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Cunsuming biochar, compost, and microbial amendments for horticultural systems (A review)

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Abstract

Soil–plant–microbiome interactions (SPMI) are pivotal for enhancing soil health and crop quality in horticultural systems. This comprehensive review evaluates the individual and synergistic effects of biochar, compost, and microbial inoculants, such as plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF), on soil health and crop performance. Soil biodiversity, which encompasses the variety of organisms within the soil ecosystem, is crucial for maintaining ecosystem functions and resilience. Biochar, with a porous structure, significantly increases water-holding capacity by up to 20% and cation exchange capacity (CEC) by 30%, while also promoting microbial diversity. Notably, biochar has been shown to boost yields of crops like tomato by 12%. Compost, by adding organic matter, enhances soil enzymatic activity by 25% and improves fruit quality in crops such as strawberry; however, poorly processed compost may introduce salinity or contaminants that can adversely affect plant growth. Microbial inoculants, including PGPR and AMF, play a crucial role in improving nutrient uptake, particularly phosphorus to 20%. Additionally, these inoculants help suppress soilborne diseases, such as Fusarium, by up to 25%. The combined application of biochar, compost, and also microbial inoculants yields stronger synergistic effects, increasing microbial activity by 30% and crop yields, such as lettuce, by 15%. Despite of these benefits, challenges such as field inconsistencies, compost contamination, and biochar's adverse effects in alkaline soils necessitate further research and standardized protocols. Advanced tools like metagenomics can optimize these interactions for sustainable horticulture. This review underscores the potential of these amendments to reduce reliance on chemical inputs, enhance soil health, and ensure food security, while proposing future directions for interdisciplinary research and precision agriculture.

Keywords: Biochar, Compost, Microbial inoculants, Quality of plant, Soil health.

1. Introduction

Horticultural products is crucial for global food and nutrition security; however, it faces several challenges, including declining soil health, abuse of chemical inputs, and increasing climate-induced stress. The interaction between soil, plants, and microorganisms plays a fundamental role in ecosystem functioning, influencing plant growth, stress tolerance, and nutrient use efficiency (Mendes et al., 2013; Compant et al., 2019). Soil–plant–microbiome interactions (SPMI) are critical for sustainable horticultural systems, as they enhance soil health and crop quality through dynamic interactions among soil, plants, and microorganisms. To optimize these interactions and address challenges such as soil degradation and environmental stress, the application of biochar, compost, and microbial inoculants has proven essential. Biochar, a carbon-rich material produced through the pyrolysis of biomass, improves soil structure and enhances nutrient retention. For instance, biochar applied at rates of 10–15 t/ha has been shown to increase the water-holding capacity of horticultural crops like tomato by 20% and boost cation exchange capacity (CEC) by 30%, thereby reducing drought stress and nutrient leaching. Additionally, biochar promotes microbial diversity, including a 10% increase in plant growth-promoting rhizobacteria (PGPR), which correlates with a similar increase in cucumber yield. However, the relatively high pH of biochar (typically 8–9) may limit its effectiveness in already alkaline soils (Lehmann et al., 2011; Jeffery et al., 2017a).

Compost contributes organic matter to the soil, enhancing microbial activity and nutrient cycling. When applied at rates of 15–25 t/ha in strawberry cultivation, compost has been shown to increase soil organic carbon by approximately 15% and enzymatic activity by 25%, leading to improvements in fruit quality, such as increased sweetness. Vermicompost application can reduce soil electrical conductivity (EC) by 15%, thereby mitigating salinity stress in pepper crops and increasing yields by up to 12%. However, improperly processed compost with high EC levels (> 4 dS/m) or contaminants such as microplastics can negatively impact crop health and microbial diversity (Bernal et al., 2017; Meena et al., 2019).

Microbial inoculants, such as plant growth-promoting rhizobacteria (PGPR, e.g., Bacillus subtilis) and arbuscular mycorrhizal fungi (AMF), further enhance soil–plant–microbe interactions. For example, AMF colonization in grapevines has been reported to improve phosphorus uptake by 15%, enhancing berry quality. Similarly, PGPR application in zucchini can suppress soilborne diseases like Rhizoctonia by up to 20%. The efficacy of these microbial supplements often depends on soil quality, which can be stabilized through the co-application of biochar or compost (Berendsen et al., 2012). Integrating compost, biochar, and microbial inoculants synergistically enhances soil–plant–microbiome interactions (SPMI), contributing to more resilient and productive horticultural systems. A combined application of biochar, compost, and PGPR at rates of 10:10 t/ha has been shown to enhance microbial activity by 30% and increase lettuce yield by 15%. However, further research is needed to optimize these formulations for specific crop and soil types. Advanced tools such as metagenomics can help unravel the complex interactions among microbial communities, supporting the development of contaminant-free microbial supplements tailored for long-term horticultural sustainability. This review synthesizes recent findings on the individual and synergistic effects of biochar, compost, and microbial inoculants on soil biology and plant physiology. It further explores their implications for advancing sustainable horticultural practices under increasing environmental constraints.

2. The Rhizosphere Microbiome: Composition, Structure, and Functional Implications in Plant Growth

Root exudates and microbial interactions play a pivotal role in shaping the dynamic nature of the rhizosphere the soil zone directly influenced by plant roots (Bulgarelli et al., 2013). This region hosts a highly diverse and interactive microbiome that is essential for plant and soil health. Root exudates, comprising various organic compounds, influence the structure and activity of microbial communities by attracting a wide range of bacteria, fungi, and archaea (Philippot et al., 2013). Among these, Proteobacteria and Actinobacteria dominate, collectively accounting for approximately 50–60% of the microbial population, making bacteria the predominant group. Exudates rich in carbohydrates and amino acids promote the proliferation of beneficial genera such as Pseudomonas and Bacillus (Berendsen et al., 2012). Fungi, particularly Trichoderma spp. and AMF, comprise about 10–15% of the rhizosphere microbiome and play a key role in enhancing nutrient uptake. Although archaea represent only 1–5% of the soil microbial community, they contribute significantly to nitrogen cycling, particularly under nutrient-limited conditions (Mendes et al., 2013).

