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Effect of Biochar Application on Soil Acidity Reclamation and Crop Production Improvements: A Review

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Abstract: Know day In most parts of the world, soil acidity has become a significant problem to agricultural production; The high buildup of H^+ ions relative to OH^- ions in the soil solution results in the acidity of the soil. Understanding the function of biochar in reducing soil acidity and enhancing crop yield was the main goal of this review. Biochar is a carbon rich substances resulting from the pyrolysis of organic material, it accumulate carbon for long time, ameliorates degraded soil and lowering soil acidity for better crop production. Additionally, using biochar as a soil amendment increases agricultural yield by boosting soil's ability to hold water, making nutrients available to plants through cation exchange capacity, adsorbing nutrients, creating favorable conditions for soil microorganisms, and enhancing carbon sequestration. Generally, soil management by biochar under acidic soil increase nutrient availability like available phosphorous, soil pH, cation exchange capacity, crop yields and reduce hazard of crop failure. However the influence of biochar application on crop production depending on soil type, soil condition, nature and rate of biochar used.

Keywords: Soil Acidity, Biochar, Amelioration

1. Introduction

Soil acidity is one of the biggest issues affecting agricultural production globally, and in developing nations in particular. More than 50% of the world's arable lands are impacted by soil acidity, which is one of the key factors limiting soil productivity worldwide [68]. Soil acidification can result in toxicity of aluminium and manganese to plants and can cause shortages in phosphorus, molybdenum, calcium, and magnesium, which can hinder plant growth and lower crop output [42].

Soil acidity can be caused by both by natural and anthropogenic processes including the use of ammonia fertilizers, crop removal of the basic cations, leakage of basic cations due to high rainfall, decomposition of organic residues, and weathering of acid parent material are the main process that causes soil acidity [46]. Due to an excessive uptake of positively charged cations from the applied inorganic fertilizer, soil acidity may accelerate the leaching of exchangeable bases and unbalance soil response. [21]. Acidity of the soil influences the availability of nutrients to the plant, the concentration of phytotoxic substances, and microbial activity. Deficiency of Phosphorus, exchangeable bases (Ca, Mg), micronutrients (Zn, Mo, and B), high concentration of Aluminum (Al), Iron (Fe), and Manganese (Mn), and low microbial activity are the most important factors that limit crop production in acidic soils [27].

The abundance of hydrogen (H^+) and aluminum (Al^{3+}) ions in the soil exchangeable complex results in acidity, which reduces crop productivity and plant uptake of several crucial nutrients [13]. Therefore, controlling soil acidity is one of the crucial requirements to raise and keep soil production. So, to overcome the limitations caused by soil acidification, the use of acidic neutralization materials such as lime and biochar is required for agriculture [25]. The use of lime is now the most popular and successful method for lowering soil acidity ($CaCO_3$) [50]. Because lime offers basic cations like calcium and magnesium, the pH of the soil rises when it is utilized; this lowers the toxicity of aluminum. [48]. Additionally, Lime treatment can also increase soil microbial activity by changing the bacterial and fungal colonization of the soil [65]. Most of the time, lime is relatively expensive, difficult for subsistence farmers to afford, and the supply is scarce, because of this biochar is an additional mechanism, as these materials are locally accessible and cheaper compare to lime material [23]. Biochar, an ecologically friendly soil amendment, it is a carbon rich organic material that has undergone the pyrolysis process of biomass thermal decomposition when heated to temperatures typically between 300 and 1000°C with little or no oxygen (O_2) [19]. Biochar can be made from a variety of plant resources, such as wood chips and pellets, tree bark, crop leftovers, grasses, and organic wastes [66]. Because biochar is typically alkaline, it can be added to soil as a soil amendment to reduce soil acidity and raise soil pH [43]. Biochar can promote carbon sequestration, aid in waste management, restore soil fertility and plant development, and immobilize contaminants when used as a soil additive [29]. Additionally, using biochar produces an environment that is favorable for soil macro- and microorganisms, increasing soil biota by enhancing soil quality, increasing crop productivity through improving water holding capacity, cation exchange capacity, and adsorption of plant nutrients, and improving soil quality [33]. The main objective of this review was to clarify how biochar helps to reduce soil acidity and crop production improvements.

