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Effectiveness of Soil-amended Biochar in Improving Crop Production, Soil Health and Environmental Aspects

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Sustainable agriculture has assumed greater importance in today's world. Biochar has the potential to increase crop yield and soil fertility in agriculture while reducing greenhouse gas emissions at the same time. Biochar production technology and biomass type has great influence on its quality and yield which in turn is responsible for altering soil fertility status and enhancing other soil properties. Biochar is produced via thermochemical conversion of biomasses by the process of pyrolysis with different pyrolysis conditions which include heating rate, temperature or residence time that affect the product distribution and yield for biochar produced from same biomass. Biochar is produced sustainably from eco-friendly sources under manageable conditions such as agricultural woody and non-woody wastes or crop residues or animal wastes. Biochar's acknowledgement in removing heavy toxic metals, organic solvents and pesticide residues from soil as well as in waste water management aids in environmental protection. Yield response of biochar produced from various feedstock sources on vegetable crop production is discussed to compare their relative

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effectiveness. Biochar is a carbonaceous substance produced that sequester carbon and remain in soil for thousands of years and thus offers stability in soil. Biochar as Negative Emissions Technology (NET) in removing CO_2 from atmosphere and other greenhouse gases such as N_2O and CH_4 is a prominent methodology in mitigating serious concern of climate change. The objective of this review paper is to extensively justify the role and importance of biochar in agriculture and sustainable growth.

Keywords: Biochar; biomass; negative emissions technology; carbon sequestration.

1. INTRODUCTION

Agriculture today faces a major setback for a decline in productivity of agricultural land owing to the poor soil condition. Intensive farming practices over decades have degraded soils and had reduced the potential of soils to sustain plant health causing decline in yields. To feed the growing population which is estimated to reach 9.8 billion by 2050 with shrinking land resources and infertile soils amid climate change stress is a challenging goal [1]. The fact that land under cultivation is limited, and there is need to improve the quality of soil under agriculture for a better yield. The negative consequences of green revolution on agricultural soils and environment have come to the fore. Soil has lost it's healthy physical, chemical and biological properties over a period of time. The direct implications on soil properties of longtime agriculture practices have caused soil salinization, soil acidification, organic matter loss, soil compaction, desertification, loss of biodiversity in soil environment and decreased productivity. It is imperative to take essential measures for improvement in agriculture with adaptability to climate change and variations.

The increase in concentration of greenhouse gases (GHG's) is responsible for relative increase in global temperatures. The implications of rising CO_2 levels on equilibrium climate sensitivity and related concerns have risen substantially in the past few years. Methane and Nitrous oxide are equally responsible for driving global climate change. As per the report by Climate Watch (2023), Agriculture sector was ranked fourth largest contributor of global GHG' emission in the year 2020 with 5.87 billion tones carbon dioxide-equivalent emissions [2]. Among non-CO_2 greenhouse gases, Nitrous Oxide (N_2O) and Methane (CH_4) are the other dominant gases responsible for greenhouse effect. For instance, according to a source, nitrous oxide warms the planet 300 times as much as carbon dioxide [3]. As for Methane, one tone of methane would generate 28 times the amount of warming as one tone of CO_2 [4]. Agriculture sector is the leading cause of Methane and Nitrous oxide emissions at 3.54 and 2.33 billion tones respectively measured in carbon dioxide-equivalents in the year 2020 as per the data source of Climate Watch (2023) [2]. Fertilizer application to the soil has been known to decrease the CH_4 sink capacity and increased N_2O and CH_4 emissions to the atmosphere. On an average, most of the applied fertilizers are lost as runoff or released into the atmosphere as GHG emissions due to multiple factors. Methane emissions are linked to livestock, rice cultivation, biomass burning, waste matter decomposition or fossil fuel production. On the other side, Nitrous Oxide emissions are mainly contributed by the application of nitrogenous fertilizers to soils.

