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Review paper

Soil-Plant Nutrient Availability Enhancements and Retentions Capacity of Biochar Review

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Biochar is the solid, carbon-rich material obtained by pyrolysis using different biomasses. The application of biochar to agricultural soils has the potential to greatly improve soil physical, chemical and biological conditions. It has been widely documented in previous studies that, the crop growth and yield can be increased by using biochar. This review exclusively aimed to summarizes a comprehensive review papers or research findings and own preliminary results on the role of biochar in plant nutrients availability and nutrient retentions of agricultural soil basically based on biochar effects on plant available nutrients, biochar nutrient contents and its contribution to the soil, nutrient retention, cation exchange capacity and liming effects of biochar within the soil solution. It has been widely documented in previous studies that, biochar application to the agricultural soil has imperative effects on the crop growth and yield can be increased by using biochar application on plant available nutrients, nutrient contents and its contribution to the soil, nutrient retention, cation exchange capacity and liming effects of biochar within the soil solution.

Key Words: Amendments, Biochar, CEC, Nutrients Availability, Nutrient Retention

INTRODUCTION

Biochar is pyrogenic black carbon derived from thermal degradation of carbon-rich biomass in an oxygen-limited environment (Mandu *et al.,* 2021). As different scholars indicated biochar, three terms (biochar, charcoal, and char) can be applied to identify the solid black residue occurring from bioenergy production. In recent years, biochar has received ever-increasing attention due to its multi-functionality including carbon sequestration and agricultural solution as a soil fertility enhancement (Laird *et al.,* 2010), bioenergy production (Field *et al.,* 2013), and environmental remediation (Mohan *et al.,* 2014a). Several recent publications have provided evidences of biochar ability to immobilize organic (Rajapaksha *et al.,* 2014) and inorganic pollutants (Mohan *et al.,* 2014b) in soil systems. The strength of soil and its productivity is directly related to the nutrient retained within the soil system and availability nutrient for plant growth. Plants require a number of soil nutrients like nitrogen (N), phosphorus (P), and potassium (K) for their growth, but soil nutrient levels may decrease over time after crop harvesting, as nutrients are not returned to the soil. Biochar is widely used in soil amendment for improving physico-chemical properties and the biological activities of agricultural soils (Andrey *et al.,* 2019). Soil organic carbon is closely linked to effective utilization of soil nutrients, and any changes can have a profound influence on the soil quality (Videgain *et al.,* 2020). Application of biochar from vine shoots (*Vitis vinifera* L.) as an organic amendment in the soil is an alternative agricultural management of interest (Conte *et al.,* 2021). Specific biochar characteristics including large surface area, highly porous structure, and cation exchange capacities may affect nutrient transformation processes in soil (Hatfield *et al.,* 2020). It has shown a greater ability to adsorb cations per unit carbon as compared to other soil organic matters because of its greater surface area, negative surface charge, and charge density (Liang B *et al.,* 2006), there by offering the possibility of improving yields (Lehmann, 2007). Biochar is considered a soil conditioner or amendment and a carrier for nutrients, but not as a fertilizer (Kathleen, 2018). Research has shown that biochar amendment significantly enhances the nutrient availability and nutrient retention of the soil.

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Dissolved organic carbon in biochar represents one of the most important factors of soil sorption complex as it may act as a mobile sorbent and thus reduce the apparent sorption to the solid phase (Marchal *et al,.* 2013a).The objective of this review is to provide a comprehensive review of recent research findings on the role of biochar in plant nutrients availability and nutrient retentions of agricultural soil.

Methods:

We searched for research articles and review paper by using "*Amendments, Biochar, CEC, Nutrients Availability, Nutrient Retention*" on the web of science for paper published to review the scientific understanding of biochar effects on the soil fertility enhancement and plant nutrient retention.

