar and compost can also lead to antagonistic effects, particularly on CO_2 fluxes, making it necessary to evaluate their combined impacts on a case-by-case basis (Rubin, Oldfield, and Sanderman, 2023) [170].

Leaching risks are another environmental concern. Labile nitrogen from manures and high-phosphorus inputs from poultry litter can increase nutrient runoff, potentially contributing to eutrophication of nearby water bodies. Moreover, the quality control of organic amendments remains a challenge, with variability in pathogen loads, heavy metals, and stability indices complicating regulatory and practical use (Lal, 2020; Johnston, Poulton, and Coleman, 2009) [108, 88].

To mitigate these challenges, adaptive management strategies are needed. These include site-specific amendment selection, pre-treatment of raw materials, and precision timing of applications. Innovations such as biostimulants and hydro-parameter integration (e.g., in paddy rice systems) are emerging tools to enhance nutrient-use efficiency and minimize emissions (Senthilraja *et al.*, 2023; Rubin *et al.*, 2023) [175, 170].

4. Combined Application: Biochar and Organic Amendments

The combined application of biochar and organic amendments has garnered considerable attention in soil management research due to its potential to harness synergistic benefits that surpass those of individual treatments. By integrating the physicochemical stability of biochar with the nutrient richness and microbial activity stimulation of organic amendments, this strategy addresses multiple facets of soil degradation simultaneously. However, outcomes vary significantly depending on several interacting factors, including soil type, amendment properties, and agronomic practices (Table 1).

Synergistic Effects

Enhanced Nutrient Retention and Availability

Biochar's high surface area and porosity allow it to act as a sorbent for nutrients, particularly ammonium and phosphate ions, thereby reducing nutrient leaching and enhancing nutrient-use efficiency (Agegnehu *et al.*, 2023) [6]. When co-applied with compost or manure, this buffering capacity supports a more gradual nutrient release, improving synchronization with crop demand (Jeffery *et al.*, 2021) [224]. In tropical soils with inherently low cation exchange capacity (CEC), such combinations have been shown to significantly increase the retention of nitrogen (N), phosphorus (P), and potassium (K) (Agyei-Baffour *et al.*, 2021; Zhang *et al.*, 2021) [7, 221].

Stimulated Microbial Activity and Soil Biological Functions

Organic amendments serve as labile carbon sources that energize microbial metabolism, while biochar provides microhabitats that protect microbes from environmental stress (Bamminger *et al.*, 2022) [28]. This complementary interaction enhances microbial biomass, enzymatic activity, and nutrient cycling processes. Studies report increases in β-glucosidase and phosphatase activities key enzymes in carbon and phosphorus cycling when biochar and compost are applied together (Agegnehu *et al*., 2023; Liang *et al*., 2021) [6, 115]. In particular, the microbial abundance and diversity in compost-treated soils are maintained or amplified with biochar addition, supporting more resilient soil ecosystems.

Improved Soil Structure and Water Dynamics

The physical contributions of biochar such as reduced bulk density and increased porosity improve infiltration, aeration, and water retention (Fu *et al*., 2023) [57]. When combined with compost, which contains sticky organic matter that promotes aggregation, the resulting improvements in soil structure are more pronounced. This is especially beneficial in sandy and degraded soils, where water holding capacity is a major constraint to plant productivity (Celik *et al*., 2020; Fang *et al*., 2023) [39, 54].

Antagonistic or Neutral Effects

Despite the promise of synergy, not all combined applications result in additive benefits. In some cases, antagonistic effects such as nutrient lock-up or microbial imbalance may occur. High rates of biochar can adsorb soluble nutrients excessively, especially immediately after application, reducing short-term nutrient availability for crops (Jeffery *et al*., 2021) [224]. Moreover, biochar with a high pH or ash content may increase soil alkalinity, reducing the availability of micronutrients such as zinc and iron (Kumar *et al*., 2023) [102]. In certain instances, the microbial response to biochar can be neutral or even negative, particularly if the biochar is produced at high temperatures and lacks labile carbon to support microbial growth (Bamminger *et al*., 2022) [28]. Additionally, studies have shown that under some conditions, combining biochar with nutrient-rich compost does not outperform compost alone in terms of yield response, suggesting a diminishing return from co-application in already fertile soils or temperate environments (Thomsen *et al*., 2021; Jeffery *et al*., 2023) [197, 83].

