Review Article

Effectiveness of soil amended biocharfor improving the vegetable production, soil healthand environmental considerations

Notes: The words with red color words are meaning the words after correction.

UNDER PEER REVIEW

Abstract

Increasedemphasis on sustainable growth in agriculture without endangering the environment has assumed greater importance. The introduction of biochar has the potential to increase crop yields and soil fertility in agriculture while reducing greenhouse gas emissions at the same time. Biochar production technology and biomass type has a great influence on its quality and yield which in turn is responsible for altering soil fertility status and enhancing other soil properties. Biochar is obtained by thermochemical conversion from biomasses by the process of pyrolysis and different pyrolysis conditions which include heating rate, temperature or residence time affects 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 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. Biochar The objective of this review paper is to extensively justify the role and importance of biochar on agricultural fields in long run to harness the benefits for sustainable growth.

Keywords: biochar, biomass, negative emissions technology, carbon sequestration

Introduction

The major setback faced by agriculture globally is decline in productivity of agricultural lands owing to the poor soil condition. Intensive farming practices over decades has degraded soils and has 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(Shubham *et al.* 2022).The fact that land under cultivation is limited, there is need to elevate the quality of soils under agriculture for better yield through application of soil remedy techniques. 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 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 is the fourth largest sector contributor of GHG's globallyin the year 2020 with 5.87 billion tones emissions measured in carbon dioxide-equivalents while agriculture being the dominant sector in different countries(Anonymous2020). Among non-CO_2 greenhouse gases, Nitrous Oxide (N_2O) and Methane (CH_4) are the dominant gases responsible for greenhouse effect not in terms of mass since they make up only small fraction of GHG's emissions. For instance, according to a source, nitrous oxide warms the planet 300 times as much as carbon dioxide(Canfield *et al.*,2010).As for Methane, one ton of methane would generate 28 times the amount of warming as one ton of CO_2 (Saunois *et al.*,2020).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)(Anonymous2020). 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 majorly 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 sustainable goals of development. A wealth of benefits that biochar withhold include increased nutrient availability as well as fertility in soil, 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

UNDER PEER REVIEW

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. Production of biochar offers multitude of advantages ranging from production of renewable fuels to reduction of methane and nitrous oxide emissions from soil. Biochar is an excellent soil conditioner with potent 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.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 make robust decisions for enhanced productivity. The utilization of biochar to decrease greenhouse gas (GHG) footprint per unit yield within agricultural ecosystems is studiedto not just illustrate potentialsbut 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.

Decisive factors influencing biochar yield

The key factors that influence the yield and properties ofbiochar include feedstock material used in biochar preparation and processing conditions which in turn determine its role as a soil applicator for soil remediation and productivity. Organic matter undergoes thermal transformation in an oxygen-limited environment to produce biochar. The common thermochemical techniques used for biochar production include pyrolysis, hydrothermal carbonization, gasification, flash carbonization and Torre faction(Yaashikaa*et al.*2020). Pyrolysis has been considered as the mostcost-effective and highly efficient method for biochar production(Cha *et al*. 2016).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. Thebiochar properties are heavily affected by the extent of pyrolysis (pyrolytic temperature and pressure) and entirely by the size of biomass and kiln (or furnace) residence time(Anonymous 2018).Pyrolysis is divided into slow pyrolysis (300 -700℃), fast pyrolysis (600 -1000℃), intermediate and flash pyrolysis (> 1000 ℃).The data in table 1provides the range of operating parameters and product distribution of different categories of pyrolysis processes(Kazawadi *et al.* 2021). From table 1, 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 increase, moisture and volatile matter content decrease while fixed-carbon content increase. Also, ash content per unit mass increase with increase in temperature. Figure 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.