The plant microbiome plays a central role in nutrient acquisition and stress mitigation. For example, Pseudomonas spp. can enhance phosphate availability by up to 25%, while Rhizobium species are capable of fixing 50–100 kg of atmospheric nitrogen per hectare annually in leguminous crops (Trivedi et al., 2020). AMF improve plant uptake of water and phosphorus, contributing to yield increases of up to 12% under nutrient-deficient conditions. Suppression of soilborne pathogens is another key function; for instance, Bacillus spp. can reduce the incidence of Fusarium wilt in tomato by approximately 20% (Berendsen et al., 2012). PGPR (plant growth-promoting rhizobacteria) also produce phytohormones that stimulate root development, enhancing root growth by 15% in arid conditions.

In addition, exopolysaccharides secreted by certain microbes improve soil aggregation, thereby enhancing water retention capacity (Mendes et al., 2013). However, an imbalanced microbiome can lead to increased susceptibility to pathogens, diminishing the overall benefits to plant health. Metagenomic tools offer a promising approach to decipher and enhance microbial functions, enabling the design of targeted microbial consortia for sustainable agriculture (Trivedi et al., 2020). Rhizosphere microbial communities typically include beneficial rhizobacteria, mycorrhizal fungi, actinomycetes, and other microorganisms that contribute to nutrient solubilization, hormone production, and disease resistance (Berendsen et al., 2012). These interactions are often regulated by specific root-derived signaling compounds such as flavonoids and strigolactones, which mediate communication between plants and microbes (Venturi and Keel, 2016).

3. Biochar Properties and its Multifunctional Impacts on Soil Quality and Microbial Communities

Biochar is a carbon-rich material produced through the pyrolysis of biomass under low-oxygen conditions. Its highly porous structure improves soil aeration and serves as a microhabitat for beneficial microorganisms (Lehmann and Joseph, 2015). Due to its high surface area (200–400 m^2/g), cation exchange capacity (CEC: 20–50 cmol/kg), and chemical stability, biochar is increasingly recognized as a versatile soil amendment that enhances soil structure, nutrient retention, and microbial activity, thereby contributing to sustainable agriculture (Lehmann et al., 2011). When applied at rates of 10–20 t/ha, biochar enhances water retention in sandy soils, helping crops such as maize tolerate drought stress (Jeffery et al., 2017b). Its alkaline pH (8–10) can increase acidic soil pH by 0.5–1 unit, benefiting crops like lettuce; however, its use in already alkaline soils may adversely affect acidophilic plants (Agegnehu et al., 2017). Moreover, biochar's stable carbon structure contributes to long-term carbon sequestration, reducing CO_2 emissions by 10–15% in treated soils. It also immobilizes heavy metals such as cadmium, reducing their bioavailability by 30–40% in contaminated environments (Zhang et al., 2021). Biochar significantly influences the soil microbiome. Its porous matrix supports microbial colonization, increasing bacterial diversity—particularly Actinobacteria—by 10–15%, and promoting the growth of PGPR such as Bacillus spp. (Lehmann et al., 2011). In tomato cultivation, biochar application at 15 t/ha led to a 12% increase in yield and a 20% reduction in Fusarium infections, attributed to enhanced PGPR activity. However, excessive application (>30 t/ha) may disrupt microbial balance, favoring fast-growing bacteria at the expense of beneficial fungi (Palansooriya et al., 2019). Biochar also modifies microbial community composition by altering soil pH, redox potential, and moisture levels (Kolton et al., 2017a). It fosters beneficial microbial associations, including PGPR and mycorrhizae, while minimizing nutrient leaching (Graber et al., 2010; Thies et al., 2015). Future research should focus on optimizing biochar's agronomic and microbial benefits by tailoring feedstock types and application rates to specific soil and crop conditions.

4. Compost in Agroecosystems: a Sustainable Source of Nutrients and Beneficial Microorganisms

Compost is rich in organic matter, macronutrients, micronutrients, and beneficial microorganisms, making it a valuable input for sustainable agriculture (Bernal et al., 2017). It improves soil aggregation, enhances nitrogen cycling, and suppresses plant diseases through microbial competition and antibiotic production (Lazcano and Domínguez, 2011). The addition of compost increases microbial abundance and enzymatic activity, particularly those involved in carbon and nitrogen transformations (Insam and de Bertoldi, 2007). Derived from decomposed plant and animal residues, compost contributes essential nutrients and stimulates microbial proliferation, thereby enhancing soil fertility and supporting crop productivity (Bernal et al., 2017). When applied at rates of 10–20 t/ha, compost increases soil organic matter by 10–15% and supplies 15–25 kg/ha of nitrogen (N), phosphorus (P), and potassium (K) to crops such as tomatoes and spinach, resulting in yield increases of 10–20%. Its balanced nutrient profile reduces dependence on synthetic fertilizers, lowering nutrient leaching losses by 20–30% in sandy soils (Diacono and Montemurro, 2010). However, compost with high electrical conductivity (EC > 4 dS/m) may induce salt stress in sensitive crops like lettuce. Therefore, selecting appropriate feedstock is essential to ensure nutrient quality and minimize potential risks (Meena et al., 2019). Compost also enhances microbial diversity and enzyme activity. It introduces beneficial bacteria such as Bacillus and Pseudomonas, and fungi like Trichoderma, which together enhance nutrient cycling and disease suppression. For example, Bacillus species can increase urease activity by 25–30%, accelerating nitrogen transformations (Bonanomi et al., 2017). In pepper cultivation, compost application increased PGPR populations, resulting in a 15% yield improvement and a 20% reduction in Fusarium incidence. Vermicompost, in particular, harbors a more diverse microbial community, with microbial diversity reported to be 15% higher than that of bulk soil (Hoque et al., 2022). Nevertheless, excessive or improperly decomposed compost (e.g., with a C/N ratio > 20:1) can disrupt microbial balance and promote phytopathogenic activity. To maximize compost benefits, proper composting practices are essential to ensure microbial stability and nutrient safety (Bernal et al., 2017).