Among various amendment measures, biochar is a unified approach for improving soil fertility as well as mitigating climate change. Biochar has wider applications possibly required not just to comply with food security demand but also to meet the goals of sustainable development. A wealth of benefits that biochar include, increased soil fertility, nutrient availability, improved crop yield and reduction in GHG's emissions. Biochar is prepared from waste biomass and therefore is sustainable and has an economical approach since it can be produced at feasible cost. The range of waste biomass that can be used in biochar preparation is vast and thus aids in waste management. Biochar is a carbonaceous material produced from biomass residue that plays an important role in enriching soil carbon pool. The concept of capturing carbon and storing it in agricultural lands seems to be an innovative approach that can be defined as carbon sequestration. However, it would be resourceful to not only capture carbon emissions from bulk industrial sources but also channelizing the focus to sequester carbon from crop residues rich in biomass. Biochar preparation is the potent way of converting residues into useful resources. Application of biochar offers multitude of advantages ranging from production of renewable fuels to reduction of methane and nitrous oxide emissions from the soil. Biochar is an excellent soil conditioner for its ability to reduce the impact of heavy metal pollution in soil. Therefore, it is crucial to acknowledge the scope of biochar for agricultural lands in long run. In this regard, the factors responsible for quality of biochar and their relative soil dynamics are further explored. A comprehensible knowledge of influence of biochar on vegetable cropping system is reviewed to allow grower's robust decisions for enhanced productivity. The utilization of biochar to decrease greenhouse gas (GHG) footprint per unit yield within agricultural ecosystems is studied to not just illustrate potentials but to occupy knowledge gap to maximize the benefits. Biochar's recognition as negative emissions technology has also been discussed to unleash the comparative edge over other options in mitigating climate change.

2. DECISIVE FACTORS INFLUENCING BIOCHAR YIELD

"The key factors that influence the yield and properties of biochar include feedstock material and processing conditions that determine its role in soil remediation and productivity. Biochar is produced when organic matter undergoes thermal transformation in an oxygen-limited environment. The common thermochemical techniques used in biochar production include pyrolysis, hydrothermal carbonization, gasification, flash carbonization and torrefaction" [5]. "Among these techniques, pyrolysis is the most cost-effective and highly efficient method in biochar production"[6]. "During pyrolysis, besides biochar, bio-oil (can be used as energy source) and gaseous by-products which is a mixture of CO, CO_2, H_2, CH_4, H_2O and other volatile compounds are released. The biochar properties are largely affected by the extent of pyrolysis (pyrolytic temperature and pressure) and entirely by the size of biomass and kiln (or furnace) residence time" [7]. "Pyrolysis is divided into slow pyrolysis (300 -700℃), fast pyrolysis (600 - 1000℃), intermediate and flash pyrolysis (> 1000 ℃). The data in Table 1 provides the range of operating parameters and product distribution of different categories of pyrolysis processes" [8].