RESULT

Biochar Effects on Plant Available Nutrients

Plant available nutrients are the nutrients found within the soil solution in the form of easily accessible to a plant roots. A number of scholars have also reported that, biochar application increased the availability of nutrients by 61-70% for Ca^{++}, 39-53% for total N, 179-208% for P, and 14-184% for K (Widowati and Asnah, 2014). The increased Potassium content in stems, leaves, and roots of green in spring spinach (72%), mustard (16%), and autumn spinach (36% on average) due to biochar application were reported by (Mohan *et al.,* 2014). It has been suggest that, the addition of compost based on agricultural residues with biochar improves chemical properties and nutritional status of soil that favor and increase plant growth (Medina *et al.,* 2021). Biochar additions to soil may alter soil microbial populations or provide habitat for them those are actively giving a contribution to transformations of nutrients including N, P, or S (DeLuca et al. 2015). The availability of nutrients in biochar relies on their structural stability, which in turn is determined by the feedstock type, production conditions, and soil environment (Asadullah *et al,.* 2010). Elemental ratios of H/C, O/C, and C/N are the main indicators of structural stability of biochar. Increasing the pyrolysis temperature generally reduces H/C and O/C ratios while transforming the biochar structure into chemically and biologically more stable arrangement (Ahmad *et al.,* 2014; Mohan *et al.,* 2014). Researchers have reviewed that biochar amendment significantly enhances the nutrient availability and nutrient retention of a wide range of soils (Avanthi *et al.,* 2015). The capacity of a biochar to provide or enhance soil available nutrients, however, is determined by the feedstock and production conditions of the biochar. Biochar produced from nutrient rich feed stocks contain comparatively high readily available nutrients. Biochar can affect soil structure, thereby influencing water retention and nutrient availability (Baiamonte *et al.,* 2015; Conte P *et al.,* 2021), while it can be a source of several plant nutrients once it is functionalized as in the case, for example, of Kon-Tiki kiln quenching by cow urine (Schmidt *et al.,* 2015). With the aim to produce new generation and more efficient fertilizers, biochar is also used as an additive to produce compost (Conte P *et al.,* 2021).

Biochar retains nutrients by capturing of nutrient containing water in its micropores, which is held by capillary forces. Addition of biochar increased soil pH, EC, organic carbon, total nitrogen, available phosphorous, CEC and exchangeable captions of chromium polluted and unpolluted soils. Uptake of nitrogen, phosphorous and potassium was also increase by the addition of biochar (Abebe, 2012). However, biochar with relatively high nutrient content that were produced from nutrient-rich feed stocks, such as manure, might be considered as a fertilizer. Most biochar do not contain significant amounts of nutrients needed by plants but develop a high nutrient holding capacity (Kathleen, 2018). Nutrient availability and nutrient use efficiency in soil directly increases through the addition of nutrients contained in biochar and indirectly through improved nutrient retention, modified soil microbial dynamics and increased decomposition of organic material in the soil as reported by (Laird *et al.,*2009). However, biochar application should be at the optimum level that should not antagonistically affect the N-availability within the soil. A number of researchers suggest that, biochar application did not increase a yield at the highest rate of application (Adrien D, 2016). Given the low N content and high C/N (200) of the biochar, biochar-amended soil alone was likely to be limited by N supply (Adrien D, 2016, Leta *et al.,* 2019).

The additional increases in radish yield observed at higher rates of biochar applications (50 and 100 t/ha) in the presence of N fertilizer (up to 266% in the case of 100 t/ha biochar application) indicated the potential of green waste biochar in increasing nitrogen fertilizer use efficiency of plants (Adrien D, 2016). Biochar application increased soil organic matter (SOM), soil pH, phosphorus (P), potassium (K), sulfur (S) contents, and the shoot and root biomass of wheat (Prakriti B, *et al.,* 2019).

Biochar nutrient contents and its contribution to the soil

Biochar can be directly or indirectly contribute for soil nutrient contents and nutrient stability of the soil (Table 1).

It was been observed that, the nitrogen content of the media used for coffee seedling rising was increased from 0.33% for topsoil alone to 0.49% for higher (one to one) ratio of biochar to topsoil. Potassium content of the soil

Table 1:. Effect of biochar application ratio on soil (pH, EC, OM, OC, N, P, and K (cmol/K)) of the potting media

Treatments	pH	ECdS/m	%OM	%OC	%N	C:N ratio	P ppm	K cmol/kg
Biochar	11.26	-	9.04	5.24	0.35	14.77	353.30	3.06
Top soil	4.90	0.10	6.23	3.62	0.37	9.79	18.00	0.79
BTs1	7.42	0.34	6.93	4.03	0.48	8.39	36.00	1.15
BTs2	7.19	0.36	6.26	3.64	0.45	8.09	33.41	1.04
BTs3	6.40	0.25	7.21	4.19	0.41	10.22	22.67	0.86
BTs4	6.96	0.34	6.60	3.84	0.44	8.72	23.00	0.70
BTs5	4.73	0.12	7.85	4.56	0.36	12.68	71.25	0.63

Source: *Own soil laboratory result.* ***Note:*** B0TS = No Biochar or Topsoil only, BTs1 = one to one biochar to topsoil ratio BTs2 = one to two biochar to topsoil ratio, BTs3 = one to three biochar to topsoil ratio, BTs4 = one to four biochar to topsoil ratio, BTS5 = Top soil plus 2g DAP per pot.

also increased from 0.45 Kgcmolk-1 for the topsoil 1.150 Kgcmolk^{-1} due to applications of biochar to topsoil at 1:1(v/v) ratio (*Own preliminary study*) (Table 1). Biochar application increased soil organic matter (SOM), soil pH, phosphorus (P), potassium (K), sulfur (S) contents, of the soil (Prakriti B *et al.,* 2019).