UNDER PEER REVIEW

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.* 2021]

Table 1: Classification of pyrolysis processes

REVIEW

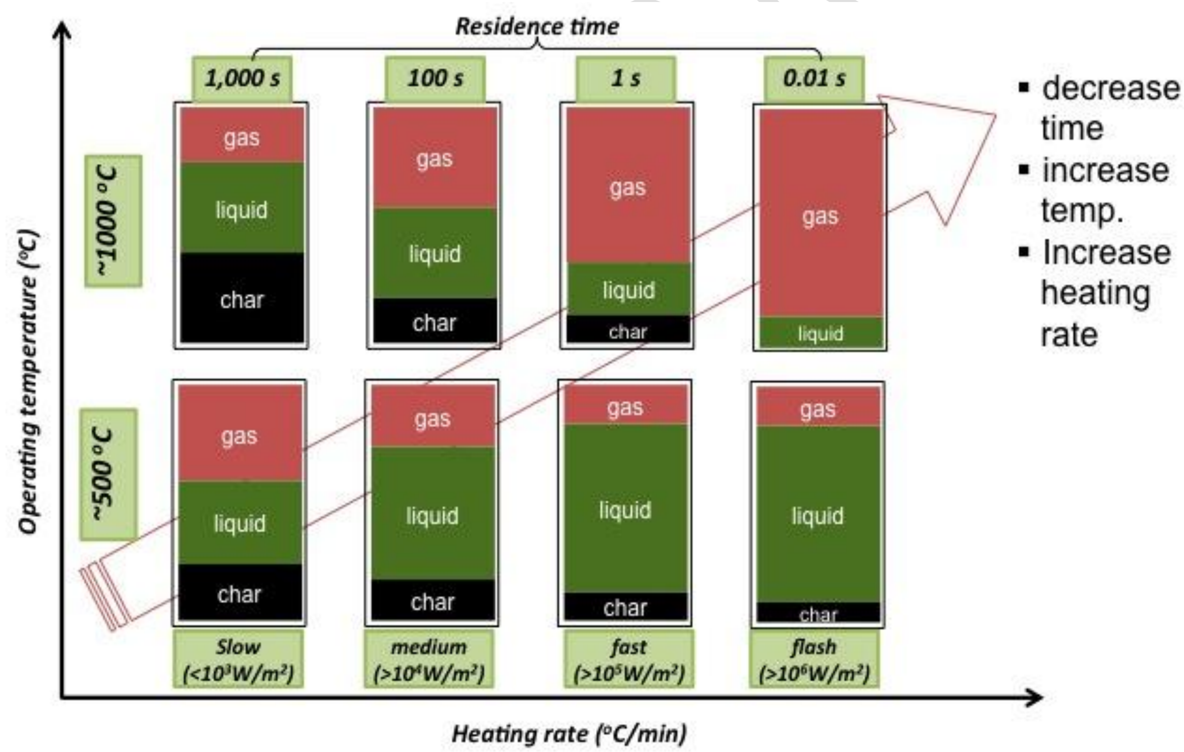

Figure 1:Summarizing different pyrolysis conditions and the effect on product distribution.

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)]

In order to maximize the biochar yield, theproduction techniquemust 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 void age; in contrast, non-woody biomass exhibits the opposite characteristics(Tomczyk *et al.* 2020). The analysis of heterogeneity of different biomasses is crucial for understanding their respective composition.There are several parameters to 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)(Huang *et al.* 2021). Since majority of plant-based biomass is composed of cellulose, hemicellulose and lignin; these components undergo different reaction conditions to produce biochar(Yaashikaa *et al.* 2020). The pyrolysis temperature and feedstock type influences the physical and chemical properties of bio char due to stage wise decomposition of structure and chemical bonds(Huang *et al.* 2021).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(Hassan *et al.,* 2020).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 as the pyrolysis temperature increased from 400 to 800-degree Celcius(Khater *et al.*2024).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(Khater *et al.* 2024) but it yields more energy and offers more stability of carbon in soil. In table 2, Yield and proximate analysis (volatile matter, ash, carbon fixed) of biochars produced at different pyrolysis temperatures for animal source biomass and plant-based biomass is demonstrated (Domingues *et al.* 2017). 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.

