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Review Article

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Significance of Biochar for Acidic Soil Management: A Review

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Abstract

Soil acidity which affects more than 50 % of the arable land of the world becomes a serious problem for plant production throughout the world. The application of lime is a common and widely used method used to ameliorate acidic soils which are not economically feasible for small-scale farmers. Application biochar from different organic sources has been suggested to ameliorate and improve the productivity of acidic soils. The objective of this review is to understand the potential effects of different biochar sources on the bio-physicochemical properties and productivity of acidic soils. Application biochar is effective to correct soil acidity problems and improve crop production by maintaining soil nutrients and improving its bioavailability. It has the potential to increase soil pH, available phosphorus, organic carbon, cation exchange capacity, and exchangeable bases and reduces exchangeable acidity. The alkaline nature and the presence of carbonate make biochar used as liming material and improve soil pH. However, the efficiency of biochar to ameliorate acidic soils is dependent on the feedstock type, pyrolysis temperature, and soil properties. Therefore, farmers are encouraged to use biochar as an alternative liming agent to improve crop productivity in acidic soils.

Keywords: Biochar, soil acidity, organic amendment, liming.

Introduction

Soil acidity-related soil fertility problems are the main factors that limit the productivity of soils throughout the world and affect more than 50 % of the world's arable lands[1]. Soil acidity can be caused by both by natural and anthropogenic processes including the use of ammonia fertilizers, crop removal of the basic cations, leaching 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[2]–[4]. 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[5]. Soil acidity affects plant growth directly or indirectly by affecting the plant's available nutrients, level of phytotoxic elements, and microbial activity. Therefore, mitigation of soil acidity is a major priority to improve soil health and crop productivity as well as to achieve food and nutrition security.

Various remediation methods have been applied to improve and sustain crop productivity in acidic soils. Application of lime is the most common and effective methods used to correct soil acidity and improve crop productivity in acidic soils [6]. However, it is not economically practical in poor scale farmers due to its high cost [7]. Application of easily available organic amendments alone or integrated with lime is more effective and economically feasible mechanisms for acid soil management [8], [9] and uplifting crop productivity [5]. Organic amendments, such as biochar, could therefore be used as efficient alternative for lime to ameliorate acidic soils [10]–[13] and can improve the physical , chemical and biological properties of the soil [14].

Biochar (BC) is a carbon rich material produced from the conversion of various organic wastes including woody biomass, crop residues, animal litter, composts, and biosolids through incomplete combustion processes or pyrolysis at relatively low temperatures (<700 °C) [15], [16]. It can be used for several purposes ranging from power and heat production to soil amendment [17]. Biochar application has been identified as a low-cost technology that provide a potential sink for carbon in the soil due to the presence of relatively stable carbon there by promoting carbon sequestration. However, beyond carbon storage biochar provides multifunctional values in agriculture by improving soil physical, chemical, and biological properties, thereby increasing soil health and productivity [18].

Recently, biochar amendment is widely known as the most effective means for correcting soil acidity by improving soil pH, alleviating aluminum toxicity and decreasing phosphorus fixation. 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 [19], [20]. Biochar improves soil fertility by raising soil PH [12], [21], [22], improves water holding capacity [23]–[25], increasing cation exchange capacity and exchangeable bases[13], reducing exchangeable acidity and aluminum[26]. Besides due to its high nutrient retention and sorption capacity, biochar has a potential to sequester carbon and[21], [27], [28] and reduces the loss of NO_3-N, P, K, Ca, Mg and Na through leaching and improves its efficiency uptake by plants[29]thereby improving crop production [30]. The increase in crop yield with different biochar application has been reported such as rice[13], peanut[31], maize [32], [33], and cowpea[34].

However, The effect of biochar on soil fertility and crop productivity of acidic soils may vary depend on the feed stock type used and pyrolysis temperature [17], [35], [36] and soil type [37]. Biochar derived from biosolids and manure sources generally contains a higher level of nutrients than those derived from plant residues. Similarly, biochar produced at lower pyrolysis temperature tends to contain a higher level of ‘volatile’ nutrients such as nitrogen and Sulphur [18]. Organizing information on the potentials of biochar to improve soil fertility and crop productivity of acidic soils is important. Therefore, the objective of this review was to assess and summarize the significant effect of different biochar sources on soil physicochemical properties and productivity of acidic soils.

