

Biochar, Compost, and Organic Amendments in Tomato Soils: Impacts on Soil Properties and Crop Performance

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Abstract

The integration of biochar, compost, and other organic amendments in tomato (*Solanum lycopersicum L.*) cultivation addresses key challenges in modern intensive production systems, including soil degradation, nutrient depletion, reduced microbial diversity, and vulnerability to abiotic stresses such as drought and salinity. This comprehensive review synthesizes recent evidence demonstrating that biochar produced via pyrolysis of diverse feedstocks (rice husk, wheat straw, cow bone, poultry litter) fundamentally enhances soil physicochemical and biological properties. Key improvements include reduced bulk density, increased porosity and water retention, elevated cation exchange capacity (CEC), pH buffering in acidic soils, enhanced nutrient retention (nitrogen and phosphorus), and stimulated microbial biomass, enzyme activities (urease, phosphatase), and beneficial microbial communities (*Pseudomonas*, Bacteroidetes) that suppress soil-borne pathogens like bacterial wilt. When combined with composts (vermicompost, farmyard manure, poultry litter), these amendments exhibit synergistic effects, further boosting aggregate stability, nutrient cycling, and resilience to environmental stressors. In tomato crops, such strategies promote seedling vigor, vegetative growth, reproductive parameters (e.g., fruits per plant, fruit weight), and overall yield increases ranging from 13.7% to 33.2% (or higher in integrated systems), alongside improved fruit quality metrics such as total soluble solids, vitamin C, lycopene, firmness, and extended shelf life (notably via Ca/P-enriched cow bone biochar). These benefits are modulated by factors including biochar production conditions (feedstock, pyrolysis temperature), application rates (optimal often 10–20 t/ha or 1–2 kg/m²), soil texture/initial properties, and integration with inorganic fertilizers. Economic assessments indicate

favorable benefit-cost ratios when using locally produced or waste-derived amendments, supporting sustainable intensification.

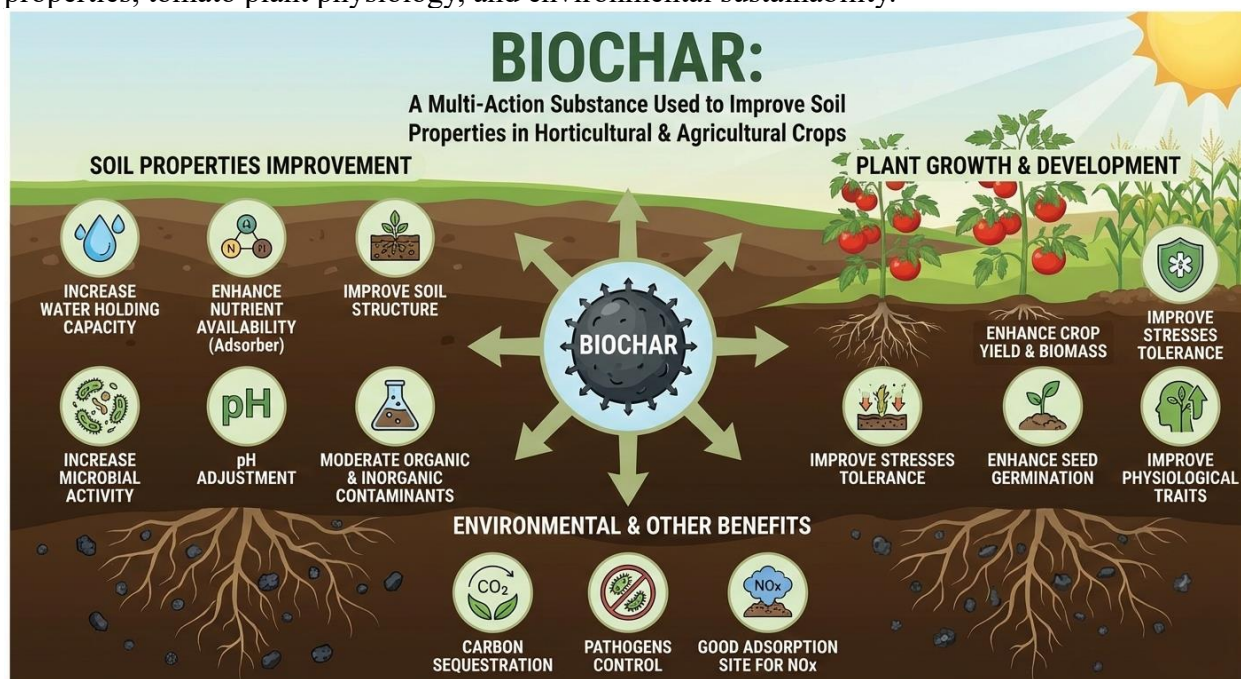
Keywords: Biochar, Compost, Organic Amendments, Tomato (*Solanum Lycopersicum*), Soil Health, Yield Improvement, Fruit Quality, Nutrient Cycling, Microbial Community, Abiotic Stress Mitigation, Sustainable Agriculture

