Review Article

# BIOCHAR: A BLACK CARBON FOR SUSTAINABLE AGRICULTURE

Biochar review: A black carbon for sustainable agriculture

## ABSTRACT

Biochar refers to the black carbon that is produced by the process of slow pyrolysis and act as a vehicle of carbon sequestration from renewable and sustainable biomass. It has the ability to improve the physical, chemical and biological properties of soil thus increasing crop yield and productivity. Application of biochar lowers bulk density, and improves porosity, aggregation, water infiltration and water holding capacity of soils. It also darkens the soil colour which affects soil surface reflectance and thus helps to moderate soil temperature. Biochar addition enhances cation exchange capacity, increases soil pH, improves the supply and uptake of nutrients, reduces nutrient leaching losses, captures $NH_3$ and leads to reduction in volatilization loss of nitrogen thus improving nutrient availability in soils. Application of biochar can also remediate soils contaminated with heavy metals and organic pollutants. It can also facilitate microbial colonisation in soil, enhance soil microbial biomass carbon, enzyme activity and the activity of mycorrhizal fungi.

***Keywords***

Biochar, soil physical properties, soil chemical properties, soil biological properties, abiotic stress and nano-biochar.

## 1. INTRODUCTION

Black carbon is the name given to the spectrum of chemical and thermal solid conversion products formed from carbonaceous materials, which could be biomass or fossil fuels. The black carbon continuum contains all charred residues ranging from char, charcoal, bone char, carbon ash, carbonized carbon, coke, soot, and biochar. Biochar refers to the black carbon that is produced as a vehicle of carbon sequestration from renewable and sustainable biomass [1]. It is a stabilized, recalcitrant organic carbon compound created when biomass is heated by the process of pyrolysis to temperatures usually between 300 $^0$C and 1000 $^0$C under low oxygen concentrations [2] and has been produced and utilized for several thousand years. Applications of biochar are very diverse, ranging from heat and power generation, flue gas cleaning, metallurgical applications, agriculture and animal husbandry, as building material and for medical use [3].

Biochar has created interest because of its unique role in sustainable agricultural production and environmental protection. It is known to reduce nitrogen (N) loss from soils in terms of nitrous oxide ($N_2O$) emission and ammonia ($NH_3$) volatilization, improve nutrient retention capacity and structural and chemical properties of soil, and increase plant growth and productivity [4]. In an incubation study conducted by Jien et al. [5], it was reported that the application of biochar produced from the waste wood of *Leucaena leucocephala* improved the physical, chemical and biological characteristics of soil like water holding capacity, bulk density, pH, cation exchange capacity (CEC) and microbial biomass carbon. Biosolids, municipal waste, paper mill sludge, manure, agricultural residue, wood processing residue, algae and livestock/ poultry waste are some of the feedstocks used for biochar synthesis. Being rich in nutrients and due to the efficient carbon sequestration ability, biochar produced using these waste products are highly effective for crop health and productivity.

Biochar is not pure carbon, but rather a mix of aromatic carbon compounds containing carbon (C), hydrogen (H), oxygen (O). nitrogen (N), sulphur (S), and ash in different proportions. The main structure of biochar is a stacked crystalline graphitic sheet and randomly ordered amorphous aromatic structure. Biochar can be produced by slow or fast pyrolysis. As the pyrolysis process continues, the biomass is reduced by releasing volatile organics resulting in a disproportional amount of volume decrease or biomass shrinkage [6]. The properties of biochar vary depending upon the sources of biomass used, the rate at which it is heated, the maximum temperature of heating and the extent to which volatiles are produced during pyrolysis. Several studies demonstrated that feedstock choice, pyrolysis temperature, and pyrolysis type influence the final physicochemical characteristics of biochar. Therefore, both production technology and the original composition of the feedstock source strongly influence biochar yield as well as its physical and chemical properties [7].

## 2. EFFECT OF BIOCHAR ON SUSTAINABLE AGRICULTURE

Biochar is a renewable, environment friendly, low-cost material that can be used in agriculture as a soil amendment [8]. Application of biochar improves the physical, chemical and biological properties of the soil (Fig 1). The efficiency of biochar as a soil amendment depends on various characteristics such as specific surface area, porosity, surface charge at operating pH, surface functionality and morphology, CEC, ash content, etc. [9,10]. Biochar improves soil health due to its high residence time in the soil and its ability to improve soil structure and hold available nutrients. Biochar has a high degree of carboxylate esterification and aromatization structure, high carbon content, very low solubility, high boiling point, high stability and strong resistance to physical, chemical and biological degradation [11,12]. These characteristics allow biochar to persist in the soil for thousands of years under natural environmental conditions [13]. The estimated residence time of biochar in soils ranges from hundreds to thousands of years [14]. Biochar increases the organic matter content of the soil thus leading to improvement in the water-holding capacity, increased microbial activity, nutrient retention, nutrient cycling and crop productivity [15].