Effects on soil physical properties

Biochar can improve the soil physical properties such as moisture content, bulk density, aggregate stability and infiltration rate due to its high carbon content that can remain constantly for many years without dissolving in the soil. Depending on the production conditions biochar contains about 60 to 80% carbon[38] which helps biochar to decreases bulk density[12], [13], [27]**,** improve water retention[23], [39], increase saturated hydraulic conductivity of soils[23], [24]. According to [40] application of Lantana camara biochar at the rate of 18tha^{-1} to acidic Nitisols southern Ethiopia decreases the bulk density from 0.9 to 0.72gcm^{-3} and increase its porosity from 67 to 74%. [13] also found that total soil porosity and available soil water was increased from 40 to 50% and 11.34 to 15.47% respectively due to the application of rice husk biochar in acid sulphate soils. The improvement of such soil physical properties has positive effect on root and microbial respiration.

Effects on soil chemical properties

Effects on pH and Exchangeable Acidity

Soil reaction (pH), a measure of soil acidity and alkalinity is fundamental to understand the nature and property of soils. It is a master soil variable that influences myriads of soil biological, chemical, and physical properties[41] and it is therefore a dominant factor which regulates the bioavailability of soil nutrients and crop productivity[42]. Acidic soils are characterized by low pH and high concentration of exchangeable aluminum. Addition of organic fertilizers such as biochar in acidic soils are beneficial to improve soil pH and reduce exchangeable Aluminum [13], [22]. The formation of strong proton affinity organic anions during decarboxylation (removing carboxyl and substitution by proton) and ammonification (conversion of the amendments to ammonia by microorganisms) enhances neutralization of hydrogen ion (H^+) which results increasing of soil pH [43]. Besides these the high carbon and ash content, as well as high specific surface area, volatile matter and alkaline pH [16], [21], [44], and the presence of carbonates of alkali and alkaline earth metals [12] in the ash of biochar are also responsible for increasing of soil pH and can effectively alleviate the toxicity of aluminum [45]. The reduction of exchangeable acidity in biochar amended soils is due to either the capacity of biochar to binding Al and Fe with the soil exchange sites or due to the formation of Al complex by the oxidized organic functional groups such as carboxylic and phenolic at the biochar surface[21].

Table 1: Effect of different biochar sources on soil pH.

Biochar source	Application rate	Pyrolysis T^O (^{O}C)	pH Change	Soil type	Reference
Corncob	2% (w/w)	350	4.6 to 5.8	Haplic Ferralsol	[21]
Corncob	2% (w/w)	350	4.8 to 6.1	Alfisol	[21]
Coffee husk	15 t ha^{-1}	350	5.2 to 6.2	Nitisol	[22]
Coffee husk	15 t ha^{-1}	500	5.2 to 6.6	Nitisol	[22]
Rice husk	50 t ha^{-1}	ND	4.61to 7.55	Tabela sand	[12]
Rice husk	1% (w/w)	600	4.53 to 5.12	Alfisol	[23]
Sesame	10 t ha^{-1}	ND	5.73 to 6.81	ND	[46]
Soybean	10 t ha^{-1}	ND	5.73 to 6.73	ND	[46]
Maize	1 t ha^{-1}	ND	5.73 to 6.28	ND	[46]
Canola strow	2% (w/w)	350	4.21 to 4.56	Ultisol	[47]
Rice strow	2% (w/w)	350	4.21 to 4.44	Ultisol	[47]
Corn strow	2% (w/w)	350	4.21 to 4.37	Ultisol	[47]
Wheat strow	2% (w/w)	350	4.21 to 4.31	Ultisol	[47]
Mung bean strow	2% (w/w)	350	4.21 to 4.88	Ultisol	[47]
Peanut strow	2% (w/w)	350	4.21 to 4.87	Ultisol	[47]
Soybean strow	2% (w/w)	350	4.21 to 4.74	Ultisol	[47]
Pea strow	2% (w/w)	350	4.21 to 4.61	Ultisol	[47]

The increase in pH due to application of biochar could also responsible for reduction exchangeable aluminum. As soil pH increase Al and Fe precipitated as insoluble Al and Fe hydroxides[19]. in the soil solution. Different research findings (table 1) indicate that application of biochar could increase the pH of acidic soil to optimum crop pH range. [40] Indicated that application of biochar to the soil increased soil PH from 0.5 to 1.5 units.