1. Introduction

The global cultivation of tomato (*Solanum lycopersicum L.*) is a cornerstone of intensive horticulture, providing an indispensable source of micronutrients, antioxidants, and dietary fiber. However, the intensive nature of modern tomato production systems, characterized by high-input reliance and monoculture-oriented management, has precipitated a crisis in soil health (Almaroai et al., 2020). Soil degradation, manifesting as the depletion of organic matter, secondary salinization, and the loss of microbial diversity, now represents a critical bottleneck for sustainable yield increases (Bogoescu et al., 2024). To address these multifaceted challenges, the integration of biochar, compost, and diverse organic amendments has emerged as a transformative strategy to reconcile the requirements of high-productivity agriculture with ecological stewardship (Eissa et al., 2021).

The current research landscape emphasizes the shift from conventional chemical-heavy fertilization toward integrated nutrient management (INM). This transition is not merely a substitution of inputs but a fundamental redesign of the soil's physical, chemical, and biological architecture (Gaete et al., 2021). Organic amendments such as biochar a recalcitrant carbonaceous material produced through pyrolysis and composted materials like vermicompost and animal manure, serve as complex modifiers that interact with soil minerals and microorganisms across various temporal and spatial scales (Lei et al., 2024). By enhancing the soil's buffering capacity, moisture retention, and enzymatic activity, these amendments mitigate the deleterious effects of environmental stressors, including drought and salinity (Zhu et al., 2025).

Figure 1: Schematic representation of the multi-faceted impacts of biochar on soil physicochemical properties, tomato plant physiology, and environmental sustainability.



2. Feedstock Engineering and Pyrolysis Dynamics: The Foundation of Biochar Efficacy

Biochar's efficacy as a soil amendment is fundamentally determined by its physicochemical properties, which are a function of the parent biomass feedstock and the thermal conditions of its production (Nicholas et al., 2024). The process of pyrolysis, conducted at temperatures ranging from 300 to 1000 degrees Celsius in the absence or limitation of oxygen, converts labile organic matter into a stable, porous carbon matrix. High-temperature pyrolysis typically results in biochar with greater surface area, higher porosity, and increased aromaticity, whereas lower temperatures preserve more functional groups and labile carbon. (Obadi et al., 2024).

Feedstock selection is equally critical. Research trials in tomato systems have utilized a diverse array of materials, including rice husk, wheat straw, poultry manure, wood chips, and specialized materials like cow bone and fecal sludge (Pantelides et al., 2023). For instance, cow bone biochar is uniquely characterized by its high calcium and phosphorus content, which directly influences fruit firmness and shelf life (Suarez, 2025). Fecal sludge biochar, applied to acidic soils, has demonstrated the capacity to increase plant biomass by over 500% through dramatic improvements in nutrient availability and soil buffering (Tolesaa et al., 2018).

