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Biochar: A concept to sustain soil health in horticultural crops

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Abstract

Horticultural crops require high nutrient levels to support intensive growth, frequent cropping cycles, and optimal yield. Due to the increasing cropping intensification globally specially in horticultural crops has led to soil nutrient depletion and in the requirement for nutrients coming from external sources for crop production simultaneously increasing. Biochar has been identified as a “black gold” in horticultural crops due to its own exceptional features such as high composition of stable carbon. Biochar aids long term carbon immobilization in the soil and improve soil health by the controlled release of immobilized carbon and nutrients for a longer time in a sustainable manner. It is also facilitate to ameliorate climate change by the reduction of atmospheric carbon and gases from the recurrent uses of fertilizers.

Keywords: Biochar, Soil health, Horticultural crops, Carbon sequestration, Soil fertility, Nutrient retention, Water holding capacity, Soil microbial activity, Sustainable agriculture, Climate change mitigation

Introduction

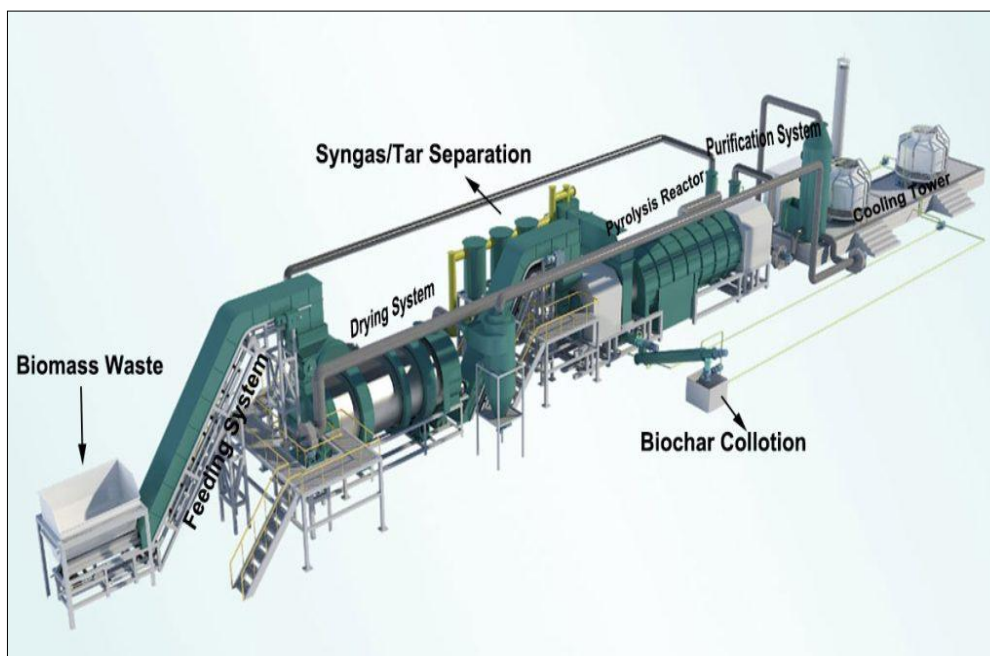
Cropping systems play a pivotal role in shaping soil fertility, influencing nutrient cycling, soil structure, and microbial activity. Sustainable cropping practices enhance soil organic matter, improve nutrient availability, and mitigate soil degradation. Conversely, intensive mono-cropping and excessive chemical inputs can lead to soil depletion and biodiversity loss. Unfortunately, soil has been and is currently being rapidly degraded at a global scale due to a range of invasive anthropic activities in intensive agriculture, with concomitant adverse effects on human and ecosystem health. This is concerning as soil is a non-renewable resource at a human temporal scale (i.e. soil loss and degradation are not recoverable within a human lifespan). Soil health is defined as the ability of a soil to function and provide ecosystem services (Van Es and Karlen, 2019) ^[45], or the soil's fitness to support crop growth without degrading soil or otherwise harming the environment (Acton and Gregorich, 1995) ^[10]. The terms ‘soil health’ and ‘soil quality’ have been used interchangeably, with the emphasis mostly on crop production with some concern for environmental sustainability (Doran *et al.*, 1996) ^[16]. Among the various cropping systems, horticultural is an essential multidisciplinary approach that contrasts with traditional agriculture regarding crop types, higher production intensity, and greater profit margins. Horticultural plants encompass fruits and nuts, vegetables and herbs, flowering ornamental plants, trees and shrubs, lawns, along with medicinal herbs. Certain plants are cultivated in containers utilizing substrates or growing media within greenhouses. Container substrates mainly consist of organic materials such as peat moss, pine bark, coconut coir, and composted substances (Chen and Wei, 2018) ^[8]. Horticultural crops require high nutrient levels to support intensive growth, frequent cropping cycles, and optimal yield. Due to the increasing cropping intensification globally specially in horticultural crops has led to soil nutrient depletion and in the requirement for nutrients coming from external sources for crop production simultaneously increasing (Jones *et al.*, 2013) ^[18]. The use of chemical fertilizers that provide nutrient sources like nitrogen (N), potassium (K), and phosphorus (P) etc. restores certain nutrients lost due to intensive cropping system. Nonetheless, insufficient application of fertilizers will not restore other depleted nutrients effectively and will adversely impact soil health and crop nutritional requirements (Jones *et al.*, 2013) ^[18]. In present era, due to adopting the highly intensive cropping system, biochar has been identified as a “black gold” in agricultural circles owing to its exceptional features such as high composition of stable carbon. This aids long-term carbon immobilization in soil and improves fertility due to its controlled release of locked up carbon and nutrients for several decades. This also helps to ameliorate climate change due to reduced atmospheric carbon and gases from recurring fertilizer applications. Also, biochar's large surface area and porosity aid water and nutrient retention alongside beneficial microbes' growth in soil directly increasing agricultural yield by improving

