



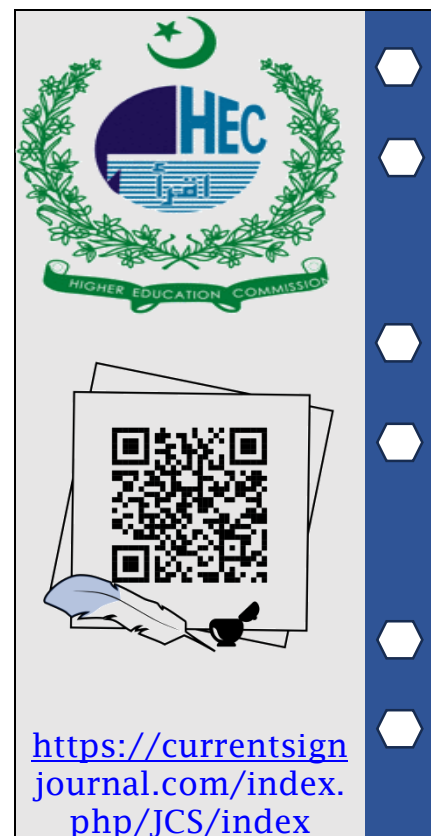
Impact of Biochar and Organic Fertilizer Integration on Growth, Yield, and Soil Health in Tomato (*Solanum lycopersicum* L.)

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Abstract

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The modern agricultural transition toward sustainable agroecological management necessitates alternatives to synthetic chemical inputs to address soil degradation and environmental contamination. This study explores the integration of biochar, a carbon-rich material produced via pyrolysis, with organic fertilizers (such as vermicompost, poultry litter, and compost tea) to optimize growth, yield, and soil health in tomato (*Solanum lycopersicum* L.) cultivation. Biochar's unique physicochemical properties including high porosity and surface area provide a stable structural framework and microbial habitat, while organic amendments mitigate biochar's inherent nutrient poverty. Studies indicate that integrated applications significantly enhance soil physical health by reducing bulk density and increasing water-holding capacity, which improves drought resilience. Biologically, the synergy boosts microbial biomass carbon by up to 40.5% and nitrogen by 105.7%, fostering enzymatic

activities essential for nutrient mineralization. These improvements translate to superior physiological efficiency, including increased net photosynthetic rates and root proliferation. Results demonstrate a yield increase of approximately 29.55% through biochar application, with integrated systems further enhancing fruit quality parameters like Vitamin C and lycopene. Additionally, this approach provides a dual strategy for heavy metal immobilization and offers economic viability, with benefit-cost ratios reaching 2.08 in specific poultry litter-biochar trials.

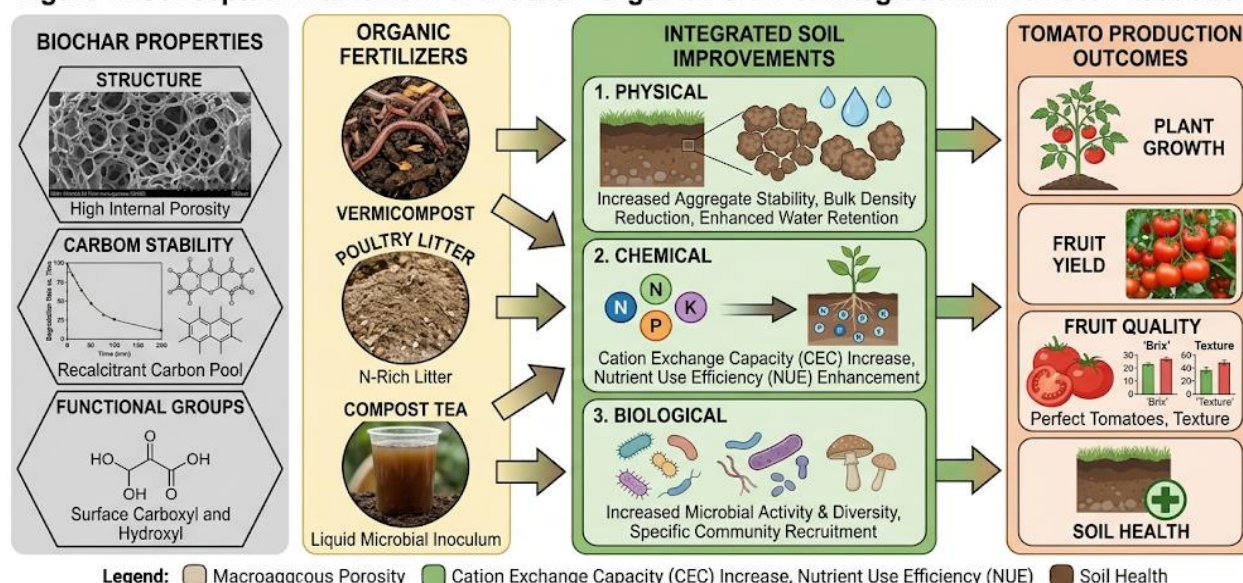
Key Words: Biochar, Organic Fertilizer, Tomato (*Solanum lycopersicum* L.), Soil Health, Sustainable Agriculture, Synergistic Mechanism, Pyrolysis.