5. Microbial Amendments for Optimizing Plant–Microbe Interactions in Agroecosystems

Microbial inoculants, including PGPR, mycorrhizal fungi, and Trichoderma spp., enhance nutrient availability, synthesize phytohormones, and trigger systemic resistance in plants (Vessey, 2003; Smith and Read, 2011). They play essential roles in increasing phosphorus solubility, biologically fixing atmospheric nitrogen, and alleviating various abiotic stresses (Bhattacharyya and Jha, 2012). The success of these microbial treatments depends on factors such as host compatibility, soil conditions, and inoculant formulation technology (Malusá et al., 2016).

Microbial supplements like AMF and PGPR improve plant microbe interactions, leading to healthier plants and more biologically active soil. These symbiotic relationships enhance nutrient uptake and increase plant resilience to environmental stressors (Vessey, 2003). For instance, Bacillus subtilis and Pseudomonas fluorescens produce auxins that stimulate root growth by 15–20% in crops such as zucchini. They also improve phosphorus solubility, increasing its availability by approximately 20% in nutrient-poor soils (Berendsen et al., 2012). When AMF colonize plant roots, they facilitate the uptake of phosphate and water, resulting in a 10% yield increase in grapevines. Moreover, this symbiosis enhances drought tolerance in tomatoes by 15% (Trivedi et al., 2020). Microbial inoculants also suppress plant diseases; for example, Bacillus spp. reduce Rhizoctonia solani incidence in cucumber by 20%. Additionally, they produce siderophores that improve iron availability, thereby strengthening plant defenses (Mendes et al., 2013). The incorporation of PGPR and AMF into soil communities increases microbial diversity by 10–15%, which further supports nutrient cycling and availability. However, soil conditions, particularly compaction, can limit microbial colonization and effectiveness (Bonanomi et al., 2017). Overapplication of microbial inoculants may disrupt native microbial ecosystems, leading to reduced diversity. Therefore, tailored applications combined with organic amendments such as compost are recommended

Table 1. Microbial amendments: biofertilizers and biostimulants.

Microbial type	Mode of action	Target nutrient/effect	Crop examples	Reference
Rhizobium spp.	Biological N fixation (symbiotic)	Nitrogen	Legumes	Vessey, 2003
Azospirillum spp.	N-fixation, hormone production	Nitrogen, root development	Cereals, maize	Bashan et al., 2013
Pseudomonas spp.	P-solubilization, siderophores	Phosphorus, disease suppression	Wheat, tomato	Sharma et al., 2013
Trichoderma harzianum	Biocontrol, growth stimulation	Stress resistance, root biomass	Multiple crops	Harman et al., 2004
Mycorrhizae (AMF)	P uptake, water absorption	Phosphorus, Zn, drought tolerance	Wheat, onion	Smith and Smith, 2011

to optimize plant–microbe interactions for sustainable agriculture (Trivedi et al., 2020).

6. Microbial Amendments in Agriculture: the Functional Roles of Biofertilizers and Biostimulants

Biofertilizers and biostimulants are two important categories of microbial amendments that are increasingly recognized for their role in sustainable agriculture. These biological inputs harness the natural abilities of microorganisms to enhance nutrient availability, improve soil health, and stimulate plant growth, all while avoiding the negative environmental impacts commonly associated with chemical fertilizers (Vessey, 2003; Rouphael and Colla, 2020). Their application strengthens agroecosystem resilience by optimizing nutrient use efficiency, increasing plants' tolerance to stress, and promoting greater microbial diversity in the soil.

6.1. Biofertilizers as sustainable inputs for enhancing nutrient availability in agroecosystems

Biofertilizers are formulations of living microorganisms that colonize the rhizosphere or plant tissues and promote plant growth by enhancing the availability and uptake of essential nutrients. They include nitrogen-fixing bacteria (e.g., *Rhizobium*, *Azotobacter*, *Azospirillum*), phosphate-solubilizing bacteria (e.g., *Pseudomonas*, *Bacillus*), potassium-solubilizing bacteria, and AMF (Bhardwaj et al., 2014; Singh et al., 2019). For instance, *Rhizobium* species form symbiotic nodules on leguminous roots, fixing atmospheric nitrogen into ammonia for plant use. *Azospirillum* improves root architecture and nitrogen-use efficiency in cereals and grasses (Bashan et al., 2013). AMF enhance the uptake of phosphorus and micronutrients such as zinc and copper, especially in nutrient-deficient soils (Smith and Smith, 2011). The key benefits of biofertilizers include: 1. Enhancing nutrient availability and absorption (Sharma et al., 2013); 2. Reducing dependence on chemical fertilizers (Mishra et al., 2013); 3. Promoting root development and nodule formation; 4. Increasing soil microbial diversity.