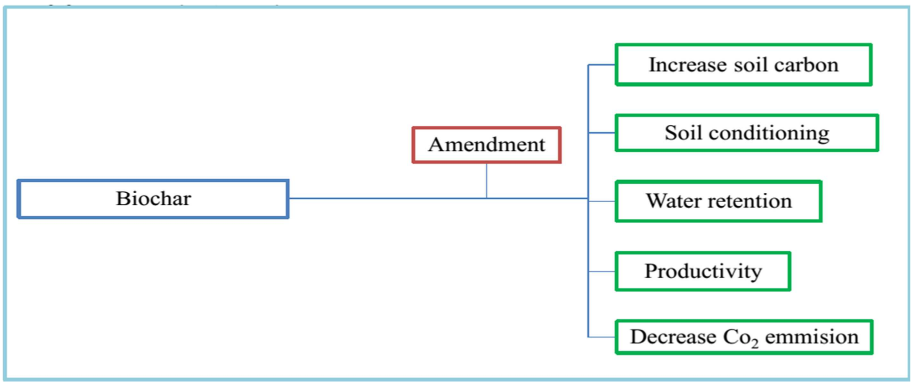

Figure 1. *Biochar effect on soil health, source: Jagnade et al., (2022).*

1.1. Over View of Soil Acidity

The relative acidity or alkalinity of a soil can be strong-minded by looking at the pat the pH of the soil. The pH scale has a range of 0 to 14, and the soil is given a value to indicate how acidic or alkaline it is. The pH value of 7 is referred regarded as neutral since it is in the middle of the pH scale. Although pH levels above 7 are alkaline and those below 7 are acidic. Soil acidity is a state that occurs when the pH of the soil is lower than neutral (less than 7) pH. Soil pH is a measure of the hydrogen (H^+) ion concentration expressed as the negative common logarithm of H^+ concentration. Recall that the hydrogen ion is an acidic cation. The pH of the soil water solution declines with increasing hydrogen ion concentration. Conversely, the soil will be more acidic the lower the pH value. In direct proportion to and in balance with the hydrogen ion maintained on the soil's cation exchange complex, the concentration of hydrogen ion the soil solution. As a result, the hydrogen ions in the soil water are replenished or buffered by the hydrogen ions held by the clay particles. In agriculture, soil acidity is a significant issue with regard to plant growth [68]. It is the main concerns with land degradation, which affects over 50% of the world's potentially arable soils [32].

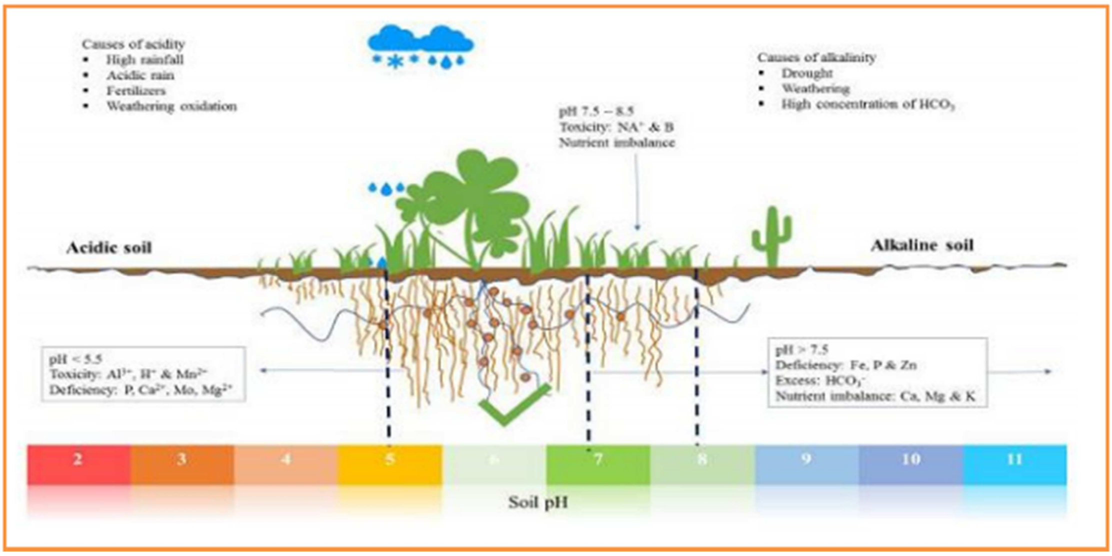

Figure 2. *Different soils with respect to pH, nutrient availability, deficiency and imbalance. Source: Msimbira et al., [30].*