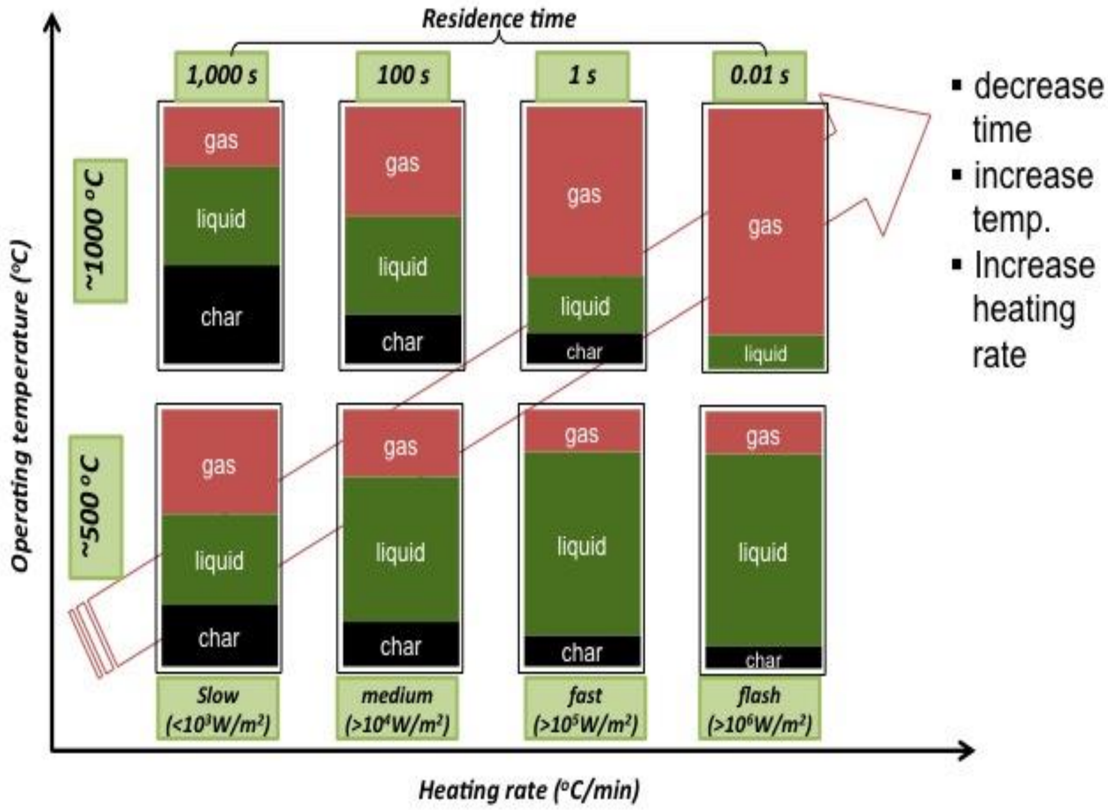

Fig. 1. Summarizing different pyrolysis conditions and the effect on product distribution
Credit: (Created based on Xavier DEGLISE, Emeritus Professor at University Henri Poincaré, France. 2006 BEEMS Module C2, Brian He.)
[Source: 4.1 Biomass Pyrolysis | EGEE 439: Alternative Fuels from Biomass Sources (psu.edu)]

Table 1. Classification of pyrolysis processes

Property	Slow	Intermediate	Fast	Flash
Heating rate (°C/s)	1.1–1	1–10	10–200	>1000
Feed size (mm)	5–50	1–5	<1	<0.5
Reaction temperature (°C)	400–500	400–650	850–1250	>1000
Vapor residence time (s)	300–550	0.5–20	0.5–10	<1
Feed water content (%)	Up to 40	Up to 40	<<10	<<10
Biooil yield (%)	20–50	35–50	60–75	60–75
Biochar yield (%)	25–35	25–40	10–25	10–25
Gas yield (%)	20–50	20–30	10–30	10–30

[Source: Kazawadi et al.[8]

Table 2. Yield and proximate analysis (volatile matter, ash, carbon fixed) of biochars produced at different pyrolysis temperatures

Biomass	Temp. (°C)	Yield (%)	Proximate analysis (wt. %)		
			Volatile Matter	Ash	Carbon Fixed
Chicken manure	350	69.7	36.9 Ab	52.0 Ba	11.1 Cd
	450	63.0	30.6 Ba	55.3 Aa	14.1 Be
	750	55.9	26.5 Ca	56.4 Aa	17.0 Ae
Eucalyptus sawdust	350	42.5	36.9 Ab	0.9 ABe	62.2 Cb
	450	36.0	28.5 Bb	0.7 Be	70.8 Bb
	750	28.2	6.5 Cd	1.1 Ae	92.4 Aa
Coffee husk	350	43.5	34.6 Ac	12.9 Bb	52.5 Cc
	450	37.7	26.2 Bc	12.9 Bb	60.9 Bc
	750	31.6	17.6 Cb	19.6 Ab	62.8 Ad
Sugarcane bagasse	350	37.5	35.0 Ac	1.9 Ad	63.0 Ca
	450	33.2	24.0 Bd	2.1 Ad	73.9 Ba
	750	26.9	7.7 Cc	2.2 Ad	90.1 Ab
Pine bark	350	59.6	38.5 Aa	8.3 Bc	53.2 Cc
	450	49.3	29.3 Ba	7.9 Bc	62.8 Bc
	750	38.9	6.0 Cd	14.5 Ac	79.4 Aa