Factors Influencing Outcomes

Amendment Type and Ratio

The origin, feedstock, and pyrolysis conditions of biochar influence its reactivity and interaction with compost or manure. For example, biochar from woody biomass often exhibits lower nutrient content but better structural benefits, while manure-derived biochar contributes more nutrients (Zhang *et al*., 2021) [221]. The ratio between biochar and organic matter must be optimized to avoid nutrient dilution or excessive alkalinity.

Soil Type and Texture

Sandy soils benefit most from the water retention and nutrient holding improvements of biochar-organic combinations. In contrast, clay-rich or organic soils may show limited response due to their inherent fertility and buffering capacity (Agyei-Baffour *et al*., 2021; Agegnehu *et al*., 2023) [7, 6].

Climate, Crop Species, and Cultivation Practices

Warmer climates accelerate microbial activity and decomposition, enhancing the efficacy of organic amendments. However, they also increase volatilization and leaching risks, making biochar's stabilizing function more critical (Jeffery *et al*., 2021) [224]. Crop-specific nutrient demands and rooting behavior also influence outcomes; for instance, deep-rooted crops like maize benefit more from improved subsoil structure and moisture retention than shallow-rooted vegetables (Kumar *et al*., 2023) [102].

Table 1: Impacts of combined biochar and organic amendments on soil fertility and crop performance.

Category	Indicator	Impact of Combined Amendments	Context/Notes
Chemical Indicators	Soil pH	Increases pH in acidic soils (ameliorates Al^{3+}/Mn^{2+} toxicity). Alkaline biochar may reduce micronutrient bioavailability in high-pH soils.	Critical for nutrient solubility and metal toxicity thresholds. Synergistic effect most pronounced in acidic soils.
	Cation Exchange Capacity (CEC)	Significantly improves CEC, enhancing nutrient retention (especially in sandy/weathered tropical soils with low inherent CEC).	Driven by biochar's porous structure and compost's organic matter. Reduces leaching losses.
	Nutrient Availability	• **N and K:** Enhanced by compost. • **P**: Improved by biochar (reduces fixation in acidic soils). • **Micronutrients (Zn, Fe, Mn):** Bioavailability sensitive to pH shifts.	Optimal amendment ratios and long-term dynamics require further study.
Biological And Physical Health	Microbial Biomass And Activity	Increases microbial biomass carbon by up to 85%. Enhances enzymatic activity (e.g., β-glucosidase, phosphatase).	Due to habitat protection (biochar) and labile carbon (compost). Supports nutrient cycling and disease suppression.
	Soil Structure	Improves aggregation and water retention, especially in sandy/degraded soils.	Biochar's porosity and compost's organic "glue" synergize to enhance aggregate stability.
	Water Retention	Increases water-holding capacity (critical in drought-prone/degraded soils).	Most effective in coarse-textured soils.
Crop Performance	Crop Yield	• **Maize:** 20-85% yield increase in tropical Acrisols (due to improved N/P availability and root growth). • **Legumes:** Enhanced nodulation and N fixation. • **Vegetables:** Rapid biomass accumulation and nutritional quality.	Benefits highly dependent on soil type, climate, and crop species. Greatest gains in degraded tropical soils.
	Nutrient Uptake Efficiency	Improved synchrony of nutrient release enhances uptake of N, P, and micronutrients. Chelation mechanisms and pH correction contribute.	Dynamics vary across soil types (acidic, calcareous, arid) and crop nutrient demands.