The main limiting factors related to acidic soils include toxic consequences, nutritional imbalance, and decreased microbial activity. Soil acidity limits the availability of nutrients such as calcium (Ca), magnesium (Mg), phosphorus (P), nitrogen (N), boron (B), and molybdenum (Mo) and causes the toxicity of aluminum (Al) and manganese (Mn). Similarly inhibits biological activity in the rhizosphere, particularly the mutually beneficial connection of plant with beneficial fauna and flora [60]. These issues directly and indirectly affect plant growth. Severe water stress brought on by constrained root growth in the subsurface horizon is another key restriction linked to acidic soils [2]. the presence of acidifying minerals and inadequate soil management practices are two additional variables that increase soil acidity. For instance, agricultural activities (such as mineral nitrogen fertilizer) frequently result in increased acidity. It could hasten the leaching of exchangeable bases and throw the soil's reaction out of balance because of an excessive uptake of positively charged cations from the inorganic fertilizers provided [21]. These factors collectively severely restrict the potential for raising crop productivity.

1.2. Causes of Soil Acidity

1.2.1. Rainfall and Leaching

Leaching of basic cations over a prolonged period of time is mostly caused by heavy rainfall. This may make the soil more acidic by leaving toxic and insoluble alumunium and iron compounds in the soil [70]. The nature of these compound are acidic and its oxides and hydroxides react with water and release hydrogen (H^+) ion in soil solution and soil become acidic [54]. Likewise the basic cations of the colloidal complex are replaced by the H^+ ions of the carbonic acid and other acids created in the soil when the soluble bases are lost. Constant leaching gradually depletes the soil of its exchangeable bases, which causes de-saturation and an increase in acidity [18]. Rainfall is most efficient at causing soils to become acidic if a lot of water permeates the soil profile, increasing the leaching of bases [39].

1.2.2. Parent Material

Whether a soil is acidic or alkaline depends on the types of rocks from which it can be created. Due to differences in the chemical makeup of the parent materials, soils will turn acidic at different times. As a result, soils created from granite are probably more acidic than soils created from calcareous shale or limestone.

1.2.3. Organic Matter Decay

The microbial breakdown of organic matter produces humus components in soils, which contain various functional group like carboxylic (-COOH) and phenolic (-OH) etc. which are capable of attracting and dissociating hydrogen ions [56]. The H^+ produced by decaying organic matter is what causes the acidity of the soil. When water and carbon dioxide from decaying organic matter combine in the soil, form a weak acid (carbonic acid). This acid is the same one that naturally occurs when rain and atmospheric CO_2 mix to generate acid rain. In addition, several weak organic acids are formed by the decomposition of organic materials. Like rainwater, decomposing organic matter typically has a relatively little contribution to the creation of acid soil, and it would only be the accumulated effects of many years that might ever be measured in a field.

1.2.4. Removal of High Crop Product

Due to crop absorption of lime-like elements as cations for nutrition, crop harvesting affects the development of soil acidity [40]. When these crops are harvested or their crop leftovers are removed from the field, some of the basic substance that was used to balance the acidity produced by other processes is lost, which has the overall effect of making the soil acidic.

1.2.5. Usage of Acid Forming Fertilizers

Acidity results from the application of fertilizers containing ammonium sulphate and ammonium nitrate to the soil. Ammonium ions of these fertilizers substitute calcium and magnesium from the exchange complex and the calcium sulphate so formed is lost due to leaching. in case the soils not having free lime, the acidity increase continuously by the use of acidic fertilizers. Residual acidity of different fertilizers produced acidity in the soils [45].