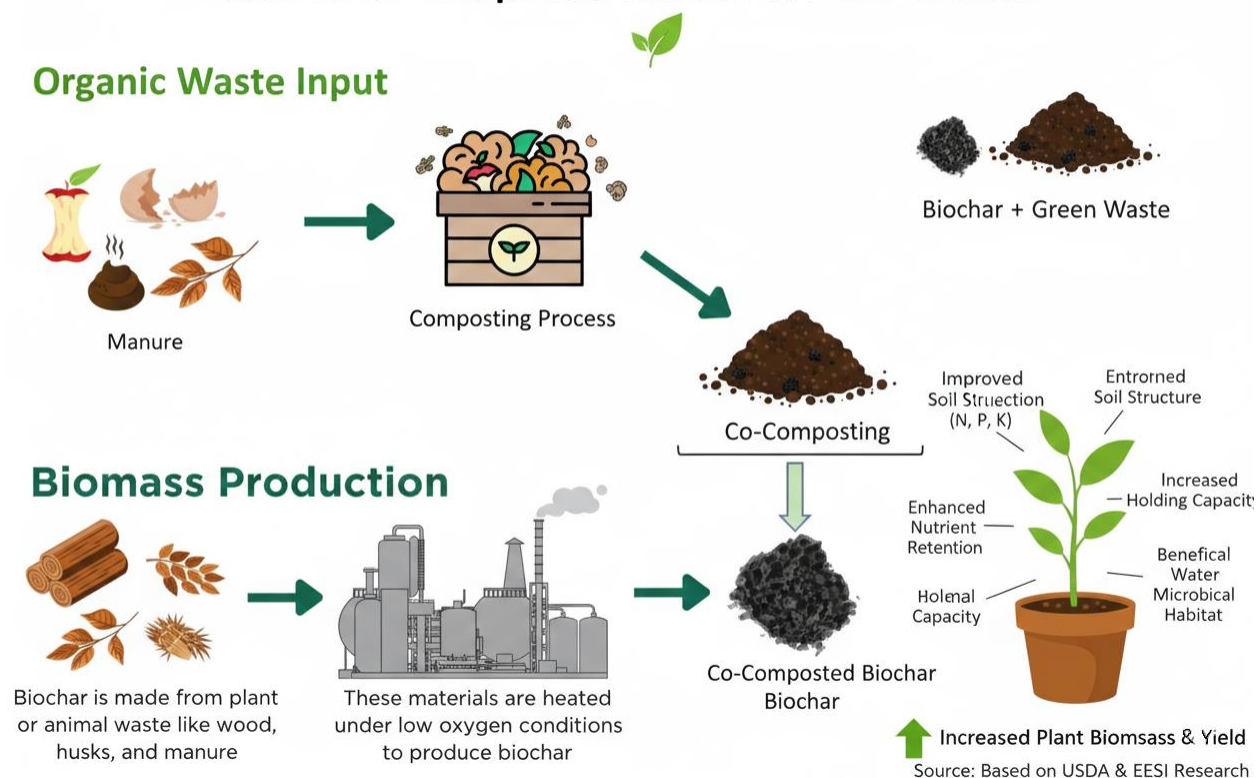
Table 1: Comparative Chemical and Functional Properties of Common Organic Amendment Feedstocks

Feedstock Source	Primary Advantage	Nitrogen (%)	Phosphorus (%)	pH Range	Documentation
Wheat Straw Biochar	Carbon Sequestration	0.5 - 0.8	0.1 - 0.2	8.5 - 10.0	(Tolesaa et al., 2018).
Rice Husk Biochar	Porosity / Water Retention	0.4 - 0.7	0.15 - 0.3	7.5 - 9.0	(Pantelides et al., 2023).
Poultry Litter	Rapid Nutrient Release	2.5 - 4.5	1.5 - 2.5	6.5 - 7.5	(Obadi et al., 2024).
Vermicompost	Microbial Inoculation	1.5 - 2.5	1.0 - 2.0	6.8 - 7.2	(Nicholas et al., 2024).
Cow Bone Biochar	Ca and P Enrichment	0.1 - 0.3	10.0 - 15.0	8.0 - 9.5	(Zhu et al., 2025).
Cotton Gin Trash	Organic Matter Stabilization	1.0 - 2.0	0.5 - 1.0	6.5 - 7.5	(Eissa et al., 2021).

