Archives of Agriculture and Environmental Science 6(1): 108-113 (2021)
https://doi.org/10.26832/24566632.2021.0601014

e-ISSN: 2456-6632

This content is available online at AESA

Archives of Agriculture and Environmental Science

Journal homepage: journals.aesacademy.org/index.php/aaes

REVIEW ARTICLE

A review on biochar as a potential soil fertility enhancer to agriculture

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ARTICLE HISTORY

Received: 30 December 2020
Revised received: 06 March 2021
Accepted: 20 March 2021

Keywords

Biochar
Fertilizer
N-cycling
Productivity
Soil fertility
Stability

ABSTRACT

Biochar is a carbon rich material produced from the pyrolysis of biomass at high temperature under oxygen deficit condition. It is recently introduced as one of the effective soil amendments with wide range of environmental benefits. This paper summarizes and discusses the effects of biochar on different soil parameters and crop productivity by reviewing scientific studies conducted around the globe. The benefit is derived especially from the improved soil physical and chemical properties through improvement in soil moisture content, soil bulk density, nitrogen uptake and availability and retention of other soil nutrients, but its effect is highly dependent on feedstocks used, pyrolysis temperature and soil types. It has been found to be more effective on infertile and degraded land. Further research is required to completely reveal the capacity of biochar in enhancing the soil characteristics.

Citation of this article: Kandel, A., Dahal, S., & Mahatara, S. (2021). A review on biochar as a potential soil fertility enhancer to agriculture. *Archives of Agriculture and Environmental Science*, *6*(1), 108-113, https://dx.doi.org/10.26832/24566632.2021.0601014

INTRODUCTION

Depletion of soil carbon, excessive emission of greenhouse gases and global heating are the major concerns of the present time (Abrishamkesh *et al.*, 2015). Low fertility, soil acidity, weak structure and high susceptibility to crusting, compaction and accelerated soil erosion are the major challenges especially in tropical region (Adekiya *et al.*, 2020). Leaching of chemical fertilizers from arable soils is the major constraint in soil production as well as a potential source of environmental pollutions (El Sharkawi *et al.*, 2018). Organic manure such as compost, farm yard manure etc. added to increase soil organic matter undergo rapid decomposition and require frequent application on one hand whereas acts as the potential contributor to greenhouse gases on the other (Islami *et al.*, 2011). The rapid decline in global soil fertility has increased the need of efficient soil amendments with wider environmental benefits that ensure long term sustainability of crop production (Šimanský *et al.*, 2016).

Biochar, a carbon rich material produced from pyrolysis of biomass in the absence of oxygen at high temperature (Adekiya *et al.*, 2019) has been reported to alleviate climate crisis, improve soil health and enhance crop production (Pandit, 2018). Soil physical and chemical qualities have a direct impact on soil efficiency for crop production (Benjamin *et al.*, 2003). Several studies have reported the positive effects of biochar application on soil parameters. Biochar has found to increase water holding capacity of soil (Karhu *et al.*, 2011), mainly in sandy soil (Basso *et al.*, 2013) and loamy sand soil (Yu *et al.*, 2013) and can also be used as an effective soil conservation measure because of its effect on soil infiltration improvement and soil erosion control in arid and semi-arid climates (Abrol *et al.*, 2016).The liming effect of biochar as well as improvement in Cation Exchange Capacity, soil structure (Liu *et al.*, 2012), bulk density and aggregate stability adds to its benefits (Burrell *et al.*, 2016). The decomposition of biochar by soil microbes or through maintenance of existing soil carbon, biochar has found to increase soil carbon significantly (Agegnehu *et al.*, 2015; Al-Wabel *et al.*, 2017). Inclusion of biochar enhances plant growth by expanding the accessibility of basic nutrients (N,P,K etc.) in soil and their eventual take up by plants (Berihun *et al.*, 2017; Lehmann, 2007). Biochar has constructive outcome on crop yield in general, and it is more effective when applied to degraded, low fertile soil rather than nutrient rich healthy soil (El-Naggar *et al.*, 2018). This review focuses on the impacts of biochar on soil physical and chemical properties and its potential impact on crop yield and recommends future directions for research.

BIOCHAR CHARACTERISTICS

Biochar has heterogeneous structure with variation in elemental compositions such as (C, H, O, N, S, P, K, Ca, Mg, Na and Si); among which carbon is present in higher amount. These elemental compositions greatly differ depending upon the varieties of feedstocks subjected under different pyrolysis conditions (as shown in Table 1) which in turn, greatly determine the physiochemical properties of biochar and thus, affect its reactivity and stability in soil (Chen *et al.*, 2019; Spokas, 2014).