It has also been reported that, biochar have an indirect influence on soil nitrogen concentration, through a change in microbial communities. The soil micro organisms play a leading role in the ammonification process of nitrate (NO_3^-) to ammonium ($NH4^+$)reducing nitrogen losses by leaching or gaseous fluxes (Ullah*et et al.,* 2019) and application of biochar increased the availability of N, P, K, Ca, and Na in the soil. The presence of plant nutrients and ash in the biochar, high surface area, and porous nature of the biochar and the capacity of biochar to act as a medium for microorganisms were identified as the main reasons for the increase in soil properties and highest nutrient uptake at biochar treated soils (Leta A., 2018). Biochar particles are assumed to act like clay and thus hold large amounts of immobile water even at increased matric potentials. Consequently, nutrients dissolved in this immobile water would be kept near the soil surface and would be available for plants (Abebe, 2012).

According to Chang*et et al.* (2008), N as a limiting factor might be detrimental to the efficiency of P and K added to the soil by biochar. Moreover, biochar could have similar effect as fire derived charcoal by adsorbing phenols and terpenes, which improves nitrification and mineralization rates in the forest soil, which were known to inhibit nitrification (Palviainen *et al.,* 2018). Soil amendment with biochar was recommended in particular for reducing nutrient leaching losses in areas with high rainfall as reported by Major (2009). Phosphorous in plant wastes can also conserved and released through the addition of certain types of biochar in plant available forms (Zhang *et al.,* 2017).

The high nutrient holding capacity of biochar makes it suitable to charge with organic waste nutrients such as compost, manure, or animal/human urine, which might be a freely available fertilizer to small coffee farmers (Domingues and Rimena R, 2017). When thoroughly mixed, the organic nutrient solutions enter the biochar's porous systems are prevented from leaching out when applied to soil. These organic, fortified biochars become slow release fertilizers and can provide continuous plant essential nutrients, particularly nitrogen, without the risk of ground water contamination (Kammann C, Linsel S 2011). Therefore, biochar characterization used to identify the main differences and similarities between them, offering guidelines for selecting a biomass and charring conditions to biochar end-users according to their specific soil and environmental requirements (Domingues and Rimena R, 2017). Coffee husk and chicken manure biochars were characterized by their high liming value, which make them potential materials for correcting soil acidity in crop fields. Both coffee husks have a role as P and K sources for plants. High-ash biochar produced at low-temperatures (350 and 450˚C) exhibited high CEC values, which can be considered as potential applicable material to retain nutrients (Domingues and Rimena R, 2017). The adsorption of some inorganic forms of nitrogen onto biochar decreases ammonia and nitrate losses from soil and can potentially allow the slow release of nutrients to the plant roots (Hong, C. and Lu, S. 2018). Biochar made from coffee pulp is relatively high in K, which could lower or replace imported sources of potassium. It has also high CEC as compared to other types of biochar, which can increase nutrient holding capacity of soils, leading to reduced fertilizer requirement (Domingues and Rimena R, 2017).