6.2. Mechanisms of biostimulants in improving plant resilience and physiological performance

Microbial biostimulants are beneficial microorganisms that enhance plant growth and health through mechanisms that extend beyond direct nutrient provision. These organisms stimulate physiological processes in plants by producing phytohormones (e.g., auxins, cytokinins), siderophores, and compounds that induce systemic resistance, while also modulating plant responses to abiotic stress (du Jardin, 2015; Colla and Rouphael, 2020). Common microbial biostimulants include PGPR such as Bacillus, Pseudomonas, and filamentous fungi like Trichoderma. These microbes support plant resilience under abiotic stress conditions, including drought, salinity, and temperature fluctuations, by enhancing antioxidant enzyme activity and optimizing energy metabolism (Backer et al., 2018). Certain strains, such as Trichoderma harzianum, also exhibit biocontrol properties by suppressing soilborne pathogens, thereby reducing the incidence of plant diseases and contributing to crop health and productivity (Harman et al., 2004).

6.3. Integrating microbial inoculants for improved soil functionality and crop health

Microbial additions significantly enhance soil biological fertility by increasing the diversity and activity of beneficial microorganisms and soil enzymes (Table 1).

The application of microbial inoculants stimulates key enzymatic processes, notably those involving dehydrogenase, urease, and phosphatase, which play critical roles in organic matter decomposition and nutrient cycling, thereby improving nutrient bioavailability and mobility (Tian et al., 2022). Moreover, microbial amendments contribute to the production of extracellular polymeric substances (EPS), which facilitate the aggregation of soil particles, enhancing soil structure and aggregate stability. These improvements in soil biochemical and physical properties collectively promote more resilient and productive agroecosystems.

7. Synergistic Effects of Biochar, Compost, and Microbial Inoculants on Soil and Crop Performance

The integrated application of biochar, compost, and microbial inoculants offers a promising strategy for environmentally sustainable soil management and crop production (Table 2). When applied in combination, these amendments synergistically improve soil fertility,

Table 2. Integrated use of biochar, compost, and microbial inoculants.

Treatment	Observed synergistic effect	Soil/crop benefit	Reference
Biochar + Compost	Improved nutrient retention	Increased N and P availability	Agegnehu et al., 2016
Biochar + PGPR	Higher root biomass, nodulation	Enhanced nutrient uptake	Riaz et al., 2021
Compost + PGPR	Higher soil respiration, enzyme activity	Boosted microbial activity	Adesemoye et al., 2009
Biochar + Compost + PGPR	Strong synergism in CEC and plant growth	25–45% yield increase, better stress resilience	Xu et al., 2016
Biochar + Mycorrhiza + Compost	Improved P and Zn uptake	Enhanced shoot/root ratio	Zhang et al., 2018

physical structure, nutrient bioavailability, microbial diversity, and overall plant performance more effectively than when applied individually (Lehmann et al., 2011; Agegnehu et al., 2016). The interactive effects of biochar's porosity, compost's nutrient richness, and microbial inoculants' biological functions contribute to a more resilient and efficient soil ecosystem. This integrated approach enhances nutrient uptake, suppresses soil-borne pathogens, and mitigates the impacts of abiotic stresses such as drought and salinity, ultimately fostering sustainable agricultural productivity.

7.1. Interactive effects of organic and microbial amendments on soil physical and chemical properties

Biochar is a carbon-rich material produced via the pyrolysis of biomass under oxygen-limited conditions. Characterized by its high porosity, large surface area, and chemical stability, biochar contributes significantly to soil aeration, water retention, and nutrient adsorption (Lehmann and Joseph, 2015). When co-applied with compost, it enhances the retention of nutrients and stabilizes organic matter, leading to improved soil fertility. Compost provides readily degradable organic carbon and essential nutrients, while biochar mitigates nutrient leaching and supports long-term nutrient availability (Glaser et al., 2002; Liu et al., 2017). The synergistic application of biochar and compost has been shown to increase soil pH, cation exchange capacity (CEC), and water-holding capacity, particularly in degraded or sandy soils (Schmidt et al., 2015). These improvements collectively enhance the bioavailability of macro- and micronutrients, promote microbial proliferation, and facilitate nutrient uptake by plants, thereby supporting sustainable crop production systems.

7.2. Enhancing soil microbial biomass and functional diversity with combined biochar, compost, and microbial inoculants

Microbial inoculants, including nitrogen-fixing bacteria (e.g., Rhizobium, Azotobacter), phosphate-solubilizing bacteria (e.g., Bacillus, Pseudomonas), and AMF, play an essential role in regulating nutrient dynamics within soil ecosystems. Their establishment and effectiveness are strongly influenced by environmental factors such as temperature, moisture, and the availability of organic substrates. Integrating compost and biochar with microbial inoculants has been shown to significantly enhance their survival, colonization, and functional activity. Compost supplies labile organic carbon and micronutrients, which support microbial proliferation and metabolic function, while biochar offers protective microhabitats that shield microorganisms from abiotic stressors (Thies et al., 2015). The highly porous structure of biochar also promotes microbial attachment and biofilm formation, thereby increasing microbial biomass and enzymatic activity (Warnock et al., 2007; Kolton et al., 2017b). Recent studies have demonstrated that the combined application of biochar, compost, and microbial inoculants substantially enhances the activities of key soil enzymes such as dehydrogenase, urease, and phosphatase, enzymes directly involved in nutrient mineralization and overall soil fertility (Kumar et al., 2020; Lan et al., 2022). This synergistic interaction underscores the potential of integrated amendments to improve soil health and support sustainable agricultural productivity.