The chemical maturation of these amendments significantly influences their interaction with soil minerals. For example, biochars with high carboxyl and phenolic group densities exhibit a higher affinity for nitrate sorption, thereby reducing leaching losses and enhancing nitrogen use efficiency in the tomato root zone (Tu et al., 2026)

Figure 2: Process flow diagram illustrating the production of co-composted biochar, integrating biomass pyrolysis with organic waste composting mechanisms.

Role of Co-Composted Biochar in Plant Growth



3. Structural Amelioration: Impact on Soil Physical Properties

The physical environment of the soil governs the accessibility of oxygen, water, and nutrients to the tomato root system. Biochar incorporation triggers a cascade of physical improvements, primarily through its highly developed pore structure and its role as a binding agent for soil particles (Wang et al., 2017).

3.1 Bulk Density and Porosity Dynamics

Application of biochar, particularly at rates exceeding 2.0 kg per square meter, has been shown to significantly reduce soil bulk density while increasing total porosity. In sandy loam soils, biochar acts as a physical diluent, reducing the weight per unit volume and creating a more favorable medium for root expansion (Toková et al., 2020). This reduction in density is often accompanied by an increase in soil porosity of up to 8.4%. The relationship between biochar dosage and porosity is frequently linear, with the total volume of pores increasing proportionately with the increment in biochar dose (Guo et al., 2022). These changes enhance the soil's infiltration rate and reduce penetration resistance, facilitating deeper root penetration and more efficient exploration of the soil profile (Brikmans et al., 2025).

3.2 Soil Aggregation and Mean Weight Diameter

Biochar and compost act as catalysts for the formation of stable soil aggregates. The mechanisms involve both direct physical interactions and indirect biological pathways. Biochar particles provide surfaces where organic matter and minerals can be adsorbed, forming micro-aggregates that eventually coalesce into macro-aggregates (Sarker et al., 2022). Furthermore, the presence of biochar stimulates the activity of microorganisms, which secrete extracellular polysaccharides biological "glues" that bind soil particles together (Islam et al., 2021).

Studies have shown that the application of maize straw and peanut hull biochar at rates of 7.8 tons per hectare in combination with inorganic fertilizers increases the proportion of macro-aggregates and the mean weight diameter (MWD) of those aggregates (Hamza et al., 2025). However, the sensitivity of soil aggregation to biochar additions is highly texture-dependent. Coarse-textured soils, such as sands and sandy loams, often exhibit more pronounced improvements in aggregate stability compared to fine-textured silty or clayey soils (Fischer et al., 2012).

3.3 Hydraulic Conductivity and Water Retention

The management of soil moisture is particularly critical in tomato cultivation, where water stress can lead to physiological disorders like blossom end rot. Biochar's effect on available water content (AWC) is mediated by its high internal surface area and capillary pore structure (Obadi et al., 2023). In sandy soils, biochar addition significantly improves water retention by reducing the saturated hydraulic conductivity, thereby slowing the rapid drainage of gravitational water (Rasool et al., 2021).

Research conducted in arid regions, such as Saudi Arabia, demonstrates that biochar effectively mitigates the negative impacts of water scarcity. Under deficit irrigation regimes (for example, 40% to 80% crop evapotranspiration), biochar application increased tomato water use efficiency and water productivity by as much as 79.33% compared to unamended soils (Ud Din et al., 2023). This ability to "buffer" the plant against intermittent rainfall and irrigation shortages is a critical advantage in the context of climate change (Murtaza et al., 2024).