EFFECT OF BIOCHAR ON SOIL PHYSICAL PROPERTIES

Biochar has significant impact on soil physical properties (Alghamdi, 2018; Atkinson *et al.*, 2010). Being porous natured and low density substance, its incorporation dilutes the mineral fractions in soil, reducing the soil bulk density (Pratiwi and Shinogi, 2016; Tomasz *et al.*, 2016). Jien and Wang (2013), observed the reduction in soil bulk density from 1.4 to 1.1 Mg m^{-3} in highly weathered soil. Githinji (2014) reported the reduction in soil bulk density from 1.33 g/cm^3 to 0.363 g/cm^3 and increment in porosity from 0.500 cm^3 cm^{-3} to 0.773 cm^3 cm^{-3} in sandy loam. In agreement to this, a number of findings have shown the significant reduction in soil bulk density and increment in porosity in biochar treated soil as compared to control treatment (Abrishamkesh *et al.*, 2015; Devereux *et al.*, 2013; Pratiwi and Shinogi, 2016). This reduction in soil bulk density assists the soil to hold more water and improves the water holding capacity in soil (Hussain *et al.*, 2016). Furthermore, the increase in soil surface area and improved soil aggregates due to the amendment of biochar might be another possible reasons for improving water retention in soil (Adekiya *et al.*, 2020). The moisture retention, water holding capacity, hydraulic conductivity and water infiltration rate are greatly influenced by surface area, porosity, bulk density and aggregate stability in soil (Mukherjee and Lal, 2013). An enhancement in water holding capacity up to 31% in clay soil (Lu *et al.*, 2014), 22% in soils low in silt (Peake *et al.*, 2014), 11% in silt loam (Karhu *et al.*, 2011) was studied in different experiments. However, it is greatly influenced by biochar type and soil texture (Mukherjee and Lal, 2013). The saturated hydraulic conductivity was increased by 20.9% with biochar amendment in silty clay soil (Li *et al.*, 2018). Jien and Wang (2013) reported the saturated hydraulic conductivity in highly weathered soil was increased by 1.8 times when applied with biochar. However, no effect was observed by Laird *et al.* (2010) in fine loamy soil with the application of hardwood biochar whereas Barnes *et al.* (2014) found that the application led to the reduction in sandy soil by 92% and in organic soil by 67% but in clay soil, it was increased by 328%. This suggests that the effect of biochar is greatly influenced by biochar types, its particle size, application rates and soil types.

Table 1. Chemical compositions of different biochars under different pyrolysis conditions.

Feedstocks	Temp. (°C)	pH	C (%)	H (%)	O (%)	N (%)	P (%)	K (%)	References
Maize straw	300	9.84	48.9	3.54	23.85	1.25			(Wang *et al.*, 2015)
	400	10.47	53.81	3.11	18.58	1.22			
	600	11.37	62.9	1.98	16.17	1.28			
Chinese rice straw	400	7.84	61.71	3.41		1.27			(Yoo *et al.*, 2015)
	600	9.86	72.83	1.79		1.06			
Korean rice straw	300	6.75	50.50	3.62		0.89			
	600	10.34	50.31	1.35		0.79			
Maize straw	400	10.7	76		13	5		4	(Zhai *et al.*, 2014)
Pinewood	700	6.60	95.30	0.82	3.76	0.12			(Zhengang Liu *et al.*, 2010)
Prosopis wood	350	9.4	82			0.19	0.10	0.2	(Pandian *et al.*, 2016)
Maize stalk	350	8.9	66			0.31	0.24	0.3	
Cotton stalk	350	8.8	74			0.26	0.15	1.1	
Redgram stalk	350	8.4	79			0.29	0.18	0.9	
Rice husk	750	8.6	81.8	1.72		0.47	0.003		(Pratiwi and Shinogi, 2016)
Peanut shell	500	8.6	81.8	2.9	3.3	2.7	0.26		(Githinji, 2014)
Sewage and sludge	300	6	23.4	2.53	18.67	3.3	4.11	0.016	(Sousa and Figueiredo, 2016)
Conocarpus	400	9.85	76.18			0.42			(Al-Wabel *et al.*, 2015)
Rice straw	600		78.5		13.39	0.70	0.23	1.56	(Sun *et al.*, 2014)
Cotton straw	600		74.8		17.64	0.69		4.08	
Wheat straw	600		72.9		17.2	0.81		1.82	
Corn straw	600		72.0		18.3	1.09	0.26	4.57	
Poplar shaving	600		81.1		13.3	0.95	0.35	2.61	
Hardwood	580	7.56	52			0.65	0.73	1.25	(Adekiya *et al.*, 2019)
Birch wood	300	5.1	72	4.9	23				(Hagner *et al.*, 2016)
	375	5.2	80	3.1	15				
	475	7.5	89	3.9	7				