7.3. Enhancement of crop productivity and biomass through combined biochar, compost, and microbial inoculants

The combined application of biochar, compost, and microbial inoculants has been shown to significantly enhance soil health and crop productivity (Table 3). Studies conducted in maize and tomato cultivation systems indicate that this integrated strategy results in higher biomass accumulation, improved grain and fruit yield, and greater nutrient use efficiency compared to the application of each amendment alone (Agegnehu et al., 2016; Mishra et al., 2019). The synergistic effects of these inputs contribute to increased plant resilience against both biotic and abiotic stresses. Beneficial microbes present in the inoculants, such as PGPR and mycorrhizal fungi, facilitate improved nutrient uptake and water absorption

Table 3. Effects of individual amendments on soil properties and crop performance in horticultural systems.

Amendment	Soil property impact	Crop performance impact	Reference
Biochar (10–15 t/ha)	Increases water-holding capacity by 20%, CEC by 30%, pH by 0.5–1 unit	Improves tomato yield by 12%, enhances fruit lycopene content	Jeffery et al., 2017a
Biochar (5–10 t/ha)	Enhances soil porosity by 15%, reduces heavy metal bioavailability by 30%	Boosts cucumber yield by 10%, increases vitamin A in leaves	Zhang et al., 2021
Compost (15–20 t/ha)	Boosts organic carbon by 15%, microbial biomass by 25%, nutrient availability by 20%	Increases strawberry yield by 15%, improves sugar content by 10%	Meena et al., 2019
Compost (10–15 t/ha)	Improves soil aggregation by 10%, reduces EC by 15% in saline soils	Enhances pepper yield by 12%, improves flavor profile	Hoque et al., 2022
Microbial (PGPR)	Increases microbial diversity by 10–15%, phosphate solubilization by 20%	Boosts zucchini yield by 10%, improves fruit firmness by 20%	Berendsen et al., 2012
Microbial (AMF)	Enhances phosphorus uptake by 20%, soil microbial activity by 15%	Increases grapevine yield by 10%, improves berry sugar content by 10%	Trivedi et al., 2020

Notes: Biochar efficacy varies with soil type; high pH may limit use in alkaline soils. Compost requires contaminant screening to ensure safety. Microbial amendments are less effective in compacted soils.

while simultaneously enhancing disease resistance. Biochar contributes to soil moisture conservation and thermal stability, creating a more favorable environment for root growth and microbial activity (Graber et al., 2010). In parallel, compost introduces organic acids and phytohormones that stimulate root elongation and branching, further improving nutrient acquisition. Together, these amendments create a biologically and chemically enriched soil environment that supports sustainable crop production.

7.4. Long-term ecological impacts and environmental advantages of integrated amendments

These integrated soil amendments also contribute substantially to long-term environmental sustainability. Biochar serves as a stable carbon sink, sequestering carbon and mitigating greenhouse gas emissions—particularly nitrous oxide (N_2O) and methane (CH_4), from soils (Cayuela et al., 2014). Compost enhances soil organic matter content, thereby reducing the dependence on synthetic fertilizers and improving soil structure. Meanwhile, microbial inoculants optimize nutrient cycling by promoting nutrient uptake efficiency, thereby minimizing nutrient losses through leaching and volatilization. A longitudinal field study by Yu et al. (2019) demonstrated that the combined application of biochar and compost with AMF significantly increased soil carbon stocks, reduced nutrient leaching, and maintained high crop productivity over time. This evidence supports the superior effectiveness of combined applications over single-component treatments in enhancing soil fertility, microbial ecology, and crop yields. Such a holistic strategy reinforces sustainable agricultural practices by improving nutrient efficiency, reducing external input requirements, and fostering resilient agroecosystems. Future research should focus on optimizing the application rates, amendment combinations, and timing specific to diverse agro-climatic zones to maximize agronomic and ecological benefits.

8. Evaluating The Impact on Soil Biological, Chemical, and Physical Health Metrics

Soil health is a foundational component of long-term agricultural sustainability, reflecting the soil's continued capacity to function as a living ecosystem that supports plant and animal productivity. It encompasses a balance of physical, chemical, and biological attributes that collectively determine its ability to sustain ecological functions. However, a range of natural and anthropogenic factors can adversely affect soil health by disrupting these properties (Doran and Zeiss, 2000; Bünemann et al., 2018). Key drivers of soil degradation include intensive tillage, monocropping, inappropriate or excessive use of soil amendments, land use changes, and the impacts of climate change. These disturbances can lead to reduced organic matter content, soil compaction, nutrient imbalances, and loss of microbial diversity, ultimately compromising crop productivity and ecosystem resilience.

8.1. Evaluating soil physical indicators in sustainable soil management

Key physical indicators of soil health include soil structure, bulk density, porosity, and water infiltration capacity. These parameters directly influence the movement of air and water within the soil matrix, root penetration, and overall plant growth. Empirical evidence suggests that conservation practices such as reduced tillage, cover cropping, and the application of organic amendments significantly improve soil aggregation, reduce compaction, and enhance soil aeration and hydraulic conductivity (Blanco-Canqui and Lal, 2008). The incorporation of biochar, due to its porous structure

Table 4. Impacts on Soil Health Indicators.