4. Chemical Fertility and Biogeochemical Cycling

The chemical rejuvenation of tomato soils through organic amendments involves the modification of pH, electrical conductivity, and the soil's cation exchange capacity (CEC). These changes directly influence the bioavailability of essential macro and micronutrients (Tao et al., 2024).

4.1 pH Buffering and the Liming Effect

Biochar is inherently alkaline, often possessing a significant calcium carbonate liming equivalency. In acidic soils (pH less than 6.0), biochar application has been found to raise the pH by up to 1.07 units (Iticha et al., 2024). This increase is particularly beneficial for tomato production, as it optimizes the solubility of phosphorus and reduces the risk of aluminum and manganese toxicity. Poultry litter often amplifies this pH-buffering effect through the mineralization of organic matter, which releases base cations and enhances pH stability (Sharma et al., 2025).

However, the long-term dynamics of soil pH in amended systems require careful monitoring. Over multiple cropping cycles, the process of nitrogen cycling specifically nitrification can release hydrogen ions, leading to a gradual re-acidification of the soil (Liu et al., 2025). The continuous presence of recalcitrant biochar provides a sustained buffering capacity that mitigates this acidification better than labile organic manures alone (Arwenyo et al., 2023).

4.2 Cation Exchange Capacity and Cation Retention

One of the most profound chemical impacts of biochar is its ability to boost the soil's CEC. Biochar's high specific surface area and the development of negative charges on its surface through oxidative ageing processes enhance its capacity to adsorb and retain cations (Iticha et al., 2026). Analysis using the Mehlich 1 extraction method has shown that biochar application at rates between 33.6 and 44.8 tons per hectare can improve CEC by up to 34.8% (Singh et al., 2023).

This enhancement of CEC is vital for preventing the leaching of essential nutrients like potassium and calcium, which are often prone to loss in sandy soils (Jemal et al., 2021). The synergistic

application of biochar with poultry litter further elevates the CEC, as the decomposing organic matter provides additional exchange sites while the biochar provides a stable framework to preserve those sites over time (Manso et al., 2019).

4.3 Nitrogen and Phosphorus Availability

Nitrogen management in tomato soils is a delicate balance between supply and loss. Biochar has been shown to significantly enhance nitrogen retention, particularly when paired with organic fertilizers. Total inorganic nitrogen retention was found to increase by 144.7% at high biochar rates when combined with poultry litter. This is attributed to the adsorption of ammonium and the reduction of nitrate leaching (Li et al., 2025).

Phosphorus bioavailability is also improved through organic amendments. Vermicompost and spent mushroom compost are naturally rich in phosphorus, providing a slow-release source that matches the plant's demand during the flowering and fruiting stages. Biochar further influences phosphorus cycling by altering soil pH and providing surfaces for phosphorus adsorption-desorption (Adekiya et al., 2025).

5. Biological and Microbial Transformations in the Rhizosphere

The biological health of the soil is perhaps the most sensitive indicator of the impacts of organic amendments. Tomato soils amended with biochar and compost exhibit significant shifts in microbial biomass, activity, and community composition (Jaiswal et al., 2017).