1. Introduction

The modern agricultural landscape is currently undergoing a paradigm shift, transitioning from a heavy reliance on intensive synthetic chemical inputs toward more sustainable, agroecological management practices. This transition is necessitated by the mounting evidence of soil

degradation, groundwater contamination, and the atmospheric release of greenhouse gases associated with conventional monoculture systems (Gomiero et al., 2011). The cultivation of tomato (*Solanum lycopersicum* L.), one of the most widely consumed and economically significant vegetable crops globally, presents a unique set of challenges due to its high nutrient requirements and susceptibility to both biotic and abiotic stresses (Saeed et al., 2021). To address these challenges, researchers and agronomists are increasingly exploring the synergistic potential of integrating biochar carbon-rich, porous material produced through the pyrolysis of organic wastewith various organic fertilizers and microbial amendments. This integrated approach aims not only to optimize fruit yield and quality but also to restore the long-term biological, physical, and chemical health of the soil (Ye et al., 2020). This integrated approach is best understood through a systems-level perspective. Figure 1 illustrates the conceptual framework of biochar and organic fertilizer interactions and their cumulative effects on tomato production.

Figure 1: Conceptual Framework of Biochar–Organic Fertilizer Integration in Tomato Production



2. Physicochemical Characteristics of Biochar and Production Mechanisms

The fundamental utility of biochar as a soil conditioner is derived from its unique structural and chemical properties, which are primarily dictated by the feedstock used and the specific parameters of the thermochemical conversion process known as pyrolysis. Pyrolysis involves the thermal decomposition of biomass in an oxygen-limited environment, typically at temperatures ranging from 300 °C to 800 °C (Sim et al., 2025). During this process, the volatile components of the biomass are released as syngas and bio-oil, leaving behind a solid, carbonaceous residue characterized by a highly aromatic and stable carbon matrix (Lehmann & Joseph, 2015).

2.1 Feedstock Influence on Biochar Composition

The selection of feedstock is the primary determinant of the resulting biochar's nutrient content and physical architecture. Common materials utilized in tomato research include woody biomass, crop residues such as rice husks and straw, animal manures, and specialized inputs like cow bone or date palm fronds. For example, biochar derived from woody feedstocks tends to exhibit higher carbon content and greater structural stability compared to manure-derived biochar, which often



possesses higher concentrations of ash and available nutrients such as phosphorus and potassium (Lei et al., 2024).

Table 1. Characteristics of Biochar Feedstocks and Typical Pyrolysis Parameters.