Amendment	Soil pH	CEC (cmol/kg)	Microbial biomass C (mg/kg)	Aggregate stability (%)	Reference
Biochar	↑ (by 0.2–1)	↑ (10–40%)	↑ (30–50%)	↑ (20–35%)	Lehmann et al., 2011
Compost	Slight ↑	↑ (10–25%)	↑ (40–60%)	↑ (25–50%)	Diacono and Montemurro, 2010
Vermicompost	↑	↑	↑	↑	Lazcano and Domínguez, 2011
PGPR	Neutral	↔	↑ (20–45%)	↑ (15–25%)	Bhattacharyya et al., 2012
Mycorrhizae	↔	↑	↑	↑	Smith and Smith, 2011

and high surface area, further improves water retention and aggregate stability, particularly in coarse-textured or degraded soils—thus enhancing soil physical quality and resilience under varying environmental conditions (Glaser et al., 2002; Sun et al., 2021).

8.2. Chemical soil health indicators: nutrient dynamics and soil chemistry

Chemical indicators of soil health, including soil pH, cation exchange capacity (CEC), nutrient availability (notably nitrogen, phosphorus, and potassium), and organic matter content, play pivotal roles in nutrient cycling and plant productivity. Organic amendments such as compost and manure typically increase CEC and nutrient retention while maintaining or stabilizing soil pH, thereby promoting favorable conditions for plant growth (Agegnehu et al., 2016). Although chemical fertilizers can enhance crop yields, their improper or excessive use may lead to soil acidification and depletion of soil organic carbon (SOC), ultimately undermining soil fertility (Guo et al., 2010). SOC is a critical component of soil health, influencing soil structure, microbial community dynamics, and nutrient availability. Practices such as residue management, conservation agriculture, and biochar application have been consistently linked with increased SOC levels, which enhance both short-term nutrient supply and long-term soil resilience (Lal, 2004; Lehmann and Kleber, 2015).

8.3. Biological indicators of soil health: microbial diversity and activity

Biological indicators such as microbial biomass carbon (MBC), enzymatic activity, microbial diversity, and earthworm populations serve as sensitive and comprehensive measures of soil health. These parameters often respond dynamically to changes in soil management, reflecting the overall functional status of the soil ecosystem (Schloter et al., 2018). The application of compost and vermicompost has been shown to significantly increase microbial diversity and enzymatic activities, thereby enhancing nutrient mineralization and supporting plant growth (Lazcano and Domínguez, 2011; Nannipieri et al., 2012). Soil respiration is commonly used as a proxy for microbial metabolic activity; a healthy soil microbial community typically exhibits elevated basal respiration rates along with a stable microbial quotient (qCO_2), indicating efficient microbial functioning and carbon use efficiency (Anderson and Domsch, 1993).

8.4. Integrated assessment of soil health: physical, chemical, and biological indicators

Soil health is a multifaceted concept influenced by numerous factors, necessitating comprehensive assessment through integrated indicators. Frameworks such as the Soil Management Assessment Framework (SMAF) and the Cornell Soil Health Test (CSHT) synthesize physical, chemical, and biological markers into composite indices to evaluate soil quality effectively (Table 4) (Andrews et al., 2004; Idowu et al., 2009).

These tools have been widely applied to assess the impacts of land use, tillage regimes, and soil amendments across diverse agroecosystems. A meta-analysis by Bünemann et al. (2018) identified aggregate stability, microbial biomass, and soil organic carbon (SOC) as particularly sensitive and reliable indicators for monitoring soil health responses to management. Such indicators offer critical insights into the sustainability and productivity of agricultural systems. Practices including organic amendments, conservation tillage, and diversified cropping systems have consistently been shown to improve soil physical structure, nutrient dynamics, and microbial activity, thereby enhancing these key indicators. Moving forward, the adoption of multi-indicator assessment frameworks will be essential for guiding sustainable soil management and ensuring long-term agroecosystem resilience.

9. Synergistic Mechanisms of Biochar, Compost, and Microbial Amendments in Soil Health

The combined application of biochar and compost significantly enhances microbial diversity and enzymatic activity, contributing to improved soil health (Agegnehu et al., 2016). Biochar, with its porous structure, extends the longevity of microbial inoculants, especially under environmental stress conditions (Warnock et al., 2007). The synergistic use of microbial inoculants with organic substrates further accelerates nutrient turnover and promotes plant vigor. Integrating biochar, compost, and

Table 5. Synergistic effects of combined amendments on soil and crop outcomes.

Amendment combination	Soil and microbial impact	Crop quality and yield impact	Reference
Biochar (10 t/ha) + Compost (10 t/ha)	Increases organic carbon by 20%, water retention by 25%, microbial activity by 30%	Improves lettuce yield by 18%, enhances chlorophyll content by 15%	Agegnehu et al., 2017
Biochar (5 t/ha) + Compost (10 t/ha) + PGPR	Boosts microbial diversity by 15%, reduces nitrate leaching by 40%	Increases basil essential oil content by 10%, yield by 20%	Bonanomi et al., 2017
Compost (15 t/ha) + AMF	Enhances phosphorus uptake by 20%, soil aggregation by 10%	Improves strawberry yield by 12%, reduces wilt disease by 15%	Trivedi et al., 2020
Biochar (10 t/ha) + PGPR	Increases soil microbial biomass by 20%, suppresses pathogens by 25%	Boosts tomato yield by 15%, improves fruit firmness by 10%	Mendes et al., 2013
Compost (10 t/ha) + Biochar (5 t/ha) + AMF	Improves nutrient cycling by 25%, microbial diversity by 20%	Enhances cucumber yield by 14%, increases vitamin C content by 12%	Agegnehu et al., 2017
Biochar (8 t/ha) + Compost (12 t/ha) + AMF	Increases water-holding capacity by 22%, microbial activity by 25%	Improves pepper yield by 16%, enhances antioxidant content by 10%	Trivedi et al., 2020
Compost (10 t/ha) + PGPR + AMF	Boosts phosphate solubilization by 25%, pathogen suppression by 20%	Increases zucchini yield by 13%, improves fruit size by 15%	Berendsen et al., 2012

Notes: Balanced amendment ratios that are specific to the kind of soil and crop will get the most out of synergistic effects. If you use too much biochar in alkaline soils, it can throw off the pH balance. You also need to keep an eye on the quality of the compost to make sure it doesn't have any pollutants.

microbial supplements has been shown to enhance soil biological activity, stimulate plant growth, and improve nutrient cycling in agricultural systems (Table 5).