the soil ecosystem while optimizing productivity through the neutralization of soil acidity which provides a balanced environment, thereby promoting crop development (Paulina *et al.*; 2021). All these exceptional features which made biochar a sustainable and efficient means for long term carbon sequestration, soil fertilizing, and amendment are equated to that of precious metals such as gold, thus fostering the tagging of biochar as “black gold”. What is biochar?: Biochar is black carbon produced from biomass sources [i.e., wooden chips, crop residues, manure or other agricultural waste products] for the purpose of transforming the biomass carbon into a more stable form (carbon sequestration). Black carbon is the name of the range of solid residual products resulting from the chemical and/or thermal conversion of any carbon containing material (e.g., fossil fuels and biomass) (Jones *et al.*, 1997) ^[17]. Biochar does not refer to a singular product with a given set of chemical and physical characteristics. Rather, biochar spans the spectrum of black carbon forms (Spokas, 2010) ^[41] and it is chemically and physically unique as a function of the feedstock, creation process (pyrolysis unit), cooling, and storage conditions.

Biochar is defined by the International Biochar Initiative as the "solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment"(International Biochar Initiative, 2015).

Biochar is a "Combo Pack" for Soil health & Fertility

Smith and Lee (2013) ^[39] describe biochar as "a high carbon material produced from the pyrolysis of organic matter, which enhance soil health, structure, fertility, and provides long-term carbon storage." Their definition focuses on biochar's impact on soil structure and fertility, as well as its role in longterm carbon storage, emphasizing the durability and effectiveness of biochar in soil applications. Morgan and Lehmann (2015) ^[22] define biochar as "a porous, carbon-rich material derived from the thermal decomposition of organic matter under low-oxygen conditions, with significant implications for soil management and carbon cycling." Their definition places emphasis on the structural properties of biochar, such as its porosity and high surface area, which are critical for its functionality in soil management and nutrient retention.



Source: https://www.mingjiigroup.com/news/Biochar_Making_Plant.html

Fig 1: Biochar Making Plant

Biochar and physical properties of soil

Soil Porosity: Soil porosity, the volume of spaces between soil particles, is essential for plant growth as it manages air and water supply. A balanced soil consists of roughly 50% pore space, featuring macro-pores for air circulation/drainage and micro-pores for water retention. Good porosity promotes deep root expansion, nutrient uptake, and oxygen availability. Soil porosity provides space for microbial growth and improves the aeration of the soil, nutrient availability, and water drainage and retention capacity (Li *et al.*, 2018) ^[13]. Biochar is porous and loose and the pores determine its surface area. The use of biochar increases the overall porosity of the soil, but the porosity depends on the type of biochar used and the type of soil where the biochar is applied (Herath *et al.*, 2013) ^[15]. The higher soil porosity was due to the porous nature of biochar (Mukherjee and Lal, 2013) ^[25]. (Liang *et al.*, 2006) ^[21] reported that in comparison to soil organic matter, biochar possesses a greater surface area, a negative surface charge, and a higher

charge density, which enhances its ability to adsorb cations (Nduka *et al.*, 2019) ^[26]. Due to the higher specific surface area of biochar, which improves the waterholding capacity of soil. The addition of biochar as an amendment was found to increase the total specific surface area of soil.