### 2.1. Effect of biochar on soil physical properties

#### 2.1.1 Bulk Density

Bulk density is an indicator of healthy and porous soil. It has an effect on important soil processes and crop productivity including rooting depth and its restriction, soil aeration, infiltration, plant available water, plant nutrient availability and soil microbial activity. Soil bulk density is reported to decline as biochar application rates increase [16].

Application of coconut husk and shell biochar at 10 t $ha^{-1}$ produced at a pyrolysis temperature of 350- 400 $^{0}$C in a sandy clay loam soil decreased the bulk density of the experimental soil from 1.32 Mg $m^{-3}$ to 1.23 Mg $m^{-3}$ [17]. The decrease in bulk density due to biochar application could primarily be attributed to the low bulk density of the material itself (0.128 Mg $m^{-3}$) and to the increase in soil organic matter and pore space consequent to its application. The change in soil bulk density also depends upon the order and textural class of the soil treated with biochar. Application of corn stover biochar in two different soils viz, Alfisol and Andisol, belonging to the same soil textural class (silt loam), caused a significant reduction the bulk density of Alfisol while there was no discernible difference in the bulk density of Andisol. This might be a result of the inherent low bulk density of Andisol which was only marginally lesser than the bulk density of the biochar applied [18]. When compared to fine-textured soils, coarse-textured soils show a greater decrease in bulk density on biochar application [19].

#### 2.1.2 Soil porosity

A good porous soil creates a suitable environment for root growth and microbial activity which in turn results in high productivity of the soil. Biochar application has a significant impact on soil porosity. Application of tender coconut husk biochar was found to increase the porosity of a loamy soil from 43.1 to 45.6 per cent as compared to control in a soil cultivated with banana [20]. Improvement in the porosity of soil after biochar application can be due to the pore contribution from the highly porous biochar material, modification of the pore system by creating soil aggregation and improvement of soil aggregate stability. In general, compared to fine textured soil, coarse-textured soils show a significant increase in soil porosity [21].