Effects on available phosphorus

Phosphorus (P) is one of the macro-nutrients essential for plants next to N. It is the essential component of cell membranes, plant genetic material and energy storage and transfer systems for chemical reactions in plant cells. It is important for rapid cell division and expansion [48], [49]. However, the majority of the soils of humid tropics of acidic soils are limited in plant available P, which may be due to the low P content of the parent material, high weathering intensity, long-term anthropogenic mismanagement, P loss by soil erosion, and high retention of P on mineral surfaces [50], [51]. In the soil P can be found in various forms of inorganic P(Pi) and organic P(Po) pools which makes its chemistry in the soil to be complex. The availability of P for plants is controlled by physical and chemical reactions, including desorption, precipitation and biological processes, such as the immobilization of P by other plants and soil microorganisms[52]. Besides,), environmental factors such as soil moisture content and temperature [53] and management systems[54], [55].

In highly weathered acidic soils available phosphorus (P) is very low [56]. Fixation of P by iron (Fe) and aluminum (Al) oxides and hydroxides are the main factor that limit phosphate availability in acidic soils [57]–[60]. In acidic soils, usually at lower pH ($pH < 5.5$) acidic cations like iron and aluminum becomes soluble and large amount of it will be found in the soil solution and react very quickly with phosphate ions, forming insoluble iron or aluminum phosphate minerals [50], [61], [62]. Phosphate fixation plays an important role in the fate of P added to soil from mineral fertilizers and manures and is an indicator of a soil's ability to release P to solution as well as its remaining capacity to bind added P [63]. Therefore, the availability of P in acidic soils can be improved by minimizing the fixation of P by oxides of Al and Fe in the soil and by the slow build-up of P in the soil to a point where the soil can be shown to reliably release sufficient P to meet crop demand on an annual basis.

The addition of organic fertilizers to acid soils where p-fixation is a problem has been effective in reducing phytotoxic levels of Al by forming organo-Al complexes that make Al less toxic or direct neutralization of Al from the increase in pH caused by organic matter(OM) decomposition[64]. Addition of OM is an important source of soil phosphorus and can increase soil P availability via soil mineralization or desorption of bound soil P. Three mechanisms may take place to increase the availability of P by addition of OM. First, soluble organic molecules may specifically adsorb to soil minerals by ligand exchange in competition with phosphate. Second, the soluble OM may react with bound Al^{3+} or Fe^{3+} at the surface of mineral phase to form soluble complexes of these elements and release phosphate which was previously sorbed or which was present as insoluble Al and Fe-phosphate. Third, the humic material and / or organic acids (released from decomposition of organic residues) may be adsorbed onto the surface of Al and Fe hydrous oxide sorption sites, resulted in higher negative charge (OH^-) of the particles which compete with P species (anions) for positive exchange sites on soil colloids. This process reduces the electrostatic attraction of phosphate and decreases phosphate ions activity at the reactive surface and increase P availability. However, its effect varies dependent on the type of organic fertilizer applied and soil type[65].

Biochar is one of the organic amendments used to increases the availability of P in acidic soils by increasing soil pH. It also has a potential to improve soil available P through either direct supply of P or its retention of fertilizer P.

Different studies showed that application of biochar in acidic soil can improve the availability of P by decreasing its fixation by Fe and Al oxides[60]. According to[66] the P sorption of tropical soils decreased by 55% due to application of biochar. The application of biochar transforms free Fe, Al, and Mn oxides in to hydroxides and reduce the availability of high energy sorption sites, which leads to increases in the extractable P with in the soil solution. The presence of high concentration of P in the ash also contribute to an increase in soil available P content[40]. However the effect of biochar on P availability in acidic soils is generally inconsistent and depended on the amount of the added P [67]. [19]reported that application of 15tha^{-1} coffee husk biochar in acidic soil increases the availability of phosphorus from 4.52 to 23.21mgkg^{-1}. According to[32] application of biochar in combination with lime, increased available P by 137% Biochar application in P deficient soils could also increase P uptake by crops. According to [68] the efficiency of plant P uptake increased up to 50% due to application of biochar.