Nutrient Retention

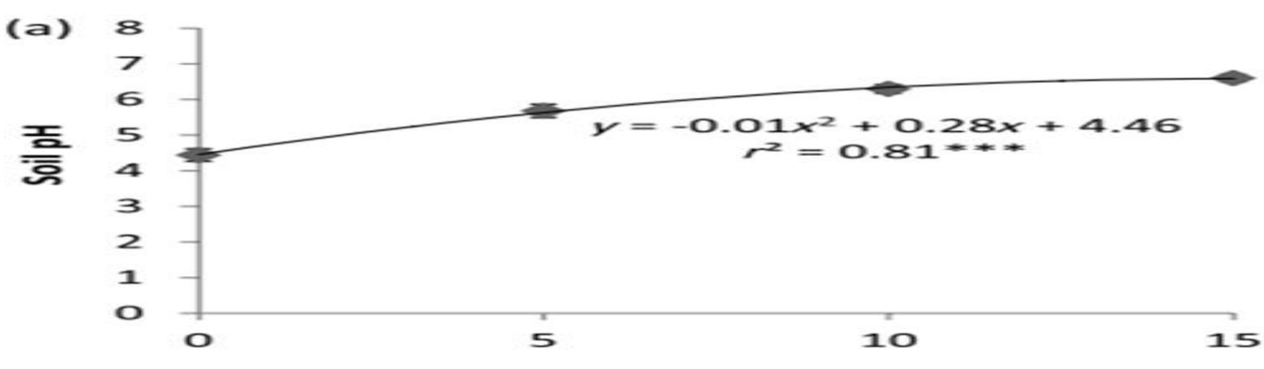
Biochar incorporation can alter soil physical properties such as structure, pore size and its distribution density, that affect the soil aeration, water holding capacity, soil workability and at the final plant growth, (Downie *et al.,* 2009). Biochar is a substance having the capacity to retain macronutrients directly, such as N (Yue, 2017; Zhang, 2017). This can be attributed to the nutrient content of biochar itself (Glaser, 2002). Biochar soil mix can increases the water and nutrient retention of soil through soil porosity modification (Li, *et al*., 2021). Addition of biochar particles with different sizes and shapes in sandy soils can reduce the volume of large space between soil particles and increase the portion of micropores (5 µm to 30 µm in diameter) contributed by pore space of biochar (Li, *et al*., 2021).

Biochar can act as an organic fertilizer by providing soil nutrients that were present in the precursor biomass (Gul and Whalen, 2016). As a reason, the application of biochar has many additional benefits for plant nutrient cycling, such as increasing retention and use efficiency, and reducing leaching, thereby improving soil fertility (Rangaswami., 2018). Mensah *et al.* (2018) reported that biochar application to low fertility sandy soils increased total C by 7–11%, K by 37–42%, P by 68–70%, and Ca by 69–75% as compared to no application. Biochar additions to soil have been found to both increase and decrease the availability of soil P (Steiner *et al.,* 2007; Nelson *et al.,* 2011). On the other hand, biochar produced at relatively low temperatures was found to mainly improve soil CEC (Mukherjee, 2011). There are two aspects which make biochar amendment superior to other organic materials for nutrient retention: the first is the high stability against decay, so that it can remain in soil for longer times providing long-term benefits to soil and the second is having more capability to retain the nutrients. Biochar amendment improves soil quality by increasing soil pH, moisture-holding capacity, cation-exchange capacity, and microbial flora (Mensah *et al.,* 2018). Biochar has also been shown to enhance nutrient availability over longer time scales by enhancing nitrogen (N) mineralization or nitrification (DeLuca *et al.,* 2006; Ameloot *et al.,* 2015) as a result of enhanced microbial growth and activity (Lehmann *et al.,* 2011) and by reducing soil nutrient losses due to its high ion exchange capacity (Atkinson *et al.,* 2010). Biochar application to the soil increases the soil pH, CEC and EC values, availability of plant nutrients, soil organic matter content, the supply of readily available C substrates (Cheng *et al.,* 2020), soil TOC, and N status, soil aggregate stability WHC, and reduction of nutrient leaching from the soil (Cheng *et al*., 2020; Taraqqi *et al.,* 2021).