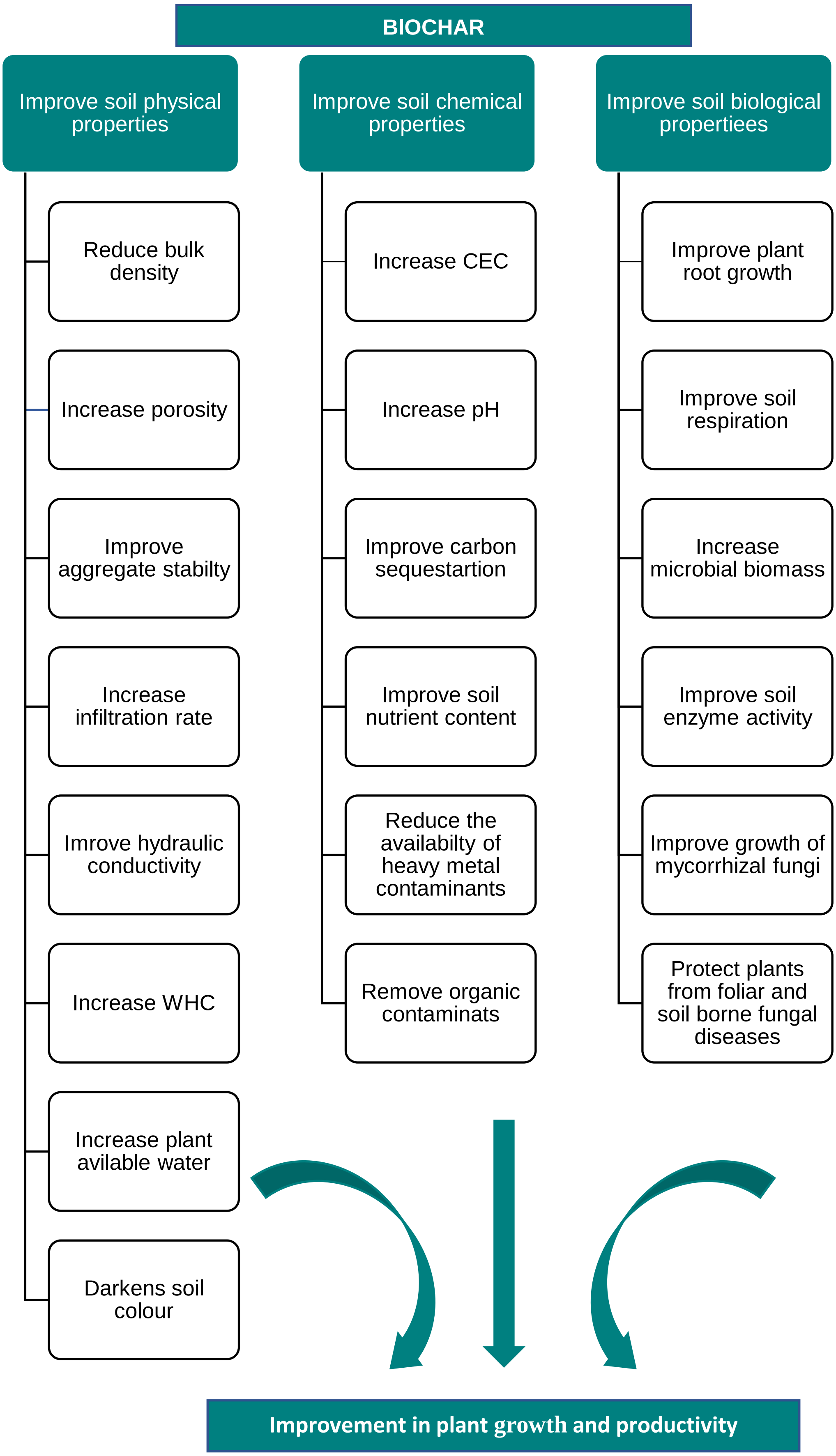

Fig 1: Effect of biochar on soil physical, chemical and biological properties

### 2.1.3 Soil aggregate stability

The ability of soil to withstand mechanical stresses like the impact of rainfall, surface runoff and water erosion is largely dependent on soil aggregate stability [22]. Biochar influences soil aggregation due to its interaction with soil organic matter, minerals and microorganisms. It contains cations that can be joined by the means of cationic bridges with clay and organic particles thus creating a favorable soil structure [23]. The labile organic matter on the surface of the biochar acts as a substrate for the microorganisms leading to enhancement of mucilage secretion, which in turn helps to create stable soil aggregates [24].

Aggregation may intensify over time resulting in the formation of a stable soil structure. Shaheen and Bukhari [25] on comparing sawdust and corn cob biochar applied to a degraded sandy loam soil cultivated with wheat reported that per cent aggregates of 5 mm, 2.5 mm, 1.25 mm and 800 µm were found to be higher for sawdust biochar and corn cob biochar application compared to all other treatments. A field experiment conducted by Kumar et al. [26] in a sandy loam soil applied with coconut shell biochar also showed a 40.30 per cent increase in water stable aggregates compared to the control.

### 2.1.4 Soil hydraulic conductivity

Biochar application can increase, decrease, or cause no influence on soil hydraulic conductivity. Das and Ghosh [27] amended a sandy loam soil with four different types of biochars (maize, *Lantana camara*, pine needle and black gram) at different rates, and observed that hydraulic conductivity decreased from the initial value of 0.41 cm $s^{-1}$ (without biochar) to a final value 0.16, 0.18, 0.19 and 0.21 cm $s^{-1}$, respectively, on the application of maize, Lantana camara, pine needle and black gram biochar @ 10 t $ha^{-1}$. The decrease in hydraulic conductivity was likely to be due to the hydrophobicity of the organic carbon present in the biochar amendment. Increase in soil hydraulic conductivity noticed in fine-textured soils amended with biochar could be due to the increased porosity and better soil aggregation that promotes soil drainage [28]. In an experiment conducted by Wong et al. [29] it was reported that the application of biochar derived from peanut shells improved the saturated hydraulic conductivity due to an improvement in the porosity of kaolin clay soil.

### 2.1.5 Water infiltration

The downward movement of water into the soil is known as infiltration. A field experiment conducted by Sharma et al. [30] in a sandy clay loam soil treated with different combinations of FYM, vermicompost and rice husk biochar produced at a pyrolysis temperature of 350-450 $^{0}$C showed that the infiltration rate increased with the application of biochar and organic manures in comparison to the control. The use of biochar increased soil infiltration rate due to its high total porosity, which could retain water in small pores and facilitate water infiltration into the soil, thus increasing the water retention capacity of the soil.

### 2.1.6 Soil water holding capacity (WHC)

The high porosity and specific surface area of biochar cause reduction in water permeability resistance of soil, increase WHC and change the water residence time and flow path [31,32]. The WHC of a soil cropped with green gram increased to 49 per cent by the application of rice husk biochar compared to the control [33]. This can be due to the microporous structure of biochar which improves WHC.

### 2.1.7 Plant-available water

Application of biochar as a soil amendment was found to increase the plant-available water, although in some cases, it had no significant effect. By incorporating biochar into the soil, especially in light soils, the chemical and physical properties of biochar are expected to cause an increase the water storage capacity leading to an increase in plant available water, thereby achieving a long-term improvement in soil productivity [16].

The high porosity of biochar could have a positive impact on soil water retention [34] and, thus, increase the plant-available water. The amount of plant available water will also change with the type of feedstock used for biochar production, pyrolysis temperature and rate of application of biochar. A pot culture study was conducted by Burrell et al. [35] by using four different biochars from mixed woodchips, wheat straw and vineyard prunings in soils of Planosol, Chernozem and Cambisol for a period of one year. All biochar treatments increased the amount of water present in the soil. A unique property of biochar which makes it an attractive soil amendment is its highly porous structure which is responsible for the increased water holding capacity and water infiltration into the soil, thus increasing soil water retention capacity.