Effects on organic carbon and nitrogen bio-availability

Organic matter is the life of soil and vital to environmental quality and sustainability. It plays a significant role in the maintenance and improvement of many soil properties and processes. It is the major source of negative charges, which is important for helping the soil to adsorb cations in the soil solution[13]. Due to this, soil organic matter (SOM) is considered as primary indicator for determining soils fertility. Therefore, enhancement of SOM is a key tool in agricultural production to enhance fertility, alleviate elemental toxicity and protect the soil[4]. Intensive cultivation coupled with high temperature and high moisture content favored faster decomposition of organic matter in soils resulting declining of soil fertility and increasing greenhouse gas emission[69]. The residence time of most organic amendments in the soil is short term and therefore its effect on soil organic carbon could be after long term application but depending on the quality of the amendments.

Biochar is more stable relative to other soil organic matter forms and contains large amount of recalcitrant carbon that is neither easily decomposed nor entirely inert. It undergoes mineralization and release labile fractions of carbon into soil which resulting an increase of soil organic carbon [70]. [69] also indicated that biochar is highly efficient in storing carbon in the soil and serve as a sink of atmospheric CO_2, and ensure ecological integrity and environmental sustainability. Application of 15tha^{-1} coffee husk biochar produced at 500 ^{o}c in nitisols of Dedesa, Southwest Ethiopia increased the SOC by 45.6% after two months of incubation period[19].

Apart from enriching soil organic C, biochar improves the soil nitrogen bioavailability by reducing nitrate leaching, N_2O emission, ammonia volatilization[71] and thus may decrease the Nitrogen fertilizer demand for crop growth[72]. [73] showed that application of peanut hull biochar produced at 600^{o}c pyrolysis temperature reduced the leaching of nitrate and ammonium by 34% and 14%, respectively.

Effects on cation exchange capacity and exchangeable bases

Cation exchange capacity (CEC) is the soil's ability to retain and supply nutrients to plant. It is highly associated with basic cations, and soils with high CEC are able to bind more exchangeable basses (Mg, Ca, and K) to exchange sites. In acidic soils that has high precipitation leaching of basic cations from the soil solution is the main factor for low availability of exchangeable bases. Due to the high pore space and retention capacity, biochar improves CEC and decreases leaching of exchangeable bases[29]. Biochar contains considerable amounts of exchangeable bases (Ca^{+2}, Mg^{+2}, K^{+}, and Na^{+}) and the introduction of these cations to the soil along with biochar application also responsible for increasing of exchangeable bases[28], [60]. [74] showed that addition of cornstover biochar had increased the CEC values by 87%, 120%, and 142% and switch grass biochar by 58%, 89%, and 122% at application rates 52, 104, and 156 Mg ha^{-1}, respectively. [43] also reported that application of 6tha^{-1} maize biochar increased the CEC of acidic soils from 13.709 to 27.18 meq/100 gm. The high surface area of biochar and high surface negative charge resulting from oxidation of functional groups, mainly carboxylic and phenolic, on the outer surface of biochar particles will probably has higher cation adsorption and decrease the leaching of basic cations like K, Mg, and Ca. Besides, the increase of CEC with the application of biochar can also minimize leaching of potassium and ammonium nitrogen [75]. The increase in organic matter and pH which facilitates the availability of exchangeable cations could also responsible for the increase in CEC of acidic soils after application of biochar[43].