Nutrient Retention: The large surface area provides numerous sites for the adsorption of nutrients, preventing their leaching from the soil and making them available to plants (Novak *et al.*, 2012) ^[27]. Biochar, a carbon-rich substance produced through biomass pyrolysis, increases soil nutrient retention by utilizing its large, porous surface area to bind nutrients (nitrogen, phosphorus, potassium) and prevent leaching. It acts as a reservoir, reducing fertilizer runoff and slowing the release of nutrients, which can improve crop yields by up to 18%.

Water Holding Capacity: The pores within biochar can retain significant amounts of water, which helps improve soil moisture

levels and reduces the need for frequent irrigation (Sohi *et al.*, 2010) ^[40]. Particle Size and Bulk Density: Biochar particles can vary widely in size, from fine powders to larger granules. The particle size distribution affects the biochar's physical properties and its behaviour in soil:

Particle Size: Smaller particles have a higher surface area relative to their volume and can enhance nutrient and water retention. However, they may also increase the risk of dustiness and are more prone to leaching (Blackwell *et al.*, 2009) ^[5].

Biochar and chemical physical properties of soil: Biochar improves soil chemical properties by elevating pH, increasing cation exchange capacity (CEC), enhancing nutrient availability (N, P, K), and boosting carbon sequestration, making it effective for improving fertility and reducing acidity.

Organic Matters: Biochar is a stable, carbon-rich form of charcoal created by pyrolyzing organic waste (biomass) at 300-900 °C in low-oxygen conditions. It acts as a permanent soil amendment, improving nutrient retention, water holding capacity, and soil structure for centuries. Biochar works best when blended with organic matter like compost, boosting microbial activity and reducing nutrient leaching. Biochar can boost Organic substance concentration, this effect depends on the amount and stability of the biochar used (Glaser *et al.*, 2001; Zygourakis, 2017) ^[14, 49]. Biochar's capacity to modulate seasonal and daily fluctuations in soil temperature is mainly driven by alterations in soil thermal conductivity and reflectance (Zhang *et al.*, 2013) ^[48]. Biochar can reduce the amount of sunlight reflected by soil and slow down heat transfer within the soil. The main reason for slower heat transfer is the increased organic matter content caused by the biochar (Abu-Hamdeh & Reeder, 2000) ^[4]

Organic Carbon: Biochar boost the soil organic carbon by an average of 26%, providing a long-term carbon sequestration tool that reduces carbon loss while enhancing soil fertility, water retention, and microbial habitat. The long-term storage of organic carbon in the soil, referred to as soil organic carbon sequestration (Lal, 2008) ^[33], is essential not only for removing carbon dioxide (CDR) from the atmosphere but also for enhancing soil health and supporting ecosystem functionality (Lal *et al.*, 2007; Lal *et al.*, 2015; Rumpel *et al.*, 2020) ^[34, 35, 7]. Enhancing soil organic carbon storage can be accomplished by employing various organic soil amendments (OSA), with the most prevalent types being straw, slurries, manures, compost, biogas digestates, and sewage sludge bio solids. These organic soil amendments are frequently utilized for fertilization because they provide essential nutrients. Yet, due to their differing levels of C-rich organic materials, the use of organic soil amendments results in a rise in soil organic carbon stocks (Alvarenga *et al.*, 2020) ^[29]. These organic soil amendments consist of various forms of carbon compounds, most of which have low stability and short mean residence times (MRT) in the soil. Consequently, these adjustments should be implemented consistently, such as at the onset of each new growing season, to enhance soil fertility and promote long-term increases in SOC stock (Alvarenga *et al.*, 2020; Gross and Glaser, 2021) ^[1]. Biochar amendments, on the other hand, feature aromatic carbon compounds in high concentrations with minimal nitrogen content (mostly polycyclic and unavailable to microbes), making them very stable against microbial degradation

pH and EC: An understanding of biochar pH is important given its likely influence on soil pH and other properties and processes in soils on biochar application. While the effect of biochar on soil pH may be beneficial for ameliorating acid soils, increased pH has been linked to micronutrient deficiencies and yield reductions in some agricultural systems (Kishimoto and Sugiura 1985) ^[19]. The term pH, first used by the Swedish scientist Sorensen in 1909, describes the intensity of acidity (or alkalinity) of a substance.