$$(NH_4)_2SO_4 \leftrightarrow 2NH4 + SO4^{\ 2-}$$

$$NH_4NO_3 \leftrightarrow NH_4^+ + NO_3^{\ -}$$

2. Influence Biochar on Soil Acidity Reclamation

2.1. Soil pH and Exchangeable Acidity

Soil pH affects many processes in soils, including nutrient availability; activity of microorganisms and root development. Because of microbial activity decreases at low pH levels, the mineralization of organic matter is hindered and often even stopped in severely acidic soils. This results in a decreased availability of nitrogen and phosphorus. The environment of the soil is severely harmed by soil acidification, which also decreases the soil's quality [22]. There are a many of finding indicated that soil pH was improved due to the use of biochar, particularly in acidic soil [69]. Application of biochar to soil recovers $NH4^+$ immobilization and consequently decreases nitrification which in turn conquers the release of H^+ content to the soil and dismisses soil acidifications [41]. Nevertheless, the biochars potential to improve acidic soil depends on pyrolytic parameter (Alkaline pH is produced by greater pyrolytic temperatures, namely those > 400°C), feed stock and soil properties [64]. According to Novak *et al.,* [43] presence of –OH ions in the biochar enhanced its pH and ultimately the soil in which biochar is applied. Additionally, Silva *et al.,* [51] revealed that after the biochar made from filtering of waste materials were applied, the pH of the soil linearly increased, which was at the maximum amount (10 L m^{-3} of soil volume), the pH of the soil was raised by 0.76, 1.17, and 1.68 units use rice husk, sawdust filter, and sorghum silage filter biochar, respectively. The incorporation of biochars, which are very alkaline, high base cation concentrations that released protons into the soil solution, acidity reduction through proton consumption reactions, and increased CaCO availability were all factors in the increase in soil pH. Ch'ng *et al.* [15] reported when the soil were modified by chicken litter biochar, there was a comparable rise in soil pH that caused a drop in exchangeable Al and Fe. High recalcitrance biochars can affect soil pH and have benefits for carbon sequestration. It was observed that we can increase the soil's capacity to hold onto nutrients and decrease its exchangeable acidity by adding biochar to acidic soil [55, 63]. After applying biochar to soil, it may mineralize and release cations into the soil solution, which may replace exchangeable acidity and lower soil pH [71]. Adding biochar at higher rates after doing so at lower rates tends to reduce exchangeable acidity [7]. Anteneh *et al.,* [1] reported that the lowest exchangeable acidity was produced by incorporating of 12 t ha^{-1} biochar (0.39 cmol kg), whereas the maximum exchangeable acidity was produced by the control plots (0.60 cmol kg^{-1}). Additionally, Berihun *et al.,* [9] reported that by adding 6 t ha^{-1} and 18 t ha^{-1} of biochar, the exchangeable acidity was reduced. By applying 18 t ha^{-1} of Lantana camara biochar, the lowest exchangeable acidity was obtained (2.02 cmolc kg^{-1}) and was followed by 12 t ha^{-1} of lantana camara (2.24 cmolc kg^{-1}). While the maximum exchangeable acidity observed from the control plots was 6.66 cmolc kg^{-1}. This is because of the displacement of H^+, Fe^{2+}, and Al^{3+} ions from soil adsorption site [45] and release of organic acids, which in turn may have suppressed Al content in the soil through chelation [45]. In terms of soil quality, lowering exchangeable acidity and raising pH can have a variety of positive effects, including chemically increasing the availability of plant nutrients and, in some situations, lowering the availability of harmful elements like Al [11]. Likewise Geng *et al.,* [22] reported that by adding biochar, soil pH was raised by 8.48 to 79.25%, while exchangeable acidity, exchangeable Al, and exchangeable H were all decreased by 56.94 to 94.95%, 34.38 to 95.6%, and 58.72 to 93.27%, respectively. The greater cation exchange capacity (CEC) of the biochar, which has the capacity to bind Al and Fe with the soil exchange sites, may be the cause of the decreased soil exchangeable acidity in the improved soils.