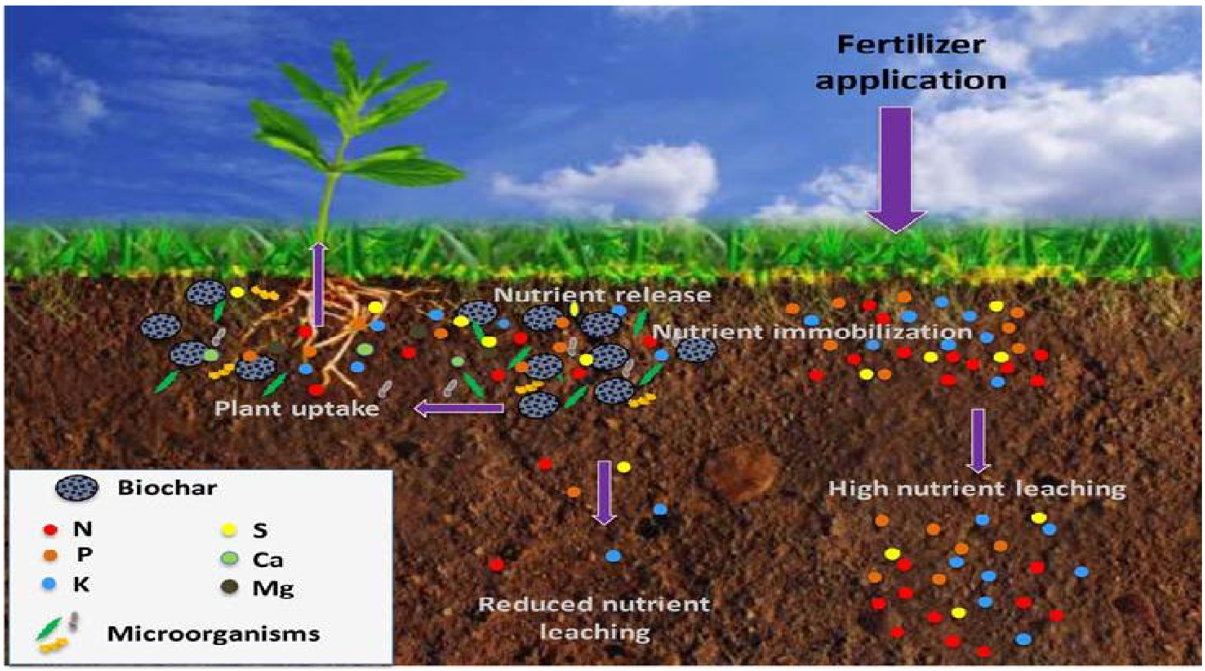

Figure 2: The mechanisms of biochar interactions with fertilizers and soil microorganisms for nutrient immobilization, release, and plant uptake while improving soil fertility (adapted from[18].

Effects on soil biological properties

Soil biological properties which include all the plant and animals those belongs to macro and micro groups of organisms, can change the whole soil environment by increase of decrease in the amount of concentration, availability or decomposition of a particular element which are directly or indirectly influences the physical as well as chemical properties of the soil. Soil microbes controls most soil nutrient cycles, and are important to healthy soil process and good soil quality[76]. There are several factors that limit its function in the soil including climate, edaphic, and land use change[77]. Soil pH is also considered as one of the predictor of biogeographical microbial patterns and is an important factor determining the diversity of microbial communities[3], [41], [78], [79]. Different microbial groups have different and well-defined pH optima for growth[80]. Soil bacteria are one of the largest functional microbial subgroups in soil, participating in many soils biological process including soil respiration, nutrient transformation, and organic matter decomposition. The bacterial diversity is higher in neutral soils and lower in acidic soils[3]. Generally, Bacteria are divided into three groups (acidophiles, neutrophiles, and alkaliphiles) in terms of their response to pH. The acidophiles grow in very acidic conditions; below pH 5.5 (e.g., Thiobacillus thiooxidans), the neutrophiles ; gown at pH 5.5 to 7.9 (e.g., Escherichia coli, Rhizobium and Brady rhizobium), and the alkaliphiles have optima in the alkaline range; grows above PH 8 (e.g., Bacillus alkalophilus)[81].