### 2.1.8 Soil colour and temperature

Biochar is a black particulate matter, and hence the addition of high concentrations of biochar darkens the soil colour which affects soil surface reflectance and soil temperature. The application of biochar can reduce the surface reflectance and thermal conductivity of the soil. The main reason for the decrease in soil thermal conductivity is due to increased soil organic carbon content [36]. Soil colour and moisture are the main factors affecting the specific heat of the soil. The addition of biochar causes the soil temperature to rise at locations with low water content and the soil heat preservation effect can efficiently inhibit harmful weed seeds in soil and improve crop quality and yield [37].

## 2.2 Effects of biochar on soil chemical properties

### 2.2.1 Influence of biochar on CEC of soil

Cation exchange capacity is used to estimate the ability of soil to adsorb, retain and exchange cations. Increasing the number of soil cation exchange sites can increase the soil CEC [38]. The acidic aromatic carbon on the surface of biochar is oxidized to form abundant functional groups (–OH, –COOH), enhancing the adsorption capacity of soil cations and increasing soil CEC [39]. Due to the presence of more anions on the surface, biochar can increase soil CEC when added to acidic or alkaline soils [40]. In an experiment conducted by Nagula [41] in a loamy soil by using banana as the test crop, a significant increase in soil CEC was noticed on the application of tender coconut husk biochar. The initial soil had a CEC of 3.36 cmol $kg^{-1}$ whereas the application of tender coconut husk biochar at 10 kg $plant^{-1}$ and 75 per cent (NPK + secondary & micronutrients as per soil test) recommended dose of nutrients recorded a significantly superior value of 5.18 cmol $kg^{-1}$ CEC at the final harvest stage.

The type of feedstock from which biochar is prepared also affects soil CEC. An incubation study conducted by Chintala et al. [40] in a clay soil (pH <4.8) for 165 days by using lime, corn stover biochar and switchgrass biochar revealed that the increase in CEC values of soil was significantly higher in corn stover biochar at all application rates followed by switchgrass biochar and lime treatment.

### 2.2.2 Effect of biochar on soil pH

The pH of biochar ranges between 7 and 12 depending on the feedstock used and this alkaline character directly affects soil pH when applied. Biochar can regulate the pH value and increase base saturation of the soil. Addition of biochar promotes exchange of $H^+$ and $Al^{3+}$ in the soil with basic cations under the action of water, thereby reducing their concentration in soil and alleviate soil acidity [42]. pH was found to increase gradually with increase in application rate of biochar [39]. The soil acidity ameliorating effect of Leucaena biochar was investigated in an incubation study in an acid soil (pH = 4.5) in northwest India by Jha et al. [43] and it was reported that the mean increase in soil pH was 0.65, 1.35, and 2 units at 2 per cent, 4 per cent, and 6 per cent (w/w) of biochar incorporation respectively.

Table 1. Nutrient content of tender coconut husk, coconut frond and rice husk biochar [20, 50]

| **Parameters** | **Tender coconut husk biochar** | **Coconut frond biochar** | **Rice husk biochar** |
|---|---|---|---|
| Total carbon (%) | 70.10 | | |
| Nitrogen (%) | 1.52 | 0.44 | 0.84 |
| Phosphorous (%) | 0.40 | 0.11 | 0.03 |
| Potassium (%) | 2.26 | 0.54 | 0.20 |
| Calcium (%) | 0.54 | 0.41 | 0.56 |
| Magnesium (%) | 0.46 | 0.16 | 0.42 |
| Sulphur (%) | 0.27 | 0.26 | 0.21 |
| Fe (mg kg$^{-1}$) | 89.9 | 86.54 | 72.16 |
| Mn (mg kg$^{-1}$) | 2.84 | 12.20 | 34.59 |
| B (mg kg$^{-1}$) | 6.78 | 5.12 | 5.45 |

Table 2. Sorption and desorption of nutrients by biochar [49]

| Nutrients | Sorption (%) after 24h | Desorption (%) After 84h |
|---|---|---|
| $NH_4^+$ | 100.00 | 32.35 |
| $PO_4^{3-}$ | 90.70 | 75.65 |
| $K^+$ | 92.00 | 45.14 |
| $Ca^{2+}$ | 87.00 | 46.00 |
| $Mg^{2+}$ | 86.15 | 23.45 |
| $SO_4^{2-}$ | 91.82 | 74.38 |
| $Fe^{2+}$ | 99.67 | 36.80 |
| $Mn^{2+}$ | 100.00 | 30.20 |
| $Zn^{2+}$ | 99.12 | 26.75 |
| $Cu^{2+}$ | 99.12 | 26.72 |