Most biochars used for soil amendment are alkaline (Mukherjee and Lal 2014) ^[23], however, biochar pH values between 3.1 and 12.0 have been reported in the literature (Mukherjee *et al.*, 2011) ^[24]. During carbonisation, acidic functional groups are removed and salts of alkali and alkaline earth elements become enriched (Ueno *et al.*, 2008; Fuertes *et al.*, 2010) ^[44, 11]. These salts include (i) readily soluble salts, (ii) carbonates, (iii) sparingly soluble metal oxides and hydroxides and (iv) silicates, the latter especially when feedstocks contain soil particles (Okuno *et al.*, 2005) ^[28]. Most of these salts provide biochars a considerable alkalinity (Vassilev *et al.*, 2013b) ^[46], although this is feedstock- and production process-dependent. Consequently, biochars with low ash content, such as those produced using woody feedstocks, generally have lower pH values than biochars with higher ash content, such as those produced using grass, crop.

Electrical conductivity (EC): Biochar application generally increases soil electrical conductivity (EC) due to its high ash content, inherent salts, and porous structure, which enhances ion exchange capacity and nutrient retention. It significantly impacts soil physicochemical properties, often improving moisture retention, reducing bulk density, and acting as a slow-release nutrient source. High pyrolysis temperatures (>500 °C) create more conductive structures. EC grew significantly in medium acidic loamy sand and medium alkaline sandy loam soil with respect to the amendment rate (Boostani *et al.*, 2020) ^[6]. On the other hand (Abagandura *et al.*, 2021) ^[2], indicated that EC in acidic sandy loam and highly acidic clay loam soils decreased non-significantly after BC amendment. A significant fluctuation EC trend started with decreasing then increasing with the biochar amendment in medium alkaline clay loam soil (Abrishamkesh *et al.*, 2016) ^[3]. BC's EC value has a great relation to BC's ash content values (Abrishamkesh *et al.*, 2016) ^[3]. Both of them depend on the feedstock and pyrolysis temperature. For example, compared to woody BC (camellia oleifera shells, garden waste), herbaceous plant biochar (rice straw, corn straw) exhibited a much higher EC, and ash content (Tu *et al.*, 2022) ^[43].

Biochar and Soil Microbial activity

Biochar can be used for multifunctional applications including the improvement of soil health and carbon storage, remediation of contaminated soil and water resources, mitigation of greenhouse gas emissions and odorous compounds, and feed supplementation to improve animal health. A healthy soil preserves microbial biodiversity that is effective in suppressing plant pathogens and pests, recycling nutrients for plant growth, promoting positive symbiotic associations with plant roots, improving soil structure to supply water and nutrients, and ultimately enhancing soil productivity and plant growth. Soil biological health primarily refers to the biological activity and functions of soil microorganisms (Jeziarska-Tys *et al.*, 2020; Lehmann *et al.*, 2011) ^[37, 20]. A healthy soil preserves microbial biodiversity that is effective in suppressing plant

pathogens and pests, recycling nutrients for plant growth, promoting positive symbiotic associations with plant roots, improving soil structure to supply water and nutrients, and ultimately enhancing soil productivity and plant growth (Suman *et al.*, 2022; Harman *et al.*, 2021) ^[42, 12]. As a soil amendment, biochar assures soil biological health via different approaches. First, biochar stimulates the development of stable soil microaggregates, which support more habitats for soil organisms. Biochar can optimize conditions for soil organisms by altering soil physical and chemical properties, including the immobilization of soil contaminants, which reduces their bioavailability and potential negative impact on biodiversity (Bolan *et al.*, 2023; Lv *et al.*, 2022) ^[36, 47]. Biochar is also being considered as a suitable carrier for plant nutrients and microbial soil inoculants due to its capacity to facilitate slow release of nutrients and promote microbial activity (Wu *et al.*, 2021; Dong *et al.*, 2020) ^[30, 9].

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