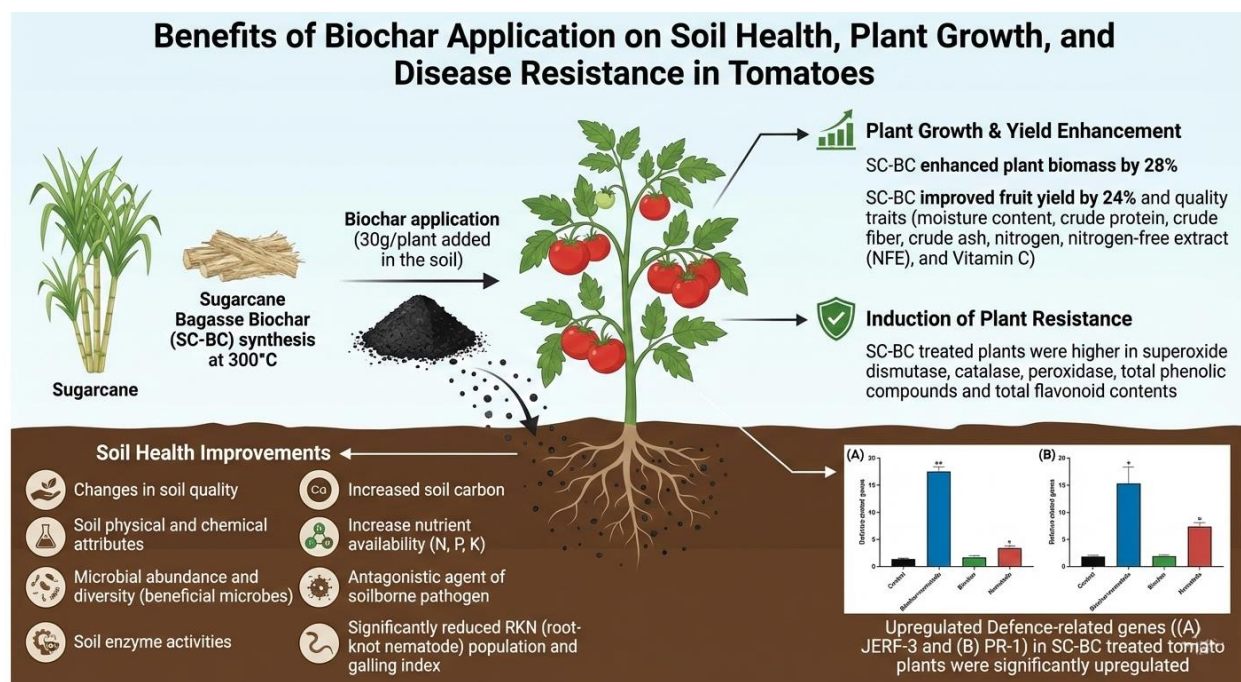
5.1 Microbial Biomass Carbon (MBC) and Activity

Organic farming practices, characterized by the application of composted cotton gin trash (CGT), animal manure, or green manure, generally result in higher MBC and microbial activity compared to conventional systems (Nazir et al., 2021). CGT additions have been shown to increase MBC by 103–151% and microbial activity by 88–170% over a two-year period. This surge in biological activity is driven by the influx of easily decomposable organic carbon, which fuels the growth of soil microorganisms (Padhan, 2022).

5.2 Taxonomic Community Shifts and Pathogen Suppression

The application of biochar induces a "biochar-shifted" bacterial community that can contribute to the resistance of tomato plants against soil-borne pathogens. In soils infected by *Ralstonia solanacearum* (bacterial wilt), biochar treatment significantly increased the relative abundance of the phyla Bacteroidetes and Proteobacteria (Dai et al., 2021). At the genus level, amendments favored the proliferation of beneficial bacteria such as *Chitinophaga* and *Pseudomonas* (Hu et al., 2020).

Figure 3: Mechanisms of biochar-induced systemic resistance in tomato, illustrating pathogen suppression, antioxidant enzyme activity, and the upregulation of defense-related genes.



This microbial restructuring is a key mechanism for disease suppression. Biochar provides a protected habitat within its pores, shielding beneficial microbes from desiccation and predators. Furthermore, the reduction in soilborne disease severity observed to be as high as 46.6% to 97.3% is linked to the enhanced competition for nutrients by the enriched microbial community (Dror et al., 2022).