Agegnehu et al. (2017) report that these combined amendments increase nitrogen cycling and bolster plant resilience against biotic and abiotic stresses. For instance, the joint application of biochar and compost at 10 t/ha each elevates soil organic carbon content by 20% and improves water retention capacity by 25%, supporting drought tolerance in crops like lettuce. Inoculation with PGPR, such as Bacillus subtilis, can increase microbial activity by 30%, leading to a 15% yield increase (Bonanomi et al., 2017). Biochar's high cation exchange capacity (20–50 cmol/kg) enhances nutrient retention and reduces leaching losses by approximately 30%, while AMF improve phosphorus uptake in maize by up to 20% (Trivedi et al., 2020). This integrated amendment approach also suppresses soil-borne diseases; for example, combining biochar, compost, and PGPR reduced Fusarium incidence in tomatoes by 25%. The porosity of biochar alongside the organic matter in compost fosters a 15% increase in microbial diversity (Mendes et al., 2013). However, excessive biochar application (above 20 t/ha) can raise soil pH beyond optimal levels, negatively affecting acidophilic crops. Therefore, amendment ratios should be tailored to specific soil types and crop requirements to maximize benefits (Bernal et al., 2017). Future research employing metagenomic analyses could elucidate the microbial interactions underlying these synergistic effects, advancing sustainable agricultural practices.

10. Impact of Organic and Inorganic Soil Amendments on Crop Performance and Quality

Crop quality and quantity are fundamental indicators of agricultural productivity and sustainability. In recent decades, there has been growing emphasis on the use of organic, inorganic, and biological soil amendments to improve soil health, enhance nutrient availability, and promote optimal crop growth. These amendments influence crop yields both directly—by increasing nutrient supply and indirectly by improving soil water retention, microbial activity, and physical structure (Van Eerd et al., 2014; Agegnehu et al., 2016a).

10.1. Role of organic amendments in enhancing crop productivity

The incorporation of organic amendments such as compost, manure, and biochar into soils significantly enhances crop yields by improving key soil properties. These amendments increase soil organic matter content, cation exchange capacity (CEC), and microbial biomass, thereby promoting nitrogen cycling and enhancing nutrient uptake by plants (Biederman and Harpole, 2013). For instance, the application of composted manure in cereal-based cropping systems has been linked to increased grain yields and improved protein content, primarily due to enhanced nitrogen availability (Chen et al., 2018). Biochar, a carbon-rich byproduct of biomass pyrolysis, has gained considerable attention for its dual role in boosting agricultural productivity and mitigating climate change. Depending on soil type and crop species,

Table 6. Crop quality and yield: response to amendments.

Amendment type	Crop	Yield increase (%)	Quality parameter improved	Reference
Biochar (5–10%)	Tomato	15–30%	Vitamin C, shelf life	Agegnehu et al., 2016b
Compost + Biochar	Maize	20–35%	Kernel weight, protein content	Zhai et al., 2015
Vermicompost	Strawberry	18%	Sugar content, firmness	Arancon et al., 2004
Rock phosphate + PGPR	Wheat	22%	Grain protein, test weight	Khan et al., 2015
FYM + Azotobacter	Rice	16%	Amylose content	Kumar et al., 2014

biochar application can improve yields by 10–20%, largely through its capacity to reduce nutrient leaching and stabilize soil pH (Lehmann et al., 2011; Jeffery et al., 2017b).

10.2. Incorporation of lime, fertilizers, and micronutrients for soil and crop improvement

To address nutrient deficiencies and correct soil pH imbalances, inorganic soil amendments such as lime, gypsum, and synthetic fertilizers are often necessary. Lime application to acidic soils improves nutrient availability and reduces aluminum toxicity, thereby promoting root development and nutrient uptake (Fageria and Baligar, 2008). Proper management of macronutrient fertilizers—particularly nitrogen (N), phosphorus (P), and potassium (K)—is critical for optimizing crop biomass and grain yield, although excessive use can compromise crop quality and increase nutrient leaching risks (Zhou et al., 2016). Micronutrient supplementation, including zinc, boron, and iron, plays a vital role in crop health and nutritional quality. For example, zinc biofortification in cereals enhances the micronutrient content of edible grains, improving their dietary value (Cakmak, 2008). Both foliar and soil applications of micronutrients have been shown to significantly increase the yield and quality of fruits, vegetables, and legumes (Alloway, 2009).

10.3. Impact of biological amendments on soil microbial communities and plant health

The application of biofertilizers and microbial consortia, including nitrogen-fixing bacteria (e.g., Rhizobium), phosphorus-solubilizing bacteria, and arbuscular mycorrhizal fungi, has gained recognition as an environmentally sustainable strategy to improve crop yield and quality. These microorganisms enhance nutrient uptake, stimulate phytohormone production, and bolster plant resilience to abiotic and biotic stresses (Vessey, 2003; Adesemoye et al., 2009). A meta-analysis by Schütz et al. (2018) demonstrated that microbial amendments can increase crop yields by an average of 11%, with more pronounced benefits observed in low-input agricultural systems. Additionally, microbial treatments have been linked to improvements in crop quality, including higher antioxidant concentrations in fruits and vegetables (Rouphael and Colla, 2020). Soil amendments, encompassing organic, inorganic, and biological inputs, are effective in enhancing both crop quantity and quality. However, the success of integrated amendment strategies depends on factors such as soil characteristics, crop species, climatic conditions, and management practices. Therefore, sustainable, site-specific amendment protocols are crucial to achieving future food security and environmental sustainability goals.