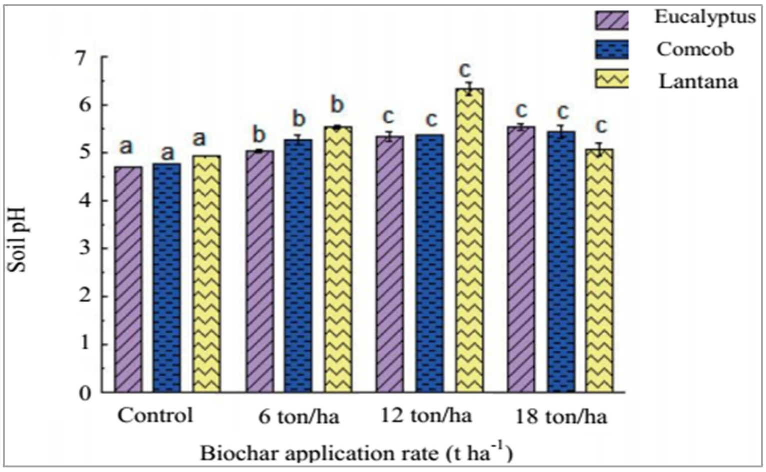

Figure 3. *The effect of different material of biochar on soil pH. Source: Berihun et al., [9].*

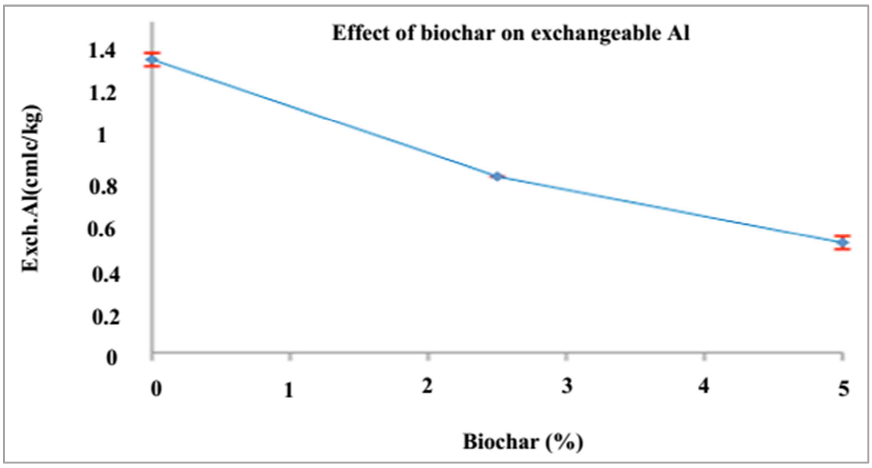

Figure 4. *Effect of biochar on exchangeable Aluminum. Source: Berek et al., [8].*

2.2. Effect on Available Phosphorous

Phosphorus is an important plant macronutrient that plays a critical role in plant growth and development [52]. It is a component of plant cells and is necessary for cell division and the growth of the plant's growing tip. However, phosphorous is a main nutrient restrictive crop production in acidic soil. Global crop output is hampered by phosphorus deficiency, which is thought to affect crop yield in more than 40% of agricultural soils [6]. Chemically, phosphorous is a stable element, Fertilizer phosphorus does not spread far from where it is applied because it reacts rapidly with soil. While mineral and organic Phosphorous fertilizers are applied to refill this pool, orthophosphate in soil solution quickly reacts with soil components and transforms into other Phosphorous forms that are not plant available. Presently a tiny portion (10–30%) of the additional Phosphorous is absorbed by the plant in the year of application as a result of phosphorus's association with calcium, iron, and aluminum shortly after it is applied to the soil as a fertilizer. The remaining of the applied phosphorous can be fixed to soil particle as adsorbed phosphorous or precipitates with soil constituents to form insoluble phosphorous compounds, they are very difficult for plants to absorb. As a result, the bulk of the phosphorus that was applied remains in the soil and ongoing use of phosphorus fertilizers (both mineral and organic) results in phosphorus buildup in the soil [14]. Understanding phosphorus retention and release mechanisms is essential for managing phosphorus effectively to improve crop output and maintain soil health.