Table 2: Influence of Biochar and Vermicompost on Soil Biological Indicators and Microbial Functions

Biological Indicator	Impact of Biochar (BC)	Impact of Vermicompost	Implication for Tomato
Microbial Biomass	Variable / Increased Habitat	High Influx of Inoculum	Enhanced nutrient cycling
Urease Activity	Increased (Nitrogen cycling)	Significant Increase	Improved N availability
Phosphatase Activity	Increased (P solubility)	Significant Increase	Enhanced P uptake
Pathogen Resistance	Shifts toward Pseudomonas	Suppression of pathogens	Reduced Bacterial Wilt
Earthworm Activity	Synergistic with BC	Core production mechanism	Improved soil structure

5.3 Soil Enzyme Dynamics

Enzyme activities are the proxies for biochemical processes in the soil. Biochar and compost consistently enhance the activities of urease, catalase, and phosphatase. Urease activity, which regulates available nitrogen, is notably higher in soils with high organic matter content. Catalase activity, an indicator of aerobic microorganisms and overall soil fertility, decomposes hydrogen peroxide formed during the oxidation of organic matter (Zaid et al., 2024).

6. Impact on Tomato Crop Performance and Agronomic Metrics

The ultimate objective of soil remediation is the enhancement of crop productivity. Organic

amendments influence tomato performance across the entire ontogeny of the plant, from seedling emergence to fruit maturation (Diacono et al., 2018).

6.1 Seedling Emergence and Early Vigor

Biochar application can reduce physiological stress in seedlings, although its effectiveness is highly rate-dependent. Low rates of biochar (approximately 15% volume/volume) in soilless media have been found to reduce the days required for emergence by 12–16% (Hafeez et al., 2017). However, excessive biochar application (above 45% or 60%) can hinder emergence due to nutrient imbalances or excessive drainage. Once established, tomato plants in biochar-amended media exhibit greater height, stem diameter, and leaf number than those in unamended controls (Shumaila et al., 2023).

6.2 Vegetative and Reproductive Growth

Long-term field experiments have quantified the accumulative effects of consecutive biochar application. Biochar rates between 1.0 and 2.0 kg per square meter (10–20 tons per hectare) have been identified as optimal for enhancing tomato growth (Cong et al., 2023). In these systems, plant height and dry matter increase proportionally with the biochar rate. Reproductive parameters improve significantly; biochar can improve fruits per plant by 2.0–17.0% and single fruit weight by 7.0–16.0% (Griffin et al., 2017).

Table 3: Comparison of Tomato Growth and Yield Parameters in Response to Organic Amendments

Growth Parameter	Response to Biochar (Optimal)	Response to Poultry Litter / FYM	Documentation
Plant Height	216% - 279% Increase	32% Increase	14
Stem Diameter	Significant Improvement	27% Increase	13
Fruit Yield (t/ha)	13.7% - 33.2% Increase	39% - 54% Increase	2
Fruits per Plant	2.0% - 17.0% Increase	High Improvement	2
Root Activity	Significant Increase	Synergistic with Biochar	35

Yield increases are particularly pronounced in "Integrated Plant Nutrition Systems" (IPNS), where biochar is co-applied with organic manures. For instance, the combination of 2% biochar with 3% farmyard manure resulted in the most substantial gains in heavy metal-contaminated soils (Vijay et al., 2021).

7. Fruit Quality, Phytochemistry, and Post-Harvest Longevity

Tomato quality is defined by nutritional content, organoleptic properties, and shelf life. Organic amendments enhance the accumulation of primary and secondary metabolites that contribute to these indices (Amr et al., 2022).

7.1 Total Soluble Solids (TSS) and Antioxidants

Tomatoes are a primary source of Vitamin C and lycopene. High biochar application rates have been found to increase tomato yield by nearly 30%, while boosting TSS by 4.28% and Vitamin C content by 6.77%. Vermicompost application similarly improves fruit quality by increasing the sugar-to-acid ratio and enhancing the concentration of total soluble sugars (Ikram et al., 2024).