Source: Domingues et al. [13]

From previous research, it can be concluded that although fast and flash pyrolysis allows for rapid thermal decomposition but main products are gases and bio-oil (thinner). On the contrary, slow and intermediate pyrolysis yields char, gases and bio-oil (tar) as major products. It can be explained by the fact that as the pyrolysis temperature increases, moisture and volatile matter content decrease while fixed-carbon content increases. Also, ash content per unit mass increases with increase in temperature. Fig. 1 summarizes different pyrolysis conditions and the effect on product distribution. Therefore, it is evident that each type of pyrolysis differs in temperature, residence time, heating rate and products obtained.

To maximize the biochar yield, the production technique must be compatible with feedstock properties. The feedstock material is classified into woody and non-woody substrates. Woody biomass is procured from trees and woody forest residues. Non-woody biomass is plant material from crop residues and agricultural lignocellulose materials; animal and industrial solid wastes. Woody biomass is characterized by low moisture, low ash, high calorific value, high bulk density and less voidage; in contrast, non-woody biomass exhibits the opposite characteristics [9]. The analysis of heterogeneity of different biomasses is crucial for understanding their respective composition. “There are several parameters that determine the compositional variance in different biomasses which are broadly categorized into physical and chemical properties of biomasses used in production of biochar. Physical properties include moisture content (%), water holding capacity (g water g^{-1} dry), bulk density (kg m^{-3}) and porosity (%). Chemical properties include pH, EC (dS m^{-1}), total organic matter (%), total organic carbon (%), C/N ratio, total nitrogen (%), total potassium (%)

and others. Animal biochars are mostly constituted of animal protein such as gelatin, collagen, and polysaccharides (cellulose, starch and carbohydrates)" [10]. "Since majority of plant-based biomass is composed of cellulose, hemicellulose and lignin; these components undergo different reactions to produce biochar" [5]. "The pyrolysis temperature and feedstock type influences the physical and chemical properties of biochar due to stage wise decomposition of structure and chemical bonds" [10]. "Different types of feedstock's respond heterogeneously to particular pyrolysis conditions due to variations of cellulose $(C_5H_8O_4)_m$, hemicelluloses $(C_5H_8O_4)$, lignin $[C_9H_{10}O_3\ (OCH_3)_{0.9-1.7}]_n$ and inorganic mineral contents" [11]. "It is evident that different materials yield varying amounts of biochar at different temperatures, for instance, in a study using different agricultural wastes (straw rice, sawdust, sugarcane and tree leaves), researchers found that biochar yield decreased variably when the pyrolysis temperature increased was from 400 to 800-degree Celcius [12]. Biochar yield decreases with increasing pyrolysis temperature as a result of the increased burning rate, because of the variation of lignin and cellulose content of biomass and conversion of organic matter to ash, which reduced the carbon content of the biochar [12] but it yields more energy and offers more stability of carbon in soil. Biochar produce from animal and plant-based biomass at different pyrolysis temperatures are shown in Table-2, [13]. It can be analyzed from the data given in Table 2 that with increase in temperature, biochar yield decreases for any feedstock source. However, it is evident from the figures in table that chicken manure (animal-based biomass) showed highest yield and ash content at temp 350- degree Celcius (slow pyrolysis) comparative to plant-based biomasses.

Uppercase letters compare pyrolysis temperatures within the same biomass and lowercase letters compare biomass at the same temperature. The same letter does not differ by the Tukey test at $p < 0.05$.