### 2.2.3 Influence of biochar on soil nutrient dynamics

Biochar is capable of enriching the soil nutrient pool by acting as a source of both macro and micronutrients (Table 1). The supply of nutrients will change according to the type of feedstock used for biochar production [44]. The production temperature of biochar is a critical factor for determining its nutrient content since a certain fraction of elements in the feedstock can be excessively lost by volatilization. During pyrolysis, volatilization of N and S will start at low temperatures, compared to other nutrients, and nutrients such as Ca, Mg, and Mn are said to be thermally stable at typical biochar production temperatures [45]. It is also important to note that only a small fraction of the total nutrient content of biochar is available to plants since a considerable fraction usually exists in recalcitrant forms [45,46]. Biochar produced at high pyrolysis temperatures contains high ash content where nutrients exist mainly as soluble salts that can be readily liberated in to the soil [47]. An incubation experiment conducted by Jabin and Rani [10] for 240 days by using laterite and sandy soils of Kerala revealed that the application of two types of biochar produced from coconut frond and coconut husk increased the amount of mineralizable nitrogen, available phosphorous and available potassium content of the soil. The uptake of nutrients was increased by the addition of biochar prepared from wheat straw, Lantana camara and dried pine needles along with a recommended dose of fertilizers [48]. The uptake of nitrogen, phosphorous and potassium was reported to be highest when full dose of recommended fertilizer was applied in combination with 5 t ha$^{-1}$ biochar. The low decomposition rate of biochar despite its high C:N ratios makes nitrogen immobilization insignificant, which is an additional advantage over the application of other organic amendments like manures [4].

A laboratory experiment conducted by Dainy [49] showed that the nutrient (especially cations) adsorption power of biochar from tender coconut husk was high. Once biochar is applied as to soil, it will prevent leaching of nutrients during runoff efficiently by adsorption and later make them available to plants through desorption. Therefore, it can be concluded that biochar as a soil amendment is a good adsorber and a slow releaser of nutrients and its application can reduce chemical fertilizer use (Table 2) and improve nutrient use efficiency.

### 2.2.4 Effect of biochar on carbon sequestration

Carbon sequestration is the process of removing carbon from the atmosphere and depositing it in a reservoir. Biochar production and utilization systems differ from most biomass energy systems because the technology is carbon negative and carbon dioxide from the atmosphere is stored as stable soil carbon sinks in the terrestrial ecosystem. Biochar also reduces $CO_2$ emission which is achieved by reducing the requirement for fertilizers while increasing soil microbial life in turn resulting in more carbon storage in soil. As per preliminary calculations, atmospheric $CO_2$ levels could be brought down to levels which existed before 1752 AD by 2050 if 2.5% of the world's agricultural land produces biochar, ideally from wastes for use in the topsoil [51].

In an incubation experiment carried out by Jabin and Rani [52] for 210 days on laterite and sandy soils of Thiruvananthapuram district of Kerala, all treatments receiving biochar either from rice husk or coconut frond resulted in lower $CO_2$ emission compared to treatments receiving FYM till the end of the incubation period. Biochar may persist in soil for millennia because the carbon contained is very resistant to microbial decomposition and mineralization leading to a net sequestration of $CO_2$. It is one of the best technological solutions to reduce $CO_2$ emission levels since biochar has the potential to sequester almost 400 billion tonnes of carbon by 2100 AD and lower atmospheric $CO_2$ concentrations by 37 parts per million [53].

When carbon from biomass is converted into biochar, about 50% of the original carbon is stored compared to the small amounts of carbon retained after residue burning and biological decomposition of organic wastes in soil (less than 10%-20% after 5–10 years) [54]. The estimated residence time of C from biochar in soils ranges from hundreds to thousands of years [14]. Only a small portion of biochar carbon is bioavailable, and the remaining 97% directly contributes to long-term carbon sequestration in soil [55]. The decomposition of biochar begins relatively quickly but slows down over time. The median rate of biochar decomposition is 0.0046% day$^{-1}$. The labile condensed fraction of biochar, which decomposes at a relatively rapid initial rate, is the primary cause for the quick initiation of biochar decomposition. After two years, this initial high rate of decomposition disappears and the decomposition rate is maintained at a very low level for extended periods [56].

The primary reason for the higher stability of biochar in soils is their resistance to microbial decomposition [14] which is due to the presence of aromatic structures [57]. In a 10-year field experiment conducted by Shi et al. [58] with three treatments, viz., no biochar (control), corncob biochar application at 4.5 Mg $ha^{-1}$ $yr^{-1}$ and 9.0 Mg $ha^{-1}$ $yr^{-1}$, it was reported that corncob biochar application significantly enhanced soil inorganic carbon content, particulate organic carbon content and total soil organic carbon content compared to the no-biochar control.