Phosphorous is fixed in acidic soils by high energy sorption surfaces like iron and aluminum oxides and hydroxides, which are formed by ligand exchange and precipitation processes to create insoluble iron and aluminum phosphate [44]. Crops may often obtain phosphorus when the soil pH is between 6 and 7. Phosphorous shortage in most crops increases when the soil pH is less than 6. Conventionally, huge amounts of lime and inorganic phosphorous fertilizer such as phosphate rocks and triple superphosphate are used to saturate aluminuim (Al) and iron (Fe). The failure of this strategy can be attributed to the fact that small farmers cannot afford it. Instead of this use of biochar is very significant to increase the availability of phosphorous in soils fertilized with biochar. Biochar is a solid substance produced by the pyrolysis of biomass in anoxic or hypoxic circumstances [58]. There is a lot of potential for biochar to be used in the area of soil improvement and remediation due to its substantial specific surface area, wide range of raw material sources, rich surface functional groups, and abundance of pore structures [64]. Biochar is one of the organic amendments used to increases the availability of phosphorous in acidic soils by increasing soil pH. It also has a potential to improve soil available phosphorous through either direct supply of Phosphorous or its retention of fertilizer Phosphorous. Due to an increase in soil pH and calcium (Ca) content brought on by biochar, phosphate availability in acidic soil can increase. This decreases the ability of iron (Fe) and aluminuim (Al) hydrous oxides and Al^{3+} to bind phosphate in the soil. [26].

Atkinson *et al.* [5] stated that by altering the microbiome, biochar indirectly impacted soil phosphorus availability and plant phosphorus uptake. DeLuca *et al.* [16] reported that through the biochar's anion exchange capacity or by affecting the availability of cations that interacts with phosphorous, the usage of biochar altered the soil's phosphorous availability. Berihun *et al.,* [9] reported that the soil treated with 18 t ha^{-1} of Lantana biochar had the highest available phosphorus value (16.37 - 0.52 ppm), while the control had the lowest value (10.8 - 0.21 ppm). Halmi *et al.,* [23] reported that in biochar-amended soil, considerable changes in the makeup of the microbial population have been seen, which may help crucial processes like phosphorus solubilization and mineralization. This can result in improved soil available phosphorous content through increased activity of soil phosphatase and improved microbial dissolution of inorganic fixed phosphorous and mineralization of organic phosphorous.

2.3. Cation Exchange Capacity (CEC)

Cation exchange capacity (CEC) is a measure of the soil's ability to hold onto important exchangeable cations in the soil and has been seen to mitigate leaching losses [52]. Because of biochar's surface oxidation and the quantity of negatively charged surface functional groups, it has been demonstrated that adding biochar over time increases cation exchange capacity (CEC) in agricultural soils. Furthermore the possible reason for the rise in cation exchange capacity (CEC) due to its high surface area, high porosity, and organic material with varying charges, biochar additions have the potential to boost soil CEC and base saturation when added to soil. (Glaser *et al.,* 2002). A possible technique for better nutrient holding and supply following biochar amendment is increasing cation exchange capacity (CEC) by up to 50% as compare to unamended soil [33].

chintala *et al.,* (2014) reported that corn stover biochar had increase the cation exchange capacity (CEC) value by 87%, 120%, and 142% and switch grass biochar by 58% 89% and 122% at application rate 52, 104, and 156 mg ha^{-1}, respectively, when compared with untreated (control) plot. The increase of soil pH due to the application of biochar makes the soil surface more negative [54]. The addition of charcoal materials had raised the cation exchange capacity (CEC) of soils by 50%. The increased Cation exchange Capacity (CEC) of soil-biochar mixture may be due to gradual oxidation of biochar material as the result of biotic and abiotic factors during incubation which can oxygenate the functional groups of biochar surface and enhance the formation of organo-mineral complexes [22].

2.4. Organic Carbon

The organic portion of the soil known as "soil organic matter" is formed of microbial organisms, decomposing plant and animal debris, and other organic elements. Organic matter is the life of soil and essential for sustainability and high environmental standards. It contributes significantly to the preservation and enhancement of numerous soil processes and qualities. Soil organic matter is the main source of negative charges, which is crucial for assisting soil in adsorbing cations in the soil solution. One important component of soils is soil organic matter, which affects the physical, chemical, and biological characteristics of soils. Soil organic carbon (SOC) is the carbon related with soil organic matter. It is significant for all three aspects of soil fertility, which is chemical, physical and biological fertility. By limiting inputs to the soil and accelerating the decomposition of soil organic materials, some soil management techniques, such as fallowing, cultivation, stubble burning or removal, and overgrazing, can diminish soil organic carbon (SOC). The amount of soil organic matter is generally low in extensively worn soils. Consequently, applying pyrogenic carbon as biochar could enhance the soil's organic matter status. [36].