5. Methodological Approaches in Current Literature.

Evaluating the synergistic effects of biochar and organic amendments demands a spectrum of methodological approaches, from highly controlled laboratory incubations to greenhouse pot trials and ecologically realistic field experiments. Laboratory incubations, typically lasting between 30 and 100 days, allow precise control over variables such as temperature, moisture, and oxygen availability, making them invaluable for probing short-term biogeochemical processes. For example, Fang *et al.* (2023) [54] reported a 48% reduction in N_2O emissions and Li *et al.* (2023) [112] observed significant increases in microbial biomass carbon under co-amendments (Figure 1).

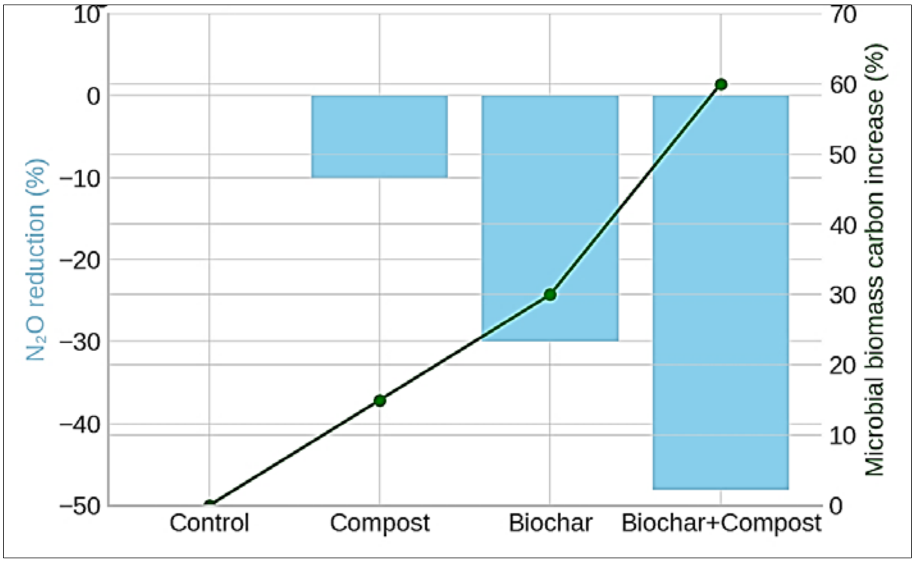

Fig 1: N_2O reduction and microbial biomass increase (Fang *et al*., 2020; Li *et al*., 2023) [53, 112].

However, despite their high replication and cost efficiency, these studies lack plant soil interaction and the environmental variability necessary for predicting long-term field performance. Greenhouse trials bridge the gap between mechanistic laboratory studies and the complexity of field conditions. They allow assessment of plant growth, nutrient uptake, root morphology, and rhizosphere dynamics under semi-controlled conditions. In Ghana, Agegnehu *et al.* (2023) [6] documented a 42% increase in maize biomass and a 30% rise in phosphorus uptake with biochar compost combinations, linked to improved pH and phosphorus availability (Figure 2).