### 2.2.4 Effect of biochar on ammonia volatilization

The physical and chemical characteristics of biochar influence their effectiveness in controlling $NH_3$ volatilization. The addition of biochar to the soil increases soil pH, capture $NH_3$ and reduce volatilization loss because of its high surface area and functional groups. Biochar with a high specific surface area contains several surface functional groups that can capture $NH_3$.The acidic surface groups on biochar with a low pH can protonate $NH_3$ gas to form $NH_4^+$ ions and since ammonia is an alkaline gas, it promotes their adsorption onto the cation exchange sites of biochar [59]. The $NH_3$ adsorbed by biochar can subsequently become available to plants [60]. In an incubation experiment conducted using five soils with pH ranging from 5.5 to 9.0 by Mandal et al. [61], ammonia volatilization was found to be reduced by approximately 70 per cent due to the application of poultry litter biochar and macadamia nut shell biochar. The decreased $NH_3$ volatilization with biochar addition could be attributed to multiple mechanisms such as $NH_3$ immobilization and nitrification. Moreover, biochar increased the wheat dry weight and N uptake by as high as 24.24 and 76.11 per cent respectively.

### 2.2.5 Effect of biochar on soil total phosphorus content

Excessive application of P fertilizers has caused P leaching from agricultural fields to aquatic systems [62]. Biochar has the ability to alter P availability in soils by reducing P leaching through sorption/adsorption. Possible mechanisms suggested to be the reasons for the influence of biochar on P availability are changes in soil pH and subsequent influence on the interaction of P with other cations, or enhanced retention through anion exchange. In a fractionation study of phosphorus in a sandy loam soil, at the end of 120 days of incubation it was revealed that the addition of wheat and rice straw biochars gradually increased the loosely bound phosphorous, Al-P, Ca-P and total P content of soil, but significantly decreased the Fe-P content. Compared with control, the addition of biochar at 10, 20 and 60 g $kg^{-1}$ increased Al-P by 24.7%, 135.5% and 163.3% for rice biochar and 195%, 184.1% and 185% for wheat biochar respectively [63].

### 2.2.6 Biochar for the remediation of heavy metal-contaminated soil

A small amount of heavy metals like Cr, Zn, Bo, Cu, Co, Fe, Mn, and Ni is required for various biochemical processes in animal and plant systems. Heavy metals are likely to enter the food chain due to their non-degradable nature, speciation, and bioavailability to living organisms since they are present in the environment at trace concentrations (less than 10 ppm or ppb). The build-up of heavy metals and metalloids in soil, including As, Pb, Cd, Hg, Se, and Cd is a matter of growing concern because of their fatal, cancer-causing, mutagenic, and multi-organ dysfunctional effects on living beings [64].

Only the ionic forms of heavy metals dissolved in the pore water of soil is bioavailable to soil organisms and plants. When biochar is added to soil, the metal ions will be transferred from contaminated soil to biochar. The high surface area, numerous surface functional groups and a structure with many pores, attract metal ions, which then associate with stronger sorption sites of biochar and dissociate from soil molecules. Thus, when applied to heavy metal contaminated soil, biochar serves as a barrier that prevents metal ions from attaching to soil molecules by developing a strong affinity for the heavy metals [65]. The mobility and availability of heavy metals are controlled by complexation with different functional groups, physical sorption on the porous surface, electrostatic attraction by the surface charge, ion exchange through replacement of cations and precipitation reaction of biochar [64].

In a study conducted by Devanand [66], application of rice husk biochar recorded a significant reduction in the adverse effect and toxicity of cadmium in different parts of the rice crop. The Cd content of 3.2 µg $g^{-1}$ and 1.5 µg $g^{-1}$ recorded in straw and grain respectively was reduced to 2.13 µg $g^{-1}$ and 1.05 µg $g^{-1}$ respectively by the application of 40 t $ha^{-1}$ biochar.

### 2.2.7 Biochar for the removal of organic pollutants

A lot of research has been done regarding the use of biochar for the removal of different organic pollutants from soil and water [67]. Agrochemicals, antibiotics/drugs, industrial chemicals like volatile organic compounds including trichloroethylene, benzene, furan, butanol, hexane, etc., polycyclic aromatic hydrocarbons like naphthalene, phenanthrene, pyrene, anthracene, polychlorinated biphenyl, m-dinitrobenzene, catechol, and p-nitrotoluene are among the targeted organic pollutants [68].

The effect of wheat straw biochar on the sorption, dissipation and bioavailability of hexachlorobenzene (HCB), a typical persistent organic pollutant (POP), was investigated by Song et al. [69]. It was observed that HCB sorption by biochar was 42 times greater than that by soil and the sorption isotherm was linear for the concentration range studied. Biochar amendments are reported to reduce HCB dissipation, volatilization and the uptake of HCB from soil by earthworms (*Eisenia fetida*).