EFFECT OF BIOCHAR ON SOIL CHEMICAL PROPERTIES

Soil pH is an important factor affecting the nutrients availability in soil. Soil acidity is mainly associated with Al species. Plants grown in acidic soil mostly suffer due to Al toxicity (Sparks, 2003). Biochar has potential in increasing soil pH in acidic soil (Chan *et al.*, 2008; Major *et al.*, 2010; Zwieten *et al.*, 2010). Biochar itself is generally alkaline in nature due to the presence of ash enriched with carbonates and phosphates (Chen *et al.*, 2019). Hence, on applying, there is release of basic cations contained in it into the acidic soil which displace the exchangeable Al^{+3} and H^{+} on soil surface and decrease the soil exchangeable acidity (Chintala *et al.*, 2014). Novak *et al.* (2009) observed the rise in soil pH from 4.8 to 6.3 and decrease in exchangeable acidity by 50% on application of pecan shell biochar in Norfolk loamy sand. Chan *et al.*, (2007) reported the rise in soil pH by 1.22 times in green waste biochar amended soil at rate 100 t/ha as compared to no biochar amended soil. Similarly, Yuan and Xu, (2011) observed the strong linear correlation between soil pH and biochar alkalinity in acidic ultisol and concluded that the liming potentiality of biochar is connected to its alkalinity. In contrast, no effects in pH was observed by (Usman *et al.*, 2016; Zhai *et al.*, 2014; Zhang *et al.*, 2011) on alkaline soil. But Abrishamkesh *et al.* (2015) observed the fall in pH in alkaline soil and the fall was more pronounced in soil treated with biochar having low pH.

Soil nitrogen

Several studies on biochar provide affirmation on effect of biochar on N cycling in soil and it provides perspectives on reinforcing the N cycle in agricultural ecosystems. Bunch of biochar-soil research so far, in relation to N cycling is scattered with variety of results depending on the types of biochar and characteristics of biochar applied soil. However, it is obvious that biochar absorbs N through ion exchange, removes NH_3 via adsorption and reduces N-leaching (Clough *et al.*, 2013). Mandal *et al.* (2015) found the significant improvement in soil available nitrogen through direct and interactive effect of biochar and fertilizer. Biochars derived from various sources alone improved the accessible nitrogen going from 4.5 to 21.3 mgkg^{-1} over control (110mgkg^{-1}) while in combination with fertilizer they enhanced N going from 4.5 to 15.7 mgkg^{-1}. Biochar had blended impact on soil available nitrogen. Biochar having high carbon content, when applied in soil may cause immobilization of accessible nitrogen in soil, but, if there is less accessible nitrogen, it stimulates mineralization thus impact may be blended. (Mandal *et al.*, 2015). The result from the laboratory experiment in Indonesia had shown the influence of biochar application on release pattern of nitrogen from urea fertilizer. Researchers found that transformation of N-NH_4 to N-NO_3 was slowed down by biochar application. There was 62 mgkg^{-1} N-NH_4 in chicken manure biochar treated soil and 52 mgkg^{-1} in city waste biochar treated soil, after 28 days of soil incubation, which on comparison were higher than untreated soil (12 mgkg^{-1} N-NH_4) or even in chicken manure treated soil (40mgkg^{-1}). The negative charge from carboxyl and phenolic group in biochar, absorbs the N-NH_4, therefore, reduces nitrogen loss due to leaching (Utomo *et al.*, 2011). Similarly, Zheng *et al.* (2013) reported reduction in NH_4^+-N and NO_3^-N leaching. This was attributed to increased water holding capacity, improved N immobilization and NH_4^+ adsoption (Zheng *et al.*, 2013).

Phosphorus

Biochar increases the phosphorus availability in soil as it contains certain amount of P in ash (Zhai *et al.*, 2014). The availability of P depends upon biochar feedstocks, pyrolysis temperature, application rate and soil pH (Glaser and Lehr, 2019). In acidic soil, Al^{3+} and Fe^{3+} forms insoluble phosphates with P and makes it less available. As biochar application increases soil pH, the concentration of these ions reduces and makes P more available (DeLuca *et al.*, 2009). In meta-analysis conducted by Glaser and Lehr (2019) found no significant effect on P availability in alkaline soil with biochar amendment. Whereas, Abrishamkesh *et al.* (2015) found higher Olsen-P in non-biochar treated alkaline soil as compared to biochar treated alkaline soil. In alkaline soil, adding of biochar limits the P availability since it adds more alkali metals which in turn enhances bonding of Ca with P (Atkinson *et al.*, 2010).

