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

A. Kandel, S. Dahal and S. Mahatara

Institute of Agriculture and Animal Science, Tribhuvan University, Bhairahawa, Rupandehi, 32900, NEPAL

 Corresponding author’s E-mail: apekshya.kandel123@gmail.com

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.

INTRODUCTION

Depletion of soil carbon, excessive emission of greenhouse gases and global heating are the major concerns of the present time (Abriashamkesh 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 (Berihu 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.

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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 physio-chemical 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/cm³ to 0.363 g/cm³ and increment in porosity from 0.500 cm³/cm³ to 0.773 cm³/cm³ 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        |     |       |       |       |       |       |       |                                 |
|                  | 600        |     |       |       |       |       |       |       |                                 |
| Chinese rice straw| 400       | 7.84| 61.71 | 3.41  |       | 1.27  |       |       | (Yoo et al., 2015)              |
|                  | 600        |     |       |       |       |       |       |       |                                 |
| Korean rice straw| 300        | 6.75| 50.50 | 3.62  | 0.89  |       |       |       |                                 |
|                  | 600        |     |       |       |       |       |       |       |                                 |
| Maize straw      | 400        | 10.77| 76    |       | 13    | 5.0   | 4.0   |       | (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  | 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                           |
| 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 potential 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$_4^+$ 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 mg kg$^{-1}$ over control (110mgkg$^{-1}$) while in combination with fertilizer they enhanced N going from 4.5 to 15.7 mg kg$^{-1}$. 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 mg kg$^{-1}$ N-NH$_4^+$ in chicken manure biochar treated soil and 52 mg kg$^{-1}$ in city waste biochar treated soil, after 28 days of soil incubation, which on comparison were higher than untreated soil (12 mg kg$^{-1}$ 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 (Utomu 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$_4^+$ adsorption (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 161/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 groundnut (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 opposed 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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