## 2.3 Effect of biochar on soil biological properties

### 2.3.1 Effect of biochar on plant root growth

Biochar has been reported to stimulate the root growth of plants. The abundance and growth behaviour of roots change in response to the application of biochar due to improvements in the chemical and physical characteristics of soil. Application of different doses of biochar derived from black cherry wood in pot experiments under greenhouse conditions for 35 days significantly increased the total root length by 30 per cent, 46 per cent and 61 per cent respectively with increasing levels of biochar viz. 1 per cent, 2 per cent and 3 per cent. Application of biochar at the rate of 3 per cent significantly increased root surface area by 47 per cent, root diameter by 37 per cent and root volume by 45 per cent over control [70]. Biochar application also affected root-associated microbes and significantly increased the number of root nodules [71].

### 2.3.2 Effect of biochar on soil respiration

Estimation of soil respiration can provide an overall indication of soil biological activity following biochar application. Biochar provides significant amount of labile carbon that is readily available to soil microorganisms for use as an energy source [72]. In a micro plot experiment with crop pasture grass mixture, the highest increase of basal respiration value of about 50 per cent was reported in a soil applied with 5 t $ha^{-1}$ of poultry litter biochar compared to the mineral fertilized soil. This suggests that the decomposition of organic matter was intensified with biochar application [73].

### 2.3.3 Effect of biochar on soil microbial biomass

Soil microbial biomass is another important parameter used to evaluate soil biological activity. An increment in microbial biomass after the addition of biochar has been reported by many researchers. Singh et al. [74] investigated the effect of rice husk biochar on microbial biomass and found an increase in biomass carbon, nitrogen and phosphorous as compared to control in rice-cultivated sandy soil. The increase in soil microbial biomass is due to the considerable amount of labile carbon and the large surface area of biochar providing a favourable micro habitat for soil microbial communities. Both the bacterial and fungal community compositions were significantly affected by the addition of corn stover biochar in an experiment conducted by Jin [75]. As a result of the addition of biochar, the Basidiomycota and Ascomycota families of arbuscular mycorrhizal fungi shifted to the Zygomycota and Glomeromycota families and thus a change in microbial diversity occurs after the application of biochar.

### 2.3.4 Effect of biochar on soil enzyme activity

Soil enzymes can also be used as indicators of soil quality since they are more sensitive to alterations in management practices than the physical or chemical properties of the soil [76]. Soil enzymes are associated with key microbial reactions involved in soil nutrient cycling. In an incubation study, Demisie et al. [77] applied three different rates (0.5, 1.0 and 2 per cent) of oak wood biochar and bamboo biochar with control in a red soil. After 372 days, the incubated soils were analysed and the highest dehydrogenase activity was measured in 0.5 per cent oak wood biochar treated soil followed by 0.5 per cent bamboo biochar. Urease activity was significantly higher in 2 per cent and 0.5 per cent oak wood biochar and 0.5 per cent bamboo biochar treatments compared to the other treatments. Thus, the effect of biochar on soil enzymes is highly variable depending on biochar types, the enzyme considered and biochar application rates.

#### 2.3.5 Effect of biochar on mycorrhizal fungi

Root colonization by mycorrhizae is reported to be improved following biochar addition [78]. Biochar along with arbuscular mycorrhiza (AM) increases plant P uptake. Biochar has been reported to increase AM colonization by 6 per cent and an AM-related Fe-P uptake increase by 12 per cent [79]. Treatment of biochar and AMF in combination mitigated the deleterious effects of drought to a considerable extent and caused a significant enhancement in relative water content and membrane stability index of plants under normal conditions [80].

#### 2.3.6 Protection of plants by biochar from foliar and soil-borne fungal diseases

Biochar can mediate plant systemic resistance against foliar diseases [81] and has the capability to diminish fungal diseases. A study conducted by Khalifa and Thabet [82] to determine whether Salix wood chip biochar as soil amendment can improve the resistance of tomato against wilt (caused by *Fusarium oxysporum*) and root rot (caused by *Rhizoctonia solani*) diseases under greenhouse conditions revealed that the disease severities were highest in the absence of biochar, reaching 75.0 per cent and 67.6 per cent for *F. oxysporum* and *R. solani* respectively. Plants grown in biochar amended substrate exhibited remarkably higher resistance to *F. oxysporum* and *R. solani* as indicated by 85 per cent and 80 per cent lower disease incidences and 84 per cent and 80 per cent lower disease severities. Increased water and nutrient availability after the application of biochar leads to enhancement in plant vigour enabling quick response of plants to pathogen attack [83]. Beneficial microorganisms can compete with soil pathogens for space and nutrients and produce antimicrobial agents thereby reducing disease incidence [84]. Biochar adsorbs extracellular degrading enzymes [85] and other phytotoxins produced by pathogens [83]. Application of biochar leads to a substantial increase in total phenolic compounds in the roots and leaves which suppress disease development by inhibiting the extracellular fungal enzymes (cellulases, pectinases, lactase and xylanase), inhibition of fungal oxidative phosphorylation, inhibition of both spore germination and mycelial growth and antioxidant activity in plant tissues [86].