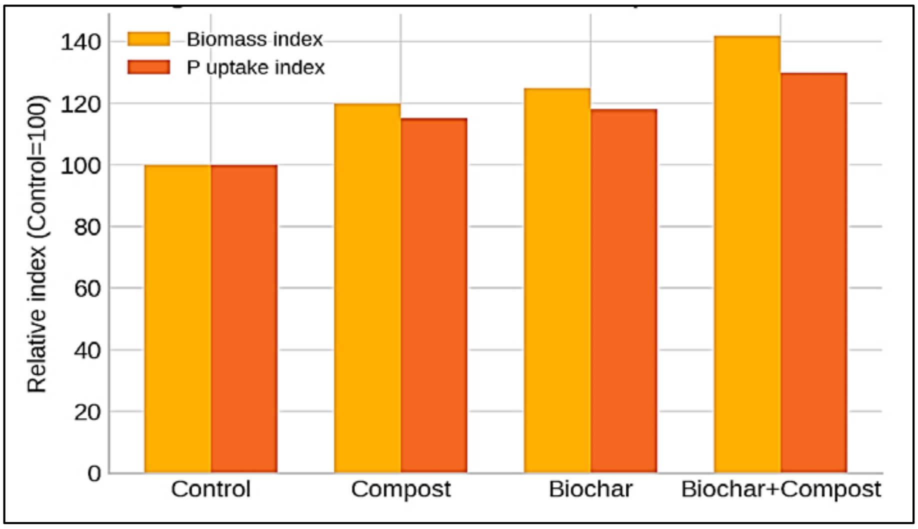

Fig 2: Maize biomass and P uptake increase (Agegnehu *et al*., 2023) [6].

Nevertheless, these setups can restrict root development, alter microclimates, and underrepresent soil heterogeneity. Field trials, regarded as the gold standard, validate amendment effects under real farming conditions. Examples include Agyei-Baffour *et al.* (2021) [7], who recorded an 85% increase in maize yield on degraded tropical soils, and Sánchez-Monedero *et al*. (2022) [172], who observed a 52% reduction in nitrate leaching in sandy soils (Figure 3).

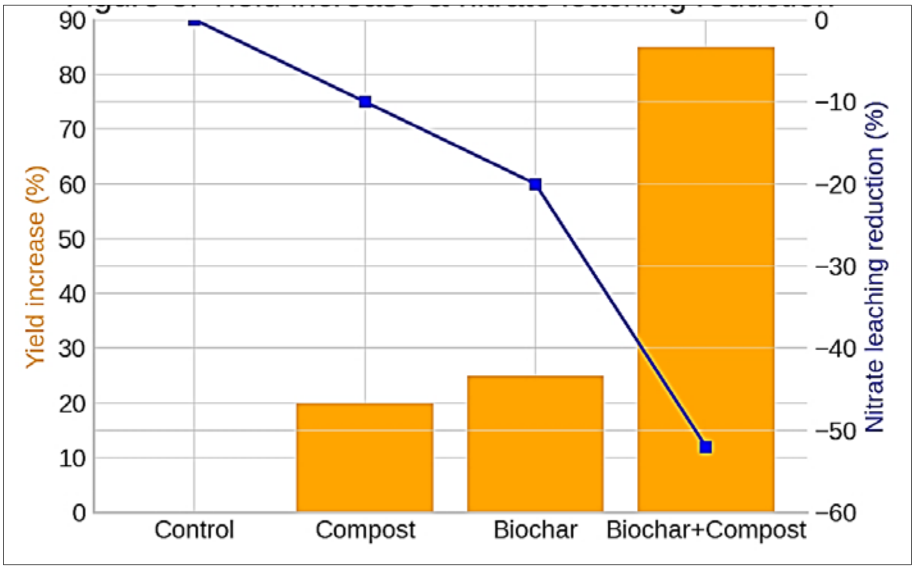

Fig 3: Yield increase and nitrate leaching reduction (Agyei-Baffour *et al*., 2021; Sánchez-Monedero *et al*., 2022) [7, 172].

Zavattaro *et al*. (2022) [219] demonstrated long-term benefits, with a 30% improvement in soil aggregation over five years when compost was applied, further enhanced by biochar addition. Despite their cost and logistical demands, such trials capture real-world variability in climate, management, and pest pressures. The most robust research strategically integrates all three approaches, though Jeffery *et al*. (2023) [83] note that fewer than 12% of studies currently do so. Analytical techniques underpinning these studies are equally diverse. Standard soil and plant chemical analyses quantify key fertility parameters, including pH, cation exchange capacity, soil organic carbon, total nitrogen, available phosphorus, exchangeable cations, and micronutrients, using methods such as spectrophotometry, atomic absorption spectroscopy (AAS), or inductively coupled plasma optical emission spectrometry (ICP-OES). Laird *et al*. (2020) [107] and Liu *et al*. (2022) [42] reported marked increases in zinc and phosphorus availability under co-amendments (Figure 4).