Feedstock Source	Pyrolysis Temp (°C)	Typical pH	Surface Area (m ² /g)	Dominant Characteristics
Wood Residues	400--500	8.0--10.0	High (>100)	High stability, high porosity (Lei et al., 2024)
Date Palm Fronds	500	10.51	87.1	Rich in surface functional groups (Tounsi-Hammami et al., 2025)
Rice Husk	Variable	7.5--9.0	Moderate	High silica content, improved water retention (Ishmam et al., 2025)
Cow Bone	Variable	Alkaline	Variable	High calcium and phosphorus content (Adekiya et al., 2025)
Walnut Shell	400--700	9.0--10.0	High	98% fixed carbon, excellent drought resilience (Dabravolski & Isayenkov, 2025)

2.2 Pyrolysis Temperature and Aromaticity

The temperature at which pyrolysis occurs significantly alters the chemical functionality of biochar. Low-temperature pyrolysis (below 450 °C) generally preserves more of the original biomass's oxygen-containing functional groups, which contribute to a higher cation exchange capacity (CEC) (Zhang et al., 2025). However, as temperatures rise above 500 °C, the biochar becomes more aromatic and recalcitrant, with a corresponding increase in specific surface area and pore volume. In tomato cultivation, wood and straw biochars pyrolyzed in the range of 401 °C to 500 °C have been identified as particularly effective for enhancing both yield and fruit quality (Song et al., 2025).

3. Organic Fertilizers and Integrated Nutrient Management

While biochar provides a stable structural framework for soil improvement, it is often nutrient-poor in its raw state, particularly regarding nitrogen availability. To mitigate the risk of initial nutrient immobilization, biochar is co-applied with organic fertilizers (Hu et al., 2024).

3.1 Compost and Vermicompost Dynamics

Vermicompost is particularly noted for its high concentration of plant growth-promoting substances and beneficial microbial communities. In tomato monoculture systems, vermicompost has been shown to be more effective than standard compost or chemical urea in promoting vegetative growth. Integrating biochar with vermicompost enhances fruit quality parameters such as Vitamin C and soluble sugar content compared to either amendment used in isolation (Rehali et al., 2026).

3.2 Poultry Litter and Animal Manures

In coastal plain soils, integrating poultry litter with biochar has proven to be a highly effective strategy for increasing tomato marketable yield and plant vigor. While poultry litter is the primary driver of yield increases, biochar is essential for maintaining soil pH stability and carbon sequestration (Agbede & Oyewumi, 2022).



3.3 Microbial Inoculants and Liquid Amendments

Compost tea serves as a microbial consortium that accelerates the mineralization of soil organic matter. When date palm biochar is combined with compost and compost tea, the resulting "triple-amendment" strategy can increase soil organic carbon by 51.9% and total nitrogen by 2.1% (Garg & Rakshit, 2024).

4. Synergistic Mechanisms in the Rhizosphere

The interaction between biochar and organic fertilizers occurs through distinct chemical, physical, and biological pathways within the tomato rhizosphere (Hammami et al., 2025).

4.1 The Carrier and Habitat Hypothesis

Biochar's porous architecture serves as a protected niche for soil microorganisms. The internal pores provide a refuge from predators and environmental fluctuations. Organic fertilizers provide the labile carbon and nutrient substrates necessary to support these microbial communities (Dincă et al., 2022).

4.2 Nutrient Loading and Stabilization

Biochar has a high affinity for ammonium (NH_4^+) and nitrate (NO_3^-) ions. This creates a "slow-release" effect, holding nutrients in the root zone and releasing them gradually. In trials using poultry litter, this combination achieved a 144% gain in total inorganic nitrogen within the root zone at high biochar rates (Fan et al., 2019).

4.3 pH Buffering and Acidification Mitigation

The alkaline nature of most biochars, combined with the high buffering capacity of compost, effectively neutralizes soil acids. Maintenance of a near-neutral pH is essential for maximizing phosphorus bioavailability (Sim et al., 2025).

5. Impact on Soil Physical Health and Water Dynamics

Integration profoundly alters soil structure, influencing water use efficiency (WUE) (Adekiya et al., 2025).

5.1 Bulk Density and Porosity

Biochar application leads to a reduction in soil bulk density and an increase in total porosity. Microbial exudates from integrated compost further enhance soil aggregation, preventing compaction in intensive systems (Sindhushree et al., 2026).

5.2 Water-Holding Capacity and Drought Resilience

Biochar's porous structure increases field capacity and available water content. Even at 3--5% application rates, walnut shell biochar can mitigate drought stress impacts, preserving leaf production and biomass by up to 92% (Dabravolski & Isayenkov, 2025).