Besides deteriorating soil physicochemical properties, soil acidity causes disastrous effects on soil microbial community structure and biochemical activity of microbes[79]. The high concentration of aluminum in acidic soils inhibits bacterial growth[81] by disrupt cell membranes, alter enzyme production, and limit reproduction[82] resulting low population, diversity and activity of beneficial microbes, primarily bacteria and fungi which are responsible for most microbial processes, including the breakdown of organic matter and cycling of nutrients . Acidity decreases the activity of nitrifying bacteria responsible for the breakdown of organic matter into ammonium and nitrate for subsequent plant uptake[41]. This slow rate of mineralization of nutrients in to plant available form by soil microbes may potentially limit plant uptake. Application of organic amendments could increase the diversity of microorganisms and stimulates bacterial biomass and activity besides increasing the soil organic matter[83]–[85]. Biochar is one of the organic amendments rich in organic carbon which could improve the tendency and distribution of microorganisms by providing more suitable growing conditions in degraded acidic soils and can be used as a source of nutrients for soil microorganisms [86]. Biochar also provide suitable natural environment to enhance microbial growth by enhancing the air movement of the soil, increasing water content, and alleviating compaction of the soil [87]. Addition of biochar increased microbial population as a result of modifying effect of biochar creating a conducive environment which stimulated the proliferation of the nitrifier community [88]. Addition of biochar in acidic soil could increase the availability of nitrogen and carbon, and the decrease the solubility of Aluminum, Iron and Manganese resulting soil microbial biomass improvement. According to[89] application of biochar produced from corn stalks at 550°C in Albic Clayic Luvisol increased relative abundance of Actinobacteria, but decreased the Acidobacteria.

Effects on crop yield and Agronomic performance

Soil acidity is a serious threat for crop production due to low plant nutrient availability and higher aluminum toxicity. It affects plant growth directly or indirectly by affecting the plant available nutrients, level of phytotoxic elements, and microbial activity. The toxicity level of exchangeable Al and Mn results sever chemical imbalance and critical deficiency of available nitrogen, phosphorus, potassium, calcium, magnesium, zinc and molybdenum which limits crop growth there by decrease crop yield. However, the degree of susceptibility to soil acidity among crops are different. For example, Crops such as cotton, alfalfa, oats, and cabbage (Brassica oleracea) do not tolerate acid soils and are considered suitable to neutral soils with a pH range of 7–8. Wheat, barley, maize, clover, and beans grow well on neutral to mildly acid to neutral soils (pH 6–7). Millet, sorghum, sweet potato, potato, tomato, flax, tea, rye, carrot and lupine are among crops tolerant to acidic soil[4]. Therefore, improving the productivity of acid soil should be given a priority to attain food demand. Various management options were practiced to improve crop yields in acidic soils. The use of cheap nutrient source such as waste materials and biomass sources is an alternative to reduce the need for inorganic fertilizers and would help to increase fertilizer efficiency and crop productivity in acidic soils[34].

Highly weathered acidic soils are poor in soil nutrients due to leaching of basic cations and P fixation. These loose of nutrients not only increases the cost of plant production, but also causes environmental problems such as water pollution. Biochar is characterized as high porosity, large surface area and high surface charge. Thus, addition of biochar to acid soils could alleviate soil nutrient losses by electrostatic adsorption and physical entrapment of the nutrients inside the pores[90]. Improvement of nutrient bioavailability and use efficiency due to application of biochar has appositive short- and long-term effect on crop yield. The increase in crop yield with different biochar application has been reported such as rice[13], peanut[31], maize [32], [33], and cowpea[34]. [91] also reported that the biomass of Pak Choy White (Tropical Type) was increased by 32.81% due to application of 25tha^{-1} rice husk biochar in Sandy-Loam Soil in Lafia, Southern-Guinea Savannah, Nigeria. Application of waste willow wood (Salix spp.) biochar also improved maize yield up to 29 % as reported by [33]. According to [34] application of biochar in combination with NPK fertilizer in the acid sandy Arenosol increased cowpea yield up to 70% as compared with NPK fertilizer alone. [15] also reported that application of 12tha^{-1} eucalyptus biochar in nitisols of Koga watershed increased teff yield from 1.437 to 2.688 tha^{-1}.

Conclusion

Soil acidity is one of the major constraints that limit crop productivity throughout the world. Thus, improving crop productivity of acidic soils is a major priority as a demand of food increase rapidly. Hence, economically feasible and environmentally friendly management options are very important to increase crop productivity in acidic soils. Application of biochar is one of the effective and economically feasible management practices used to improve soil fertility and crop productivity of acidic soils. Biochar has a potential to Increase soil pH, alleviate Aluminum toxicity and decreasing phosphorus fixation thereby improve crop yield in acidic soils. Biochar is also a good source of plant nutrients and could decrease the external fertilizer requirements. Therefore, it can be suggested farmers to use biochar integrated with inorganic fertilizers to improve the productivity of acidic soils.

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