11. Influence of Soil Amendments on Crop Quality and Yield in Horticultural Production

Research demonstrates that soil amendments can improve crop flavor, vitamin content, and shelf life (Krishnakumar et al., 2014). Integrated amendment strategies have been shown to increase yields of crops such as tomatoes, lettuce, and peppers by 15–30% (Abujabhah et al., 2018). Microbial amendments reduce plants' dependency to chemical fertilizers while enhancing plant nutrient uptake efficiency (Mahanty et al., 2017). The combined application of biochar, compost, and microbial inoculants significantly improves crop quality and yield in horticultural systems by promoting soil health and plant vigor. For example, incorporating biochar at rates of 5–10 t/ha increases soil porosity and water availability by 15–20%, resulting in cucumber fruits with 10–12% higher weight and leafy greens with elevated vitamin A content (Agegnehu et al., 2017). Similarly, compost applications of 10–15 t/ha boost soil microbial populations, facilitating nutrient mobilization and increasing nitrogen availability by 20%. This enhancement translates into a 12% yield increase in saline soils and improved flavor in herbs such as cilantro. However, unscreened compost containing high heavy metal concentrations may pose health risks by contaminating produce (Table 6) (Meena et al., 2019).

Microbial supplements, such as Rhizobium and Trichoderma, promote root growth and disease suppression, thereby enhancing crop productivity. For instance, AMF inoculation increases strawberry berry size by 10%, driven by a 20% improvement in phosphorus uptake, and reduces the severity of wilt disease in peppers by 15% (Trivedi et al., 2020). In greenhouse basil cultivation, the synergistic application of biochar, compost, and PGPR resulted in a 10% increase in essential oil content alongside a 20% yield boost. Nonetheless, over-application of amendments can lead to nutrient imbalances and toxicity, highlighting the importance of precise dosage and tailored amendment combinations to sustain horticultural productivity (Bonanomi et al., 2017).

12. Challenges and Future Directions in Soil Amendments and Sustainable Agriculture

Field inconsistencies in the efficacy of biochar, compost, and microbial amendments frequently arise from variability in biochar quality, compost maturity, and local climatic conditions (Jeffery et al., 2017b). To maximize benefits, standardized production protocols and regionally adapted microbial strains are essential (Bender et al., 2016). Variability in biochar feedstock and pyrolysis parameters can result in diverse physicochemical properties, sometimes causing unintended soil pH elevation—particularly problematic in alkaline soils (Jeffery et al., 2017b). Similarly, compost may contain contaminants such as heavy metals or microplastics, which can adversely affect sensitive crops like tomatoes. Elevated compost electrical conductivity (>4 dS/m) can exacerbate salt stress in salt-sensitive horticultural species (Meena et al., 2019). Furthermore, microbial inoculants like PGPR and AMF face challenges establishing in compacted or nutrient-poor soils, with colonization rates reduced by 20–30%. Overapplication of these inoculants can also negatively impact indigenous microbial communities, decreasing their diversity by 10–15% (Trivedi et al., 2020). Looking ahead, the development of standardized amendment protocols is critical to ensure consistent quality and safety. Enhanced feedstock screening during compost production could minimize pollutant load, thereby safeguarding crops such as lettuce (Bernal et al., 2017). Tailored biochar formulations designed specifically for different soil types hold promise to improve nutrient retention while preventing adverse pH shifts. To improve microbial inoculant performance, integrating metagenomics and multi-omics approaches can optimize strain selection and efficacy, potentially increasing effectiveness by 15–20% in diverse horticultural contexts (Bonanomi et al., 2017). Additionally, long-term field experiments are needed to evaluate the effects of these amendments on greenhouse gas emissions and soil carbon sequestration potential. These research directions will contribute to sustainable horticulture by enhancing crop yield and quality simultaneously (Agegnehu et al., 2017). Future investigations should prioritize microbiome engineering, bioinformatics tools, and precision agriculture technologies to refine amendment application specificity and optimize resource use efficiency (Fitzpatrick et al., 2020).

13. Conclusion

Biochar, compost, and microbial supplements play a pivotal role in advancing regenerative horticulture by improving soil structure, fertility, and ecosystem resilience. Their combined application enhances the sustainability of horticultural systems and supports ecosystem restoration efforts through synergistic effects that boost nutrient cycling, water retention, and microbial diversity. This integrated approach can increase crop yields and quality for crops such as tomatoes and strawberries by 10–20%. Biochar acts primarily by retaining nutrients, while compost contributes labile organic matter that fuels microbial activity. Microbial inoculants, including plant growth-promoting rhizobacteria (P7GPR) and arbuscular mycorrhizal fungi (AMF), alleviate abiotic and biotic stresses like drought and pathogens, improving fruit quality with sugar content increases upto 10–15%. These benefits collectively reduce reliance on synthetic inputs, promoting environmentally friendly practices. However, challenges such as contamination risks and inconsistent field efficacy highlight the need for site-specific customization and rigorous quality control. Adopting standardized protocols and advanced omics technologies can optimize the use of these amendments, delivering long-term improvements to soil health and food security. Enhanced interdisciplinary research coupled with precision agriculture technologies will be critical to unlocking the full potential of these biological tools for sustainable horticulture.

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