Table 2. Effect of Biochar and Irrigation Regimes on Tomato Yield and Productivity.

Irrigation Level	Biochar Rate (%)	Impact on Tomato Yield	Water Productivity (WP)
100% ETc	0	Control	Baseline
80% ETc	5	+11.92%	Improved (Liu et al., 2022)
40% ETc	5	Reduced	+79.33% (Liu et al., 2022)
60% ETc	5	Reduced	Enhanced firmness (Liu et al., 2022)

6. Biological Vitality and Nutrient Transformation Pathways

Biological health is a sensitive indicator of integrated amendment success (Hu et al., 2024).



6.1 Microbial Biomass Carbon and Nitrogen

Integrated amendments significantly increase microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN). In tomato soils, biochar at 30–70 t/ha can increase MBC by 21.5–40.5% and MBN by 51.5–105.7% (Guo et al., 2021).

6.2 Enzymatic Activity and Nutrient Mineralization

Triple-amendment systems significantly enhance the activity of key enzymes: Urease (nitrogen mineralization), Phosphatase (phosphorus mobilization), β -glucosidase (carbon turnover), and Catalase (aerobic activity) (Su et al., 2025).

6.3 Nitrogen-Related Microorganisms

Biochar promotes *amoA*-type nitrifiers (by up to 106.7%) and inhibits *nirS*-type denitrifiers (by up to 50.9%). This allows for a reduction in synthetic nitrogen fertilizer by up to 24% without compromising yield (Rehali et al., 2026).

7. Tomato Vegetative Growth and Physiological Development

Soil environment improvements manifest as superior growth and physiological efficiency (Agbede & Oyewumi, 2022).

7.1 Morphological Parameters

Combined applications outperform individual treatments in plant height and leaf area. Plants treated with biochar-poultry litter were 32% taller and had 27% larger stem diameters than those in conventional fertilizer plots (Humnessa et al., 2023).

7.2 Photosynthetic Efficiency and Chlorophyll Fluorescence

Integrating biochar and vermicompost significantly improves net photosynthetic rate (P_n) and stomatal conductance (G_s) (Liu et al., 2022).

Table 3. Synergistic Impact of Integrated Amendments on Tomato Physiological Parameters.

Physiological Parameter	Control (CK)	Vermicompost (3%)	Biochar (3%)	Impact of Integration
Net Photosynthetic Rate (P_n)	Baseline	+49%	+Significant	Synergistic increase (Liu et al., 2022)
Intercellular CO_2 (C_i)	Baseline	+65%	+Significant	Improved gas exchange (Liu et al., 2022)
PSII Max Efficiency (F_v/F_m)	Baseline	+4%	+Significant	Photo-protection (Liu et al., 2022)
Energy Flux (Absorption)	Baseline	+10%	+Significant	Enhanced light capture (Liu et al., 2022)
Potential Photo Activity (F_v/F_o)	Baseline	+25%	+Significant	Correlated with yield (Liu et al., 2022)

7.3 Root System Architecture

Biochar increases specific root length and encourages fine root proliferation. Under severe drought, biochar has resulted in 30% longer primary roots and 25% higher lateral root density (Dabravolski & Isayenkov, 2025).

8. Marketable Yield and Yield Components

Meta-analyses indicate a 29.55% yield increase from biochar application. In integrated systems, 2% biochar and 3% FYM resulted in a yield of 10.63 t/ha. Rooftop urban trials with cherry tomatoes saw a 26.28% yield increase per plant (Ishmam et al., 2025).

