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Biochar Co-Valorization Impact on Fruit Quality and Phytochemical Profile: A Mini-Review

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Abstract

Fruit crop production and its quality are facing serious challenges due to declining soil health and depletion of soil organic carbon in perennial orchards. Repurposing horticultural waste into biochar, a carbon-rich soil amendment has the potential to provide a sustainable approach for nutrient management. This mini-review draws attention to recent advances in biochar production through the conversion of crop residues and their synergistic integration with organic amendments (e.g., vermicompost, jaggery, neem cake, cow urine and microbial activators). The application of various organic amendments plays a vital role in improving soil health and enhancing fruit quality in a sustainable manner. In this mini-review, providing a comprehensive review paper after critically analyzing and synthesizing findings from existing research literature which provides substantial evidence of these amendments such as biochar improves soil aeration, water retention and cation exchange capacity, in addition to promoting carbon sequestration and mitigating greenhouse gas emissions. Finally, we address key challenges and future directions for adopting biochar-based organic waste valorization in sustainable fruit production.

Keywords: Biochar; Waste valorization; Fruit science; Soil carbon sequestration; Organic farming

Introduction

Prolonged reliance on synthetic chemical fertilizers in fruit orchards has fostered a range of environmental and health issues, experiencing a significant reduction in nutrient use efficiency and ecological damage, which ultimately impact consumer safety [1]. Chronic exposure to these chemicals is linked to severe health risks, including prostate, colon and thyroid cancers, as well as neurodegenerative conditions like Parkinson's disease and cognitive decline. Additionally, heavy metal contaminants present in fertilizers such as cadmium and lead can accumulate in soil pores, triggering systemic damage to the liver and kidneys alongside metabolic issues like diabetes and thyroid dysfunction. Immediate exposure often manifests as acute respiratory and gastrointestinal distress, including asthma flare-ups, nausea, and vomiting [2]. Due to this reason, the risks are high in horticultural communities where use is intensive and safety measures are limited which ultimately promotes organic farming, raising public awareness and continuous monitoring are essential steps to minimize the health hazards associated with chemical fertilizers [3]. On the other hand, climate change is directly impacting fruit production and quality. As we know, soil systems play a vital role in achieving sustainable development due to their multifaceted roles, encompassing the generation of organic matter for food, feed, fiber and energy, habitat provision for biodiversity, water and air purification, greenhouse gas mitigation, carbon sequestration, buffering precipitation extremes, while also promoting cultural, recreational and public health benefits [4].

In fruit crops, this overuse can lead to phytotoxicity, reduced soil microbial diversity and the emergence of resistant pest populations, ultimately compromising crop productivity and fruit quality [5,6]. It also effects soil health by degrading its physical, chemical and biological properties. It leads to reduced soil organic carbon, altered pH, nutrient imbalances and a decline in microbial biodiversity and activity [7] and results in soil compaction, reduced water-holding capacity and lower nutrient-use efficiency [8]. Furthermore, leaching of nutrients such as nitrates contributes to groundwater contamination and eutrophication of water bodies [5]. These challenges underscore the urgent need for sustainable horticultural practices that minimize chemical inputs while promoting soil and plant health. Therefore, increasing the demand of sustainable and natural farming is crucial to meet future food needs while minimizing harm to the environment [9,10]. To address these challenges, horticultural waste valorization via thermochemical conversion (pyrolysis) into biochar has emerged as a promising approach. Biochar acts as a stable carbon sink capable of remaining in soils for centuries. When co-applied with organic amendments like vermicompost and carbon activators, biochar creates a fertile micro-environment because it contains alkaline ash and basic cations, their incorporation can exert a liming-like effect in acidic soils, thereby increasing soil pH and decreasing exchangeable acidity. The magnitude and direction of the pH response depend on biochar properties and the initial soil condition. Changes in pH, carbon availability, moisture and pore structure can also modify the habitat and activity of soil microbial communities that improves soil structure, enhances moisture retention, and promotes sustainable fruit yield and quality.

Synergistic effects of biochar and organic amendments

Incorporating biochar with organic amendments into orchard soils plays a fundamental role in preserving long-term soil health and boosting fruit quality through sustainable means. By enhancing soil structure, stimulating microbial life, and increasing plant-available nutrients, these amendments establish the conditions required for robust crop productivity [11]. Each organic material offers distinct advantages such as biochar with vermicompost accelerates nutrient cycling within the rhizosphere, whereas biochar enhances aeration, moisture retention, and cation exchange capacity while simultaneously locking away soil carbon to curb greenhouse emissions. Nutrient-dense inputs like poultry manure combined with biochar provide vital macronutrients like nitrogen, phosphorus, and potassium that drive energetic vegetative growth and fruit development in fruit crops [12,13]. Additionally, inputs like neem cake with biochar enrich the root zone with essential elements while offering natural protection against soil-borne pests and pathogens [11,14]. In a similar manner, applying cow urine supplies nitrogen and trace minerals that re-energize microbial communities and spur nutrient conversion [15]. Meanwhile, traditional farmyard manures a blend of decomposed animal waste and crop residues combined with biochar builds soil organic matter, preserves moisture reserves, and provides a well-balanced nutrient matrix for long-term plant vigor [16]. Together, these inputs elevate soil organic carbon reserves, optimize both macro-and secondary nutrient availability (N, P, K, Ca, Mg, and S), and improve overall soil architecture, ultimately favoring root expansion and efficient nutrient uptake [17]. Adopting such organic and natural management strategies remains key to advancing sustainable horticulture.