UNDER PEER REVIEW

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

UNDER PEER REVIEW

	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.*2017]

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 $p < 0.05$.

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

Quality of biochar and related soil-dynamics

The IBI (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. The nutrient content and physico-chemical properties of biochar is a product of feedstock material, activators or amendments added and processing conditions. It can 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 (He *et al.* 2024).Further, application of biochar for desired purpose 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 ofseveral 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 different types of biochar on yield of vegetable crops, its role in soil nutrient enhancement and remediation as well environmental impact.

Biochar type	Yield response onvegetablecrops	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.*(2023) Asadi *et al.*(2021)
Coconut Husk Biochar	18% increase in yield of Water spinach	○ Coconut husk increases water holding capacity, improves pH, organic carbon, porosity and nutrient availabilityin soil. ○ It contains relatively high concentration of essential minerals	Soil amendment, Carbon sequestration and Water treatment are the environmental applications for coconut husk biochar.	Zhao *et al.* (2019) Nagula *et al.* (2022) Ajien *et al.* (2022)

UNDER PEER REVIEW

		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.		
Wheat straw Biochar	Amending the soil of lower fertility with wheat straw biochar of concentration BC_3% (Biochar concentration) s ignificantly increased green pepper yield, due to improved soil chemical properties (pH, P, K, SOM, and CEC), and enhanced water and nutrient use.	○ Increase the sorption of deltamethrin in soil. The enhanced sorption of deltamethrin in the biochar amended soil could reduce its leachability in 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	**1.** Wheat straw biochar aids in mitigating climate change by decreasing the N_2O and CO_2 emissions from agricultural soils. **2.** Wheat straw biochar application reduces the sensitivity to temperature changes of the decomposition of the new organic matter added to the soil.	Purkaysthа*et al.* (2022) Palangi *et al.* (2021) Duan *et al.* (2020)
Sugarcane Bagasse biochar (SBB)	Yield contributing characters of Okra treated with 10% SBB	It enhances the water holding capacity ofsaline soil which has high seepage problem. It also enhances soil	Increasing concentration of nitrate in drinking water can cause	Sikdar *et al.* (2023) Nie *et al.* (2018)

UNDER PEER REVIEW

	+ 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% (↑)	quality due to its high surface area and surface chemical functional groups	harmful effect on human health, Sugarcane Bagasse biochar is an effective adsorbent for the nitrate adsorption from aqueous solution.	Hafshejani*et al.* (2016)
Chicken Manure Biochar	An increase in yield is seen by 23.69% when chicken biochar is used in red chilli.	○ It can help inincreasing theavailabili ty ofphosphoru s 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 fromwater. For instance, it has been explored for arsenic removal.	Mahendra *et al.* (2020) Babaei*et al.* (2023)

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

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

UNDER PEER REVIEW

Biochar in mitigating climate change

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 enhances soil health, reduces GHG emissions as well as 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(Anonymous 2023). The carbon that would otherwise be released into environment from degradation of residues is being stored by converting the biomass to biochar. Biochar application has been known to reduce nitrous oxide (N_2O) emissions from soil(Woolf *et al.* 2018).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(Liang *et al.* 2023). 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(Jeffery *et al.* 2016). 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). Biochar is an effective NET 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.

Conclusion

Biochar is a single promising solution for multiple environmental remediations including soil health improvement, improving crop yields, agricultural waste management, climate change mitigation, waste water treatment and water conservation. 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. Bio-oil and gaseous by-products are yielded during biochar production that can be harvested using high-end technology. Biochar dynamics in soil depends on several factors from climate to soil. Biochar aids in increasing yield of different crops. Biochar is a definite technology for managing global temperatures in desired range by reducing impact of GHG emissions.

UNDER PEER REVIEW

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UNDER PEER REVIEW

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UNDER PEER REVIEW

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