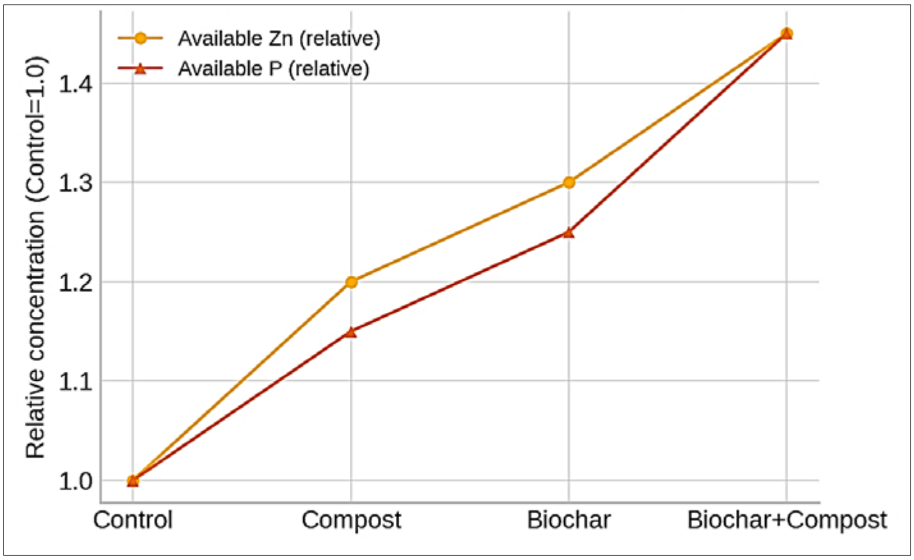

Fig 4: Available Zn and P changes (Laird *et al*., 2020; Liu *et al*., 2023) [107, 120].

Leaching assays both laboratory column studies and field lysimeters evaluate nutrient losses and environmental risk, with Sánchez-Monedero *et al*. (2022) [172] finding biochar reduced nitrate leaching by over 50% relative to compost alone. Microbial profiling, combining functional assays (e.g., microbial biomass carbon/nitrogen, enzyme activities) with molecular tools (e.g., 16S rRNA, ITS sequencing, qPCR), has shown shifts towards more diverse and resilient microbial communities, as reported by Liang *et al*. (2021) [115] and Fang *et al*. (2023) [54] (Figure 5).

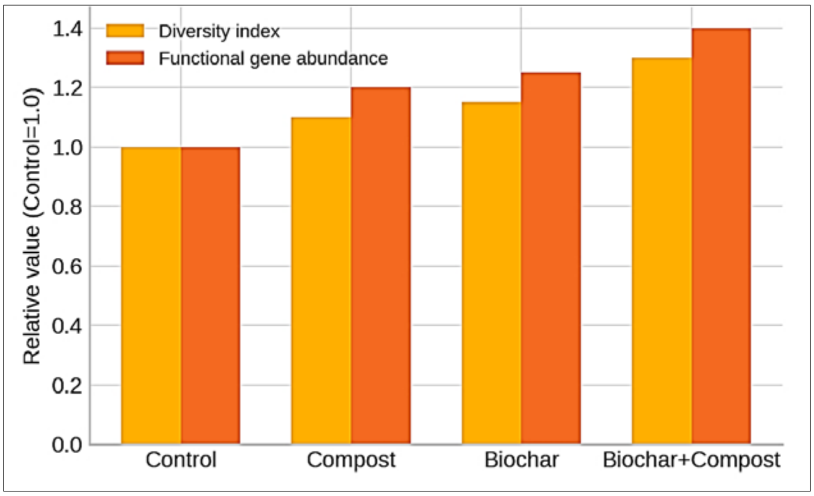

Fig 5: Microbial diversity and functional gene abundance (Liang *et al*., 2021; Fang *et al*., 2023) [115, 54].