Biochar is a carbon- based substance made by the pyrolysis of organic waste, which is provides multifunctional values in agriculture by enhance soil physical, chemical and biological properties, thereby increasing soil health and productivity. The high alkalinity nature and high calcium carbonate ($CaCO_3$) content makes biochar to act as liming agent and improve the availability of nutrients in acidic soils. Using biochar in agricultural practices is a frequent way to increase the amount of organic carbon (OC) in a soil-biochar mixture. [16]. Dong *et al.,* (2016) revealed that After three years, the application of biochar improved soil aggregate stability and increased organic carbon in the light fraction, resulting to a 44–242% increase in the organic carbon of soil macro aggregates. Wang *et al.,* [62] found that the soil organic carbon content dramatically increased with the addition of biochar at a rate of 5 tons per hectare. The main cause of these observations may be the biochar's stable carbon content, which makes it difficult for it to degrade in soil conditions and contributes to the soil carbon pool.

3. Effect of Biochar on Crop Productivity

Soil acidity is a serious risk for crop production due to low plant nutrient availability and higher aluminum toxicity. It influences the amount of phytotoxic substances present, the accessibility of nutrients to the plant, and microbial activity. Soil acidity either directly or indirectly affects plant growth. Because Al and Mn are toxicity, there is a severe chemical imbalance and essential lack of accessible nitrogen, phosphorus, potassium, calcium, magnesium, zinc, and molybdenum; this inhibits crop growth, which lowers agricultural output. Biochar is a solid carbon byproduct of anaerobic thermal decomposition of biomass that can enhance the quality of agricultural soil. Depending on the feedstock and pyrolysis circumstances, the characteristics of biochar vary, and they could have a variety of consequences on the soil. It is thought that biochar has a high surface charge, a large surface area, and a high porosity. Consequently, incorporating biochar into acidic soils could reduce soil nutrient losses by adsorbing nutrients via electrostatics and physically trapping them within the pores. [8]. by supplying additional nutrients to the soil and performing other tasks including strengthening the physical and biological qualities of the soil, biochar application is regarded as a tool for soil amelioration. Liu *et al.,* [34] revealed that the rice yield improved by 8.5-10.7% when rice straw biochar were treated at a rate of around 4.5 t/ha. In general, biochar has an alkaline pH and can improve a different of soil properties, including cation exchange capacity (CEC), base saturation, exchangeable base, organic carbon content, and aluminum saturation in acidic soils. Although applying biochar to the soil raises the pH, soil pH is one of the most significant elements enhancing yield. An increase in soil pH might have favored nutrient uptake, while the toxicity of aluminium (Al) and iron (Fe) was decreased. According to Masulili *et al.,* [35] improved soil pH may be a key element in decreasing the amount the amount of aluminum (Al) and iron (Fe) in the soil, which will likely improve plant growth. Since biochar is a basis OF nutrient like nitrogen (N), phosphorous (P), potassium (K), and other trace elements, it can help enhance plant nutrition and productivity [46]. Additionally, the bioavailability of nutrient in the soil including potassium (K), Calcium (Ca), magnesium (Mg), and Phosphorous (P) can be improved by biochar [57]. and soil aeration, ware-holding capacity, bulk density of soil, and microorganisms increased with the addition of biochar [60]. It has a high pH and comprises alkaline materials (carbonates and organic anions from acidic functional groups) [68], and thus can be used as alternative amendment for the correction of soil acidity [8]. This is the main reason why incorporation of biochar increases crop yields [28]. Nigussie *et al.,* [41] demonstrated that the pH of soil can be raised by 9% by applying 10 t ha^{-1} of maize stalk biochar. This increase in soil pH was due to the distinctive qualities of biochar, such as its large surface area and porosity characteristics. Similarly, Glaser *et al.,* [22] revealed that Plant growth responses ranged from 29% to 324% when biochar was applied at rates of 0.5 to 135 t ha^{-1}. Berihun *et al.,* [9] reported that the maximum germination percentage of garden pea seeds (95.23%), and shoot length was significantly affected at two weeks and four weeks after biochar application at a rate of 18 t ha^{-1}. Likewise Liu *et al.,* [34] stated that application of rice straw biochar at a rate of 4.5 t/ha, increase rice yield by 8.5–10.7%. In addition to this, the rates of 10, 25, and 50 t ha^{-1} of rice straw biochar application in greenhouses resulted in yield increases of 12% and 17% for rice and wheat, respectively. [63].