3. QUALITY OF BIOCHAR AND RELATED SOIL-DYNAMICS

The IBI (International Biochar Initiative) 2015 has formalised various physical parameters linked to biochar quality which include pH, volatile compound content, water holding capacity, ash content, bulk density, pore volume, and specific surface area (Anonymous). The nutrient quality and physico-chemical properties of biochar are a product of feedstock material, activators or amendments added and processing conditions. It should be noted that biochar produced from same feedstock material varies in properties due to varying conditions of pyrolysis process. "For instance, biochar produced from straw-based feedstock and low-temperature pyrolysis exhibits numerous surface functional groups, enhancing its surface activity and adsorption capacity, resulting in increased active sites for biochar surface adsorption, reduced energy requirements for reactions, enhanced atomic bonding orbitals, and improved potential for charge transfer between biochar and soil adsorbates" [14]. Further, application of biochar in soil is calibrated by balancing the parameters based on needs. The impact of biochar application in soil is not solely the function of biochar properties but includes analysis of several factors. These factors include type of climate and soil, physico-chemical properties of soil, crop-type, biochar application rate and method, treatments applied, post-application management and so on. Biochar-soil dynamics thus yields conceptual framework for analysing its effectiveness. The following table indicates the effectiveness of application of biochar on vegetable crop yield, its role in soil nutrient enhancement, and remediation.

4. ROLE OF BIOCHAR IN CLIMATE CHANGE MITIGATION

Crop residue accounts for global concern as how to manage it effectively by not polluting the surroundings further. For safe disposal of agricultural residues, biochar is the convenient approach which not only allows residue management but also enhances soil health, reduces GHG emissions and provides the most stable carbon source that takes thousands of years to degrade. Biochar sequester carbon from environment and has the potential to remove 6% of global emissions which is significant [27]. The carbon that would otherwise be released into environment from degradation of residues is stored by converting the biomass to biochar. Biochar application has been known to reduce nitrous oxide (N_2O) emissions from soil [28]. "The biochar has a strong adsorption capacity due to its high porosity, large specific surface area, and functional group properties on the surface and therefore, biochar can reduce N_2O emissions by absorbing NH_4^+-N and NO_3^--N which are N_2O precursors, as well as directly capturing N_2O"

Table 3. Yield response of different biochar types on vegetable crops, their environmental impact and impact on soil health

Biochar type	Yield response on vegetable crops	Impact on soil health	Environmental impact	References
Rice Husk Biochar	In acidic soil, biochar treatment yielded 212% more yield than the control in chili pepper, 210% in tomato, 182% in soybean and 612% in yard long bean. While in neutral soil, biochar treatment yielded 76% more tomato yield than the control; and in alkaline soil, biochar treatment yielded 189% more than the control in chili pepper, 223% in sweet pepper, 139% in Phaseolus bean and 303% in carrot.	**Alkaline Soil-**No significant response in alkaline soil **Acidic Soil**- improvement of soil physical properties such as permeability, water holding capacity and nutrient use efficiency.	**1.** Biochar has also been extensively used to remove different types of pollutants (e.g. heavy metals, dye, pharmaceuticals, pesticides/herbi cides and phenols) from wastewaters. **2.** The high efficiency of biochar to adsorb heavy metals and organic pollutants is related to its high porosity, high number of functional groups and high pH.	Williams *et al.* [15] Asadi *et al.* [16]
Coconut Husk Biochar	18% increase in yield of Water spinach	○ Coconut husk increases water holding capacity, improves pH, organic carbon, porosity and nutrient availability in soil. ○ It contains relatively high concentration of essential minerals including P, K, Na, Ca), Mg, Mo, Zn, Mn, Cu, Ni, Fe and Si. ○ Coconut based biochar is alkaline and thus promotes higher microbial activity, higher organic matter mineralization, higher plant nutrient availability and higher acid neutralization.	Soil amendment, Carbon sequestration and Water treatment are the environmental applications for coconut husk biochar .	Zhao *et al.*[17] Nagula *et al.* [18] Ajien *et al.* (2022)
Wheat straw Biochar	Amending the soil of lower fertility with wheat straw biochar of concentration BC_3% (Biochar concentration) significantly	○ Increase the sorption of deltamethrin in soil. The enhanced sorption of deltamethrin in the biochar amended soil could reduce its leachability in	**1.** Wheat straw biochar aids in mitigating climate change by decreasing the N_2O and CO_2 emissions from agricultural soils.	Purkaystha *et al.* [19] Palangi *et al.*