7.2 Fruit Firmness and Shelf Life Extension

Specialized feedstocks like cow bone biochar can enhance shelf life. Higher calcium levels in the tomato plant strengthen cell walls, leading to firmer fruits. Biochar derived from cow bone can

enhance calcium availability by over 900%. Studies have shown that applying cow bone biochar at 40 tons per hectare can increase the shelf life of tomato fruits by 70% compared to unamended controls by maintaining fruit tissue hardness (Adekiya et al., 2025).

8. Mitigation of Environmental Stress and Pollution

Biochar and organic amendments provide a robust buffer against abiotic stressors such as salinity, drought, and heavy metal contamination (Imran et al., 2022).

8.1 Salinity and Drought Resilience

Under salt stress, tomato total yield can decline by over 60%. Biochar application improves the soil solution, reducing the osmotic and oxidative stresses related to sodium and chloride ions (Kamal et al., 2024). Biochar's high adsorption capacity limits sodium uptake into plant tissues, maintaining a more favorable potassium-to-sodium ratio. In drought-prone environments, biochar application allows for a 30% reduction in irrigation water while maintaining yield (Lentini et al., 2024).

8.2 Immobilization of Heavy Metals

In heavy metal-contaminated soils, biochar acts as an effective remediation agent. Biochar application at 2.0% weight/weight markedly reduces the accumulation of toxic metals like Lead and Cadmium in fruit tissues. When combined with spent mushroom compost, metal concentrations remain well within WHO safety limits (Ogidi et al., 2024).

9. Economic Evaluation and Practical Feasibility

The transition to organic amendments is often constrained by input costs and labor. Comprehensive evaluation of the Benefit-Cost Ratio (BCR) and net returns is essential for scalability (Bett et al., 2017).

9.1 Cost-Benefit Analysis (BCR)

The economic viability of biochar and compost depends on local availability. Combining poultry litter with high biochar rates (15–20 tons per acre) achieved a cumulative BCR of 2.08, while conventional chemical fertilizer treatments remained below the threshold (BCR less than 1.0) (Srivastava et al., 2024).

In greenhouse systems where biochar is purchased at market prices, the treatment with 25% biogas slurry (BS25) without biochar provided the highest total economic benefit (672,361 yuan per hectare) due to lower input costs. Biochar addition significantly increased cumulative investment costs, exceeding 180,000 yuan per hectare primarily due to high biochar market prices (Rubel et al., 2025).

Table 4: Economic Comparison and Feasibility of Conventional versus Organic Amendment Strategies

Treatment Strategy	Net Return (Unit/ha)	Economic Feasibility	Primary Constraint
100% NPK (Conventional)	Low to Negative ⁶	Low (Due to degradation)	High variable costs ⁷
25% FYM + 75% Inorganic	59,902 Birr ³⁹	High (Optimal balance)	Initial labor for FYM
100% Biogas Slurry	35,674 Yuan ³⁵	Moderate	Transport and storage

High (Purchased) Biochar	527,410 Yuan ³⁵	Moderate (High yield, low margin)	Market price of biochar ³⁵
Local Biochar + Litter	BCR = 2.08 ⁶	High	Equipment for production

Conclusion

The incorporation of biochar and organic amendments, particularly in integrated nutrient management systems, represents a powerful, ecologically aligned approach to reversing soil degradation and enhancing tomato productivity and quality. By simultaneously improving soil physical structure, chemical fertility, biological activity, and stress resilience, these amendments enable higher yields, superior nutritional attributes, reduced environmental impacts, and greater economic viability compared to conventional chemical-intensive practices. Optimal outcomes depend on tailored selection of amendment type, rate, and combination based on local soil conditions and feedstock availability. Long-term field studies underscore sustained benefits, though periodic replenishment may be needed to counter biochar aging effects. Overall, widespread adoption of these strategies holds strong potential to advance sustainable horticulture, especially in resource-constrained or degraded environments facing climate pressures.

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