Table 1. *Effect of different biochar source on crop yield.*

Biochar type	Biochar rate	Crop	Yield increment	Reference
Hardwood 500°C	10, 20, 30 t/ha	cocoyam	by 8.1, 7.8, and 5.5 % Respectively	Adekiya *et al.,*[3]
Rice straw biochar 500°C	4.5 t/ha	Rice	by 8.5- 10.7%	Liu *et al.,* [35]
Acacia biochar 400-500°C	25-50 t/ha	Maize	by 20% in first year and 12.5% in second year	Arif *et al.,* [4]

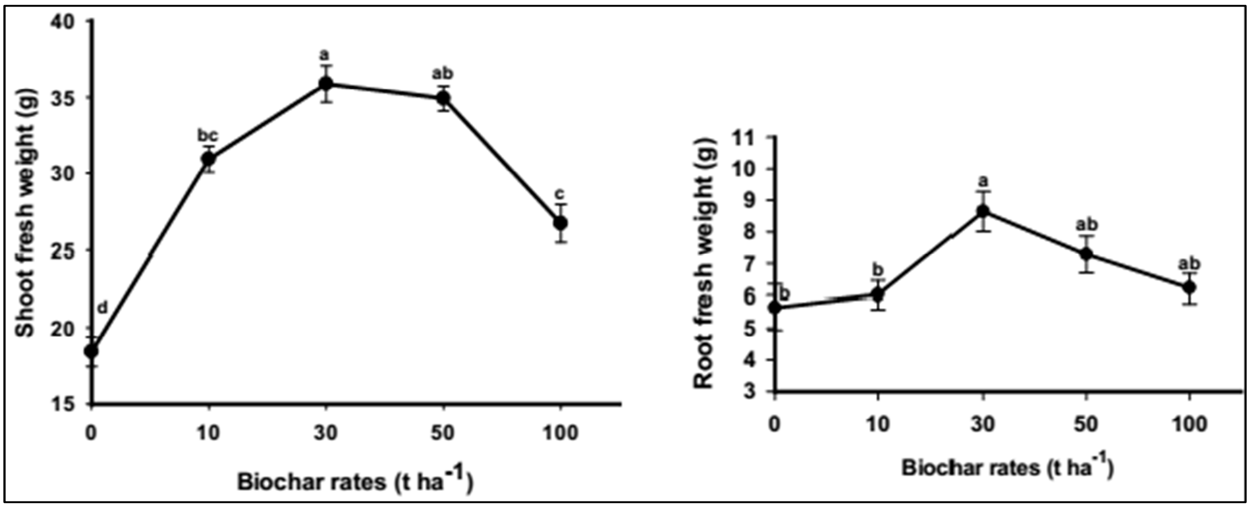

Figure 5. *Shoot and root fresh weight of lettuce influenced by application of green waste biochar. Source: [62].*

4. Conclusion

Soil acidity is a potentially serious land degradation issue; it can reduce the availability of essential nutrients, raise the influence of toxic elements, reduce plant production and water use, affect essential soil biological functions like nitrogen fixation and make soil more vulnerable to soil structure deterioration and erosion. Use of biochar as amendment can deliver a good solution to agricultural soil such as cropland deterioration due to acidity. Furthermore Increases in soil pH, accessible phosphorus, CEC, soil organic carbon, base cations, and decreases in exchangeable Al and exchangeable acidity can all be achieved by adding biochar to acidic soil. Moreover adding biochar to the soil significantly reduction nutrient leaching and increases yields and nutrient use efficiency. Likewise biochar application can increase crop yield through enhancing the chemical and biological properties of the soil including organic carbon and other plant nutrients.

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