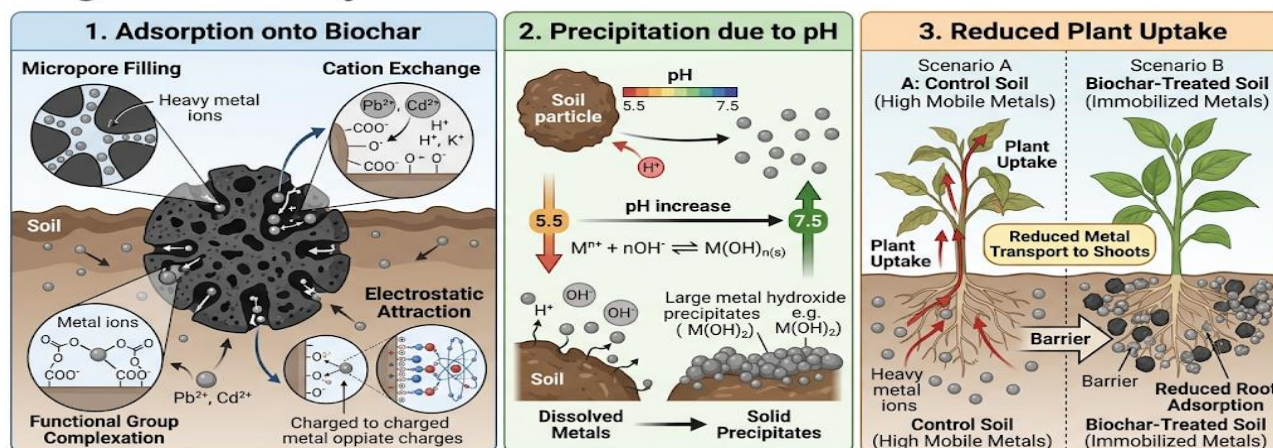
8.1 Nutritional and Organoleptic Quality

Integrated amendments improve Total Soluble Solids (TSS), Vitamin C, and antioxidants like lycopene. Cow bone biochar prolongs shelf life by up to 70% by providing cell-wall-strengthening calcium (Adekiya et al., 2025).

9. Heavy Metal Immobilization and Soil Remediation

Integration provides a dual strategy for remediating heavy metal contamination (Gomiero et al., 2011). Beyond productivity, integrated systems contribute to environmental remediation. Figure 2 depicts the mechanisms by which biochar immobilizes heavy metals in soil.

Figure 2: Heavy Metal Immobilization Mechanisms in Soil



9.1 Mechanisms of Immobilization

Biochar immobilizes metals through adsorption/ion exchange at functional groups and precipitation due to alkaline pH (Sindhushree et al., 2026).

9.2 Efficacy in Tomato Production

Applying 2% biochar with 3% organic fertilizer effectively boosts growth while reducing toxic metal accumulation in fruit to levels within WHO permissible limits (Rehali et al., 2025).

10. Economic Analysis and Practical Implementation for Farmers

Economic adoption depends on viability for the producer (Agbede & Oyewumi, 2022).

10.1 Profitability and Benefit-Cost Ratio (BCR)

In southern Georgia, combining poultry litter with high biochar rates achieved a BCR of 2.08, whereas conventional treatments remained below 1. This is driven by lower plant mortality and higher marketable yields (Saeed et al., 2021).

10.2 Logistical and Production Challenges

Barriers include high production/energy costs for co-pyrolysis, lack of uniform quality standards, and the need for specialized application machinery (Ye et al., 2020).

11. Environmental Sustainability and Future Outlook

Integration aligns with circular economy goals and climate mitigation (Sim et al., 2025).



11.1 Carbon Sequestration and Climate Resilience

Biochar serves as a long-term carbon sink. Improved water-holding capacity enhances climate resilience during extreme weather (Dabravolski & Isayenkov, 2025).

12. Conclusion

The integration of biochar with organic fertilizers represents a potent agroecological strategy for sustainable tomato production. By combining the structural stability and carbon-sequestering potential of biochar with the nutrient density of organic amendments, this approach addresses the limitations of using either material in isolation. The resulting synergy optimizes the rhizosphere environment, improves water use efficiency, and enhances the plant's physiological resilience against abiotic stresses like drought and nutrient deficiency. Furthermore, the ability of these integrated systems to reduce reliance on synthetic nitrogen by up to 24% while maintaining high marketable yields highlights their role in a circular economy. Despite challenges regarding production costs and the need for standardized quality, the long-term benefits to soil vitality, fruit nutritional quality, and environmental remediation position integrated biochar management as a cornerstone for future climate-resilient agriculture.

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