Impact on fruit quality and phytochemical profile

The highly porous structure of biochar can modify soil pore-size distribution and increase the availability of water-retaining sites. At appropriate application rates, biochar may improve aggregation, reduce bulk density and enhance the balance between water retention and aeration. These effects are strongly influenced by feedstock type, pyrolysis temperature, particle size, application rate and the initial properties of the soil. Because of its vast internal surface area and microscopic pores, it retains capillary water and prevents essential mineral nutrients from leaching away during irrigation. When combined with organic amendments such as vermicompost, jaggery, or other organic materials, it creates a thriving home for beneficial soil microbes. Consequently, the root system grows bigger, deeper, and healthier because the surrounding soil stays moist and aerated containing balanced oxygen, carbon dioxide, and nitrogen. This aeration promotes chemical reactions within the soil solution, ultimately resulting in a nutrient-rich root zone. As we know, balanced nutrition leads to healthy plant metabolism instead of forced vegetative growth. Firstly, biochar increases the soil's cation exchange capacity. This means negatively charged sites on biochar hold positively charged ions like K^+ Ca^{2+} Mg^{2+} tightly enough to prevent leaching, but loosely enough for plant roots to absorb them. In abiotic stress conditions like drought or waterlogged stress, biochar smooths out water stress. When a fruit tree suffers from dry or wet cycles, its metabolic processes stall. Consistent water uptake keeps photosynthesis operating at maximum efficiency. The tree absorbs balanced proportions of macronutrients and secondary nutrients without suffering osmotic stress or nutrient toxicities.

Co-application of biochar and amendments increases chlorophyll content and water-use efficiency which generates primary carbon skeletons, specifically Erythrose-4-phosphate (E4P) and Phosphoenolpyruvate (PEP). These primary carbon Skeltons enter the plastidial shikimate pathway and yields the essential aromatic amino acid L-Phenylalanine which serve as the precursor for phenolic compounds. Ather this step, Phenylalanine Ammonia-Lyase (PAL) acts as the main regulatory doorway enzyme induced by co-application of biochar with other amendments and activates abiotic signaling or improved nutrient status enhances PAL gene expression and enzyme activity. After that the deamination of L-Phenylalanine by PAL creates the phenylpropanoid backbone synthesis trans-cinnamic acid which helps in accumulation of phenolics, flavonoids, and antioxidants in fruit tissues, improving aroma, color, shelf life, and nutritional value. Applying biochar together with other amendments not only restores soil health and boosts primary crop yields, but also fundamentally stimulates the phenylpropanoid metabolic pathway via PAL enzyme activation. This metabolic shift converts primary photosynthetic products into high-value secondary metabolites giving fruit crops enhanced stress resilience and superior nutritional quality (Figure 1).

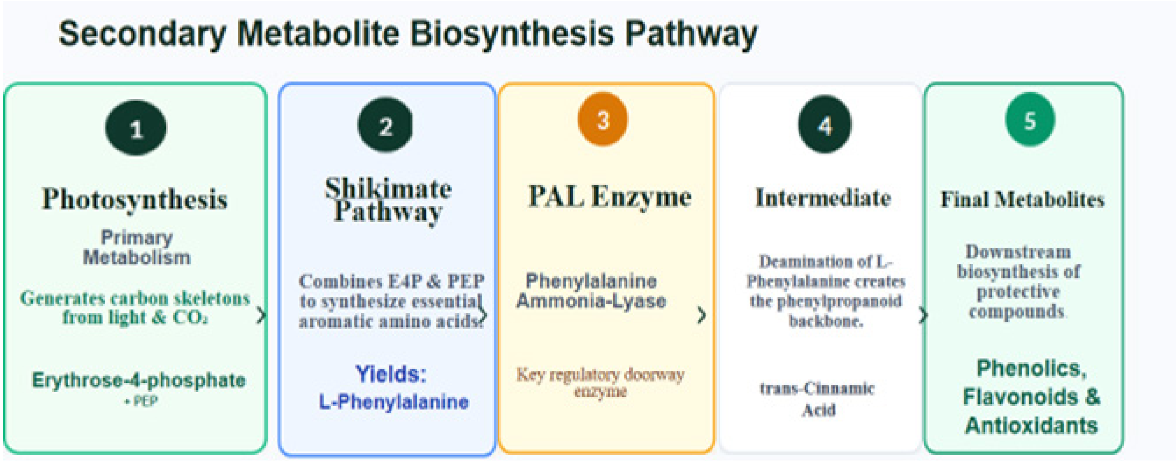

Figure 1:

Conclusion and Future Prospects

To mitigate the soil health problems, we must focus on integrated application of biochar alongside complementary soil amendments such as vermicompost, farm yard manure and poultry manure which enhances the beneficial microbes represents a highly effective strategy for advancing sustainable fruit production. Synergistic co-amendments consistently enhance soil physicochemical properties, optimize nutrient uptake, improve water-use efficiency, and boost fruit yield and quality across diverse orchard systems. However, realizing the full agronomic potential of biochar-based blends requires addressing persistent knowledge gaps. Future research must prioritize long-term field trials across varied agro-climatic zones, standardizing optimal blending ratios tailored to specific fruit crop varieties, and evaluating the multi-year economic viability for growers. Overcoming these scientific and practical hurdles will be essential for transitioning biochar co-valorization from experimental success to widespread, commercially viable orchard management practices.

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