Despite these advances, methodological inconsistencies and short study durations remain significant limitations. Over 40% of studies fail to report pyrolysis details and 30% omit feedstock descriptions (Jeffery *et al*., 2023) [83], leading to inconsistent results and hindering comparability. Application rates vary widely, with incorporation methods rarely standardized. Duration is another concern Jeffery *et al*. (2023) [83] found that 68% of studies lasted one season or less. Long-term trials, such as Zhang *et al*. (2022) [221] and Zavattaro *et al*. (2022) [219], show that biochar benefits often increase over time, while compost-alone effects may decline, highlighting the need for extended monitoring (Figure 6). Without standardization in production, consistent application methods, and long-term field data, translating promising results into reliable agricultural recommendations remains challenging.

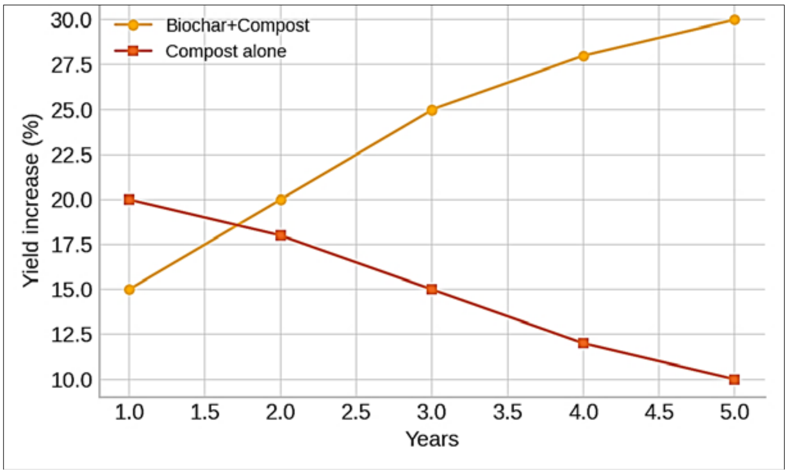

Fig 6: Multi-year yield trends (Zhang *et al*., 2022; Zavattaro *et al*., 2022) [221, 219].

6. Research Gaps and Future Directions

Despite mounting evidence supporting the co-application of biochar and organic amendments in enhancing soil fertility and crop productivity, several critical research gaps remain unaddressed. These gaps span methodological limitations, geographic representation, mechanistic understanding, and the socioeconomic feasibility of field implementation. Identifying and addressing these gaps is essential for refining best practices and maximizing the sustainability of these amendments across diverse agroecological systems.

Long-Term Effects

A persistent limitation in the current literature is the predominance of short-duration studies, typically lasting one or two cropping seasons (Jeffery *et al*., 2021; Fang *et al*., 2023) [224, 54]. Such designs fail to capture the temporal evolution of soil properties and amendment aging effects, particularly those related to biochar stability and nutrient cycling under field conditions (Agegnehu *et al*., 2023) [6]. The slow-release nature of biochar implies that its full benefits may only materialize over extended periods. Moreover, the cumulative impacts of repeated applications, residue accumulation, and interactions with fluctuating environmental variables remain underexplored. Long-term field trials, ideally spanning 5 to 10 years, are urgently needed to validate and quantify these effects and to inform models of soil carbon sequestration and nutrient-use efficiency (Zavattaro *et al*., 2022; Jeffery *et al*., 2023) [219, 83].

Tropical and Degraded Soils

Another notable gap is the limited research focus on tropical and degraded soils, which are among the most responsive yet underrepresented in amendment studies (Agyei-Baffour *et al*., 2021) [7]. These soils often exhibit low cation exchange capacity, acidic pH, and poor water retention conditions under which biochar-organic amendment combinations have shown pronounced positive outcomes

(Zhang *et al*., 2021) [222]. However, most experimental work has concentrated on temperate climates and fertile soils, limiting the transferability of findings. Future research should prioritize degraded agroecosystems, including tropical Acrisols and Ferralsols, where improvements in soil fertility can yield disproportionately high productivity gains. Furthermore, tailored recommendations for soil types with contrasting mineralogy, salinity, and erosion risk profiles are lacking and should be developed through region-specific trials (Agegnehu *et al*., 2023) [6].