Potassium

Application of biochar has positive effect on soil K availability which increased with increase in application rate. Such result could be attributed to high ash content in biochar (Abrishamkesh *et al.*, 2015). Berihun *et al.* (2017) observed *Eucalyptus* and *Lanatana* biochar treated plots were found to have high K values of 42.83 ±1.33 and 43.33 ±11.84 cmolc kg^{-1}, respectively, whereas control plot reported the lowest soil K (32.7±0.77 cmolc kg^{-1}). Application of rice husk biochar in soil significantly increased the exchangeable potassium. The rate of available potassium was found to be 3.73 mg/kg in control, 163 mg/kg in RHB 2% and 215 mg/kg in RHB 4% (Ghorbani and Amirahmadi, 2018).

Soil organic carbon

Biomass is mainly composed of C, H and O. On subjecting to pyrolysis, these elements get volatilized at higher rate leaving C behind which increases the C content in biochar (up to 80% wt.) (Mašek, 2013). Charring of biomass sequesters about 50% of initial carbon as compared to carbon remained after direct burning and biological decomposition (Lehmann *et al.*, 2006). There are several studies suggesting the increment in SOC on application of biochar. Zhang *et al.* (2010) observed the increment in SOC level by 57% in biochar treated plot comparison to untreated plot. Similarly, in two-year experiment, Zhang *et al.* (2017) studied the SOC content at different soil depth. The total SOC sequestration rate in the soil depth of 0-100cm was found to be increased by 35.6% and 28.1% on application of wheat straw biochar plots at the rates of 8 and 16t/ha respectively as compared to non-pyrolyzed wheat straw treated plot. Thus, increase in SOC in biochar amended soil is mainly associated to the high content of carbon and also due to the preservation of organic carbon from being utilized (Ouyang *et al.*, 2014).

EFFECT ON YIELD

Biochar enhances crop production system due to the improvement in soil quality. However, its performance varies greatly according to the biochar properties, soil types and crops (Zwieten *et al.*, 2010). Its application has increased yield in rapeseed and sweet potato by 36.02% and 53.77% respectively (Liu *et al.*, 2014); enhanced the pod yield by 29% in ground nut (Pandian *et al.*, 2016); increased total dry matter in radish by 96% (Chan *et al.*, 2008). A meta-analysis conducted by Liu *et al.*, (2013) found the greater increment in productivity of legumes (30.3%), vegetables (28.6%) and grasses (13.9%) on application of biochar. The average increment in productivity of maize, wheat and rice was 8.4%, 11.3% and 6.6%, respectively. The authors reported the overall average increase in crop productivity by 11.0% in biochar amended soil as compared to control. In contrast, some studies have reported no response in crops productivity (Chan *et al.*, 2007; Zwieten *et al.*, 2010) or even decline in productivity (Gaskin *et al.*, 2010) in biochar amended soil.

FUTURE PERSPECTIVE AND RESEARCH NEEDS

Various research and findings have pointed out the positive impacts of biochar in soil and crop productivity; however, there are still many areas left for further discoveries. Biochar does not give uniform result. It can improve or decline or even show no effect on soil quality and productivity. The variation in biochar properties, soil types, wide range of crops and agro-climatic conditions are the reasons for those inconsistencies. Hence, far more research needs to be conducted to find the suitability of different biochar in different crops and soil types. Similarly, additional studies should be carried out to observe the long-term effects of biochar under field conditions since most of the research till today are limited under short term period under laboratory or glass house condition. Furthermore, research should also be focused on the effects of biochar in soil biological properties since, it also has important role in maintaining soil fertility. In addition to this, future studies should focus on the longevity of biochar, address the risk related to biochar on soil properties and the use of designed biochar in soil.

Conclusion

Biochar is found to be a potential input to agriculture. Its effect is mostly observed in low fertile, acidic and degraded soil. The decrease in soil bulk density, large surface area in soil, presence of exchangeable cations and nutrient elements, increase in availability of nutrients and prevention of nutrients leaching are some of the major benefits of biochar contributing towards increase in crop productivity through improvements in soil properties. However, this does not imply that all biochar has positive effects on all types of soil and crops. We also reported no response or even negative response of biochar in some studies. The performance of biochar is greatly affected by its biomass used, pyrolysis conditions, crop types, soil types and agro-climatic conditions. Hence, still further studies are needed to understand its actual mechanisms for those variations before recommending it to farm levels.

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