Liming Effect of Biochar

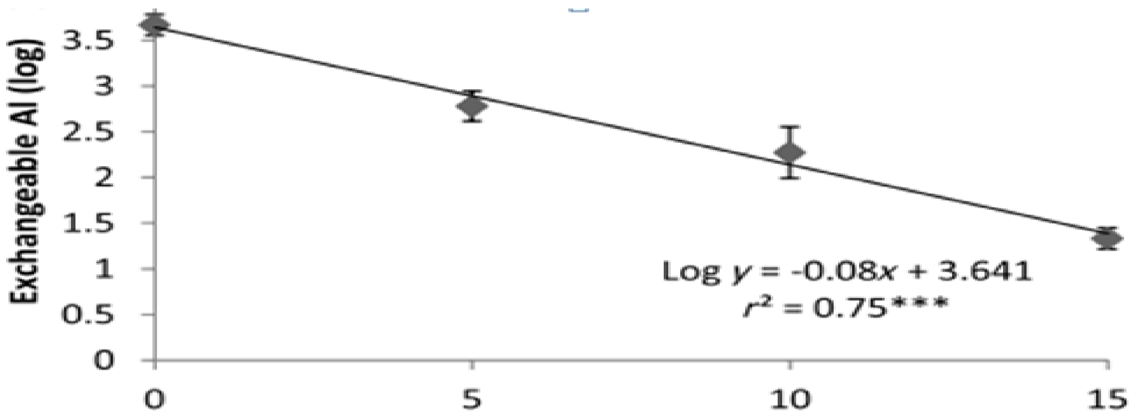
Soil pH is influenced by both acid and base forming cations (positively charged dissolved ions) in the soil. Common acid-forming cations are Hydrogen (H^+), Aluminum (Al^{3+}), and Iron (Fe^{2+} or Fe^{3+}), The pH affects the availability of nutrients to plant roots and this is influenced by the lime concentration, the plant species, plant uptake of nutrients and water alkalinity (Laird *et al.,* 2009). In Ethiopia, 40.9% of the soil is acidic; out of which 27.7% is moderate to weakly acidic (pH of 5.5–6.7) and 13.2% is strong to moderately acidic pH < 5.5 (Mesfin, 2008). Different physical properties of the soil such as bulk density, total porosity, and the chemical properties such as total nitrogen, available phosphorus, Potassium, and pH and soil organic carbon of the soil were improved due to the application of biochar (Tariku, 2017). It was reported as biochar can significantly increase both the pH from the initial value of 5.08 to 6.66 and phosphorus availability of acidic soils, by treating with 15 $tonha^{-1}$ biochar (Bayu *et al.,* 2017). Biochar with high liming equivalence typically increases the pH value in acidic soils, whereas the actual increase depends on the pH-buffering capacity of the respective soil as reported by (Mukherjee and Lal, 2014). Soil pH increased as a quadratic function ($r^2 = 0.81$, $P < 0.001$) of biochar rate (Figure. 1). Syuhada *et al.* (2016) reported the maximum soil pH was achieved at 6.42 when biochar was applied at 14 g kg^1 (Figure. 1).

According to **Syuhada, *et al.* (2016)**, soil treated with biochar (mean = 15.14, 8.72, and 2.80 mg kg^{-1} for 5, 10, and 15 g kg^{-1} biochar, respectively) also had significantly lower exchangeable Al compared with that of the control (mean= 38.22 $mgkg^{-1}$) pot experiment.



Biochar rate (g/kg)

Figure 1: Soil pH as affected by biochar application of different rates. Error bars represent ± standard error of the transformed means. Source Syuhada, J. et al., 2016



Biochar rate (g/kg):

Figure 2: Exchangeable **Al** in log scale as affected by application of different rates of biochar. Error bars represent ± standard error of the transformed means. **Source: Syuhada,** J. *et al.,* 2016.

Cation Exchange Capacity

CEC is an important parameter in retaining inorganic nutrients, such as K^+ and NH_4^+ in soil (Lei O, and Zhang R 2013), and biochar has been associated with the enhancement in CEC of some biochar-amended soils (Vanzwieten, 2010), thereby increasing the availability and retention of plant nutrients in soil and potentially increasing nutrient use efficiency. Amending soil with biochar and compost significantly improved the CEC of the soil indicate that, the retention of non-acidic cations by the soils increased (Agegnehu, 2017). Once biochar incorporated into soil, CEC varies depending on soil pH, age and weathering conditions of biochar (Major, 2009). Lei O, and Zhang R (2013), confirm that CEC is dependent on pH by observing that, at pH values below seven, acidification leads to a release of bound cations. Moreover, CEC in soil might increase over time due to oxidation, thus age biochar shows increased retention capacity when compared to fresh biochar (Mishra, 2018). Available nutrients (macro and micro) in biochar are important for its use in agricultural applications and nutrient availability depends on biochar and production conditions (Igalavithana and Ok Y, 2016). Cation exchange capacity of biochar enhances the retention of basic nutrients (Vanzwieten*et al.,* 2010), might have increased the phosphorus availability and its uptake within the soil. The other Author confirm that, the liming effects of biochar (Woldetsadik*et,* 2018), increased leaf nutrient concentration at the one to three application ratio of biochar to topsoil. Increased cation exchange capacity (CEC) following biochar application is resulting in increased nutrient and fertilizer retention (Major, 2009). When CEC increases, fertilizers applied to the soil adsorbed to the surface area of biochar consequently easier used by the plants (Steinbeiss, 2009). Since biochar contains organic matter and nutrients, its addition increased soil pH, electric conductivity (EC), organic carbon (C), total nitrogen (TN), available phosphorus (P), and the cation-exchange capacity (CEC) (Dume *et al.,* 2016). The large surface area of biochar allows adsorption of a large number and its porosity enables the soil to adsorb a much greater amount of macronutrients or cations following biochar incorporation into the soil (Saowanee W and Wichuta K, 2015). Different Authors found that, increased cation exchange capacity in soils with biochar application improved nutrient retention (Heiskanen, 2013; Saowanee W and Wichuta K, 2015).

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