Biochar type	Yield response on vegetable crops	Impact on soil health	Environmental impact	References
	increased green pepper yield, due to improved soil chemical properties (pH, P, K, SOM, and CEC), and enhanced water and nutrient use.	the soil. ○ Therefore, wheat straw biochar can immobilize deltamethrin in the soil to a certain extent and minimize deep leachability, reduce the risk of pesticide contamination	**2.** Wheat straw biochar application reduces the sensitivity to temperature changes of the decomposition of the new organic matter added to the soil.	[20] Duan *et al.* [21]
Sugarcane Bagasse biochar (SBB)	Yield contributing characters of Okra treated with 10% SBB + CF treatment is increased significantly as compared to no control treatment PL- 113% (↑) IPW-88% (↑) PD-69.7% (↑) NPP-32.8% (↑) PWP-113% (↑) NSP- 148% (↑)	It enhances the water holding capacity of saline soil which has high seepage problem. It also enhances soil quality due to its high surface area and surface chemical functional groups	Increasing concentration of nitrate in drinking water can cause harmful effect on human health, Sugarcane Bagasse biochar is an effective adsorbent for the nitrate adsorption from aqueous solution.	Sikdar *et al.* [22] Nie *et al.* [23] Hafshejani *et al.* [24]
Chicken Manure Biochar	An increase in yield is seen by 23.69% when chicken biochar is used in red chilli.	○ It can help in increasing the availability of phosphorus in the soil. ○ It contributes complete nutrients needed by plants. It increases soil pH and soil aggregates, increases soil water content. ○ Increase the ability of soil to provide Ca, Mg, P and K, increase soil microbial respiration, increase cation exchange capacity.	Chicken manure-based biochar can be used as an effective adsorbent for removing contaminants from water. For instance, it has been explored for **arsenic removal.**	Mahendra *et al.* [25] Babaei *et al.* [26]

Abbreviations: PL- Pod length; IPW- Individual pod weight; PD- Pod diameter; NPP- No. of pods/plant; PWP- Pod weight/ plant; NSP- No. of seeds/ plant; SBB- Sugarcane Bagasse Biochar; CF- Chemical Fertilizer treatment

[29]. “Methane emissions from soil is attributed majorly to microbial activities in soil. Global methane fluxes are net positive as rice cultivation is a much larger source of CH_4 than the sink contribution of upland soils” [30-31]. Biochar has more porous structure and high surface area which allows for adsorption of methane molecules and it also provides space for methane oxidizing microbes. Long term application of biochar in soils can help mitigate global temperature incline by reducing the GHG emissions. Apart from this biochar’s role as negative emissions technology for removing CO_2 from atmosphere is established by the 2018 report of Intergovernmental Panel on Climate Change (IPCC)[32]. Biochar is an effective NET (Negative Emissions Technology) since it is produced from sequestered atmospheric carbon and is highly stable, hence, carbon is stored in soil for longer period that would otherwise be released into atmosphere[33].

5. CONCLUSION

Biochar is a single promising solution for multiple environmental issues including soil health improvement, improving crop yields, agricultural waste management, climate change mitigation, waste water treatment and water conservation. Biochar dynamics in soil depend on several factors that needs more investigation. While biochar aids in increasing yield of different crops, it is a definite technology for managing global temperatures in desired range by reducing impact of GHG emissions. Physico-chemical properties exhibited by biochar is a function of availability of wide range of biomasses including both plant and animal sources and different operational parameters of biochar production.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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