Microbial and Rhizosphere Dynamics

While the synergistic effects of biochar and organic amendments on soil chemistry are relatively well-documented, the biological underpinnings particularly in the rhizosphere remain insufficiently understood. Microbial community structure, functional gene expression, and plant-microbe interactions are rarely explored using modern molecular tools such as metagenomics, transcriptomics, and isotopic tracing (Liang *et al*., 2021; Elsas *et al*., n.d.) [115, 51, 154]. These approaches can elucidate mechanisms such as nitrogen fixation, phosphorus solubilization, and pathogen suppression in amended soils. Understanding these processes at the root-soil interface is vital to optimize amendment strategies that support beneficial microbiota and plant resilience. Moreover, microbial feedback loops under repeated or long-term applications remain poorly characterized, raising questions about ecosystem stability and sustainability (Li *et al*., 2023) [112].

Scaling and Socioeconomic Aspects

Despite promising agronomic results, widespread adoption of biochar-organic amendment technologies remains limited due to cost, logistical, and knowledge barriers (Nepal *et al*., 2023) [141]. Biochar production is often capital-intensive and requires technical expertise, while the large volumes of organic amendments needed pose storage and transport challenges for smallholder farmers (Palm-Forster *et al*., 2019) [151]. Socioeconomic studies on cost-benefit ratios, labor requirements, and return on investment under real-world farming conditions are sparse. Additionally, farmer perceptions, awareness levels, and willingness to adopt these practices are not systematically documented, especially in the Global South. Behavioral research, participatory trials, and co-designed decision support tools are essential to bridge the gap between scientific potential and practical application. A systems-level approach incorporating economic, cultural, and institutional dimensions will be critical to scale these innovations sustainably (Virgolino *et al*., 2021) [205].

Conclusion

The integration of biochar and organic amendments has emerged as a promising approach to sustainable soil management, offering synergistic benefits that consistently outperform the use of single amendments. Evidence from diverse studies demonstrates that co-application enhances soil chemical properties by improving pH buffering capacity, cation exchange capacity, and nutrient retention, resulting in reduced nitrogen leaching and increased phosphorus availability across a variety of soil types. Improvements in soil physical structure, such as enhanced aggregation and greater moisture retention, further contribute to the resilience of amended soils against erosion and drought stress. These chemical and physical enhancements are complemented by marked increases in biological activity, including elevated microbial biomass and greater functional diversity, which facilitate more efficient nutrient cycling and improved plant health.

The agronomic advantages of such synergies are reflected in significant yield gains, with increases ranging from 20% to 85% in various crops, particularly in degraded tropical soils where limitations in soil fertility are most acute. Beyond productivity, the combination of biochar and organic amendments offers long-term environmental benefits, notably in carbon sequestration and greenhouse gas mitigation, with biochar providing stable carbon storage and reducing nitrous oxide emissions. Furthermore, the use of agricultural residues for amendment production promotes circular resource use, lowering waste streams and reducing input costs, while improved soil water dynamics and nutrient buffering enhance climate resilience.

Despite these demonstrated benefits, the effectiveness of biochar-organic amendment systems remains context-dependent, with outcomes influenced by soil type, climate, crop species, and management practices. The full potential of this approach can only be realized through targeted application strategies that match amendment characteristics to specific soil constraints. Long-term monitoring, standardized production protocols, and regionally adapted field trials are critical to advancing understanding and ensuring consistent results. Equally important are socioeconomic considerations, including cost-effectiveness, logistical feasibility, and farmer adoption, which will determine the scalability and practical implementation of these practices. By aligning agronomic, environmental, and socioeconomic priorities, the synergistic use of biochar and organic amendments can play a transformative role in restoring degraded soils, enhancing agricultural productivity, and contributing to global food security under changing climatic conditions.

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