### 2.4 Effect of biochar on crop growth

Multiple studies have reported improvement in crop yields after biochar application [87]. Jyothishree [88] reported that grain and straw yield increased from 18.23 q ha$^{-1}$ and 31.35 q ha$^{-1}$ to 23.34 q ha$^{-1}$ and 39.1 q ha$^{-1}$ respectively on addition of biochar produced from corn rind at 2 t ha$^{-1}$ to a finger millet (*Eleusine coracona*) cropped area.

### 2.5 Effect of biochar on abiotic stress management

Abiotic stress such as drought, high soil salinity, heat, cold, oxidative stress and heavy metal toxicity are the common adverse environmental conditions limiting crop productivity worldwide [89]. The positive influence of biochar on plant cold tolerance is due to the presence of surface organic molecules and their interaction with stress-related proteins. Research show a continuous enhancement in growth of rice plant under cold stress with increasing rate of biochar application. Application of leachate produced from rice husk biochar at a dosage of 3, 5, 7, and 10 per cent increased plant height by 12.31, 21.43, 43.37, and 52.84 per cent, root length by 11.93, 27.27, 43.18, and 52.84 per cent, and dry weight by 4.24, 8.1, 13.56, 25.42 per cent respectively compared to the control [90].

Plants have had to develop various methods to mitigate all kinds of biotic and abiotic stresses in order to survive. Superoxide dismutase, peroxidase and catalase are important enzymes within the antioxidant defence system that mitigate oxidative damage by cleaning up excessive reactive oxygen species in plant cells under low temperature. Proline and soluble sugars are also thought to play important roles as osmoregulatory solutes that improve plant stress tolerance [91]. High biochar leachate concentrations stimulate cold responsive genes at low temperatures, enhance protective enzyme activities, increase proline and sugar contents and eliminate reactive oxygen species to protect the cell membrane system.

Biochar not only improves crop productivity under normal conditions but also improves crop yield under adverse conditions like salinity and drought. Thomas et al. [92] investigated the ability of biochar (at two dosages: 5 and 50 t ha$^{-1}$) to mitigate salt-induced stress, simulating road salt additions in a factorial experiment in glasshouse involving the broadleaved herbaceous plants *Abutilon theophrasti* and *Prunella vulgaris*. Both species showed nearly 100 per cent mortality within 10 days in response to salt additions in the no biochar and low biochar dosage (5 t ha$^{-1}$) treatments. However, survival was high in the salt plus high biochar addition (50 t ha$^{-1}$) treatment. For *Abutilon theophrasti*, survival in the treatment involving salt plus high biochar addition was 100 per cent throughout the course of the experiment. In *Prunella vulgaris*, survival in the salt plus high biochar treatment was initially high but then declined after the 40th day of experiment which suggest high species-specificity of biochar. The adsorption property of biochar is largely responsible for reducing the impacts of salinity stress by avoiding exposure of plants to salt condition. Biochar can also increase the water holding capacity of soil and improve the water status of plants, particularly during drought periods which reduces osmotic stress in the plants during salinity conditions [92].

### 2.6 Nano-biochar and its prospects

Biochar is gaining huge attention in recent years due to its beneficial effects on soil and humankind. Biochar is mostly applied for improving soil health, crop production, yield and climate change mitigation. Recent studies have shown that nano biochar generated by the physical degradation of bulk biochar, having a size smaller than 100 nm [93] has excellent mobility both in soils and water and could act as a carrier for natural solutes and contaminants [8].

Nano biochar can also act as a slow-release fertilizer. Factors such as pore size, and adsorption and desorption of nutrients play a vital role in the release of plant available nutrients from nano biochar. A study conducted by Khan et al. [94] also revealed that liberation of nutrients from wheat straw nano biochar was synchronous with the uptake of nutrients by plants and hence thus biochar could act as a slow release fertilizer.

correct referencing

## 3. METHOD AND DOSAGE OF APPLICATION OF BIOCHAR

Biochar should ideally be applied to the root zone, where the bulk of nutrient cycling and uptake by plants take place. If biochar is applied to soil solely for C sequestration purposes, placement deeper in the soil would be desirable since microbial activity that can degrade biochar carbon could be reduced. The likelihood of erosion losses of biochar is lower if it is thoroughly incorporated into the soil. The different application methods are broadcasting, banding, mixing biochar with other solid amendments, mixing biochar with liquid manures etc. [53].

Due to its recalcitrant nature, a single application of biochar to the soil can provide beneficial effects compared to application over several growing seasons. Therefore, biochar need not be applied to each crop successively like manures, compost, and synthetic fertilizers. Depending on the application rate, availability of biochar and the soil management system, biochar can be applied in different doses [53].

In general, biochar materials can differ widely in their characteristics, which in turn influence the application rate. Several studies have reported positive effects of biochar application at the rate of 5-50 tonnes per hectare along with appropriate nutrient management on crop yields. Though this is a wide range, when several rates were used, the plots with the higher biochar application rate showed better results. Most biochars when applied in combination with fertilizers can ensure further improvement in crop yield [53].

## 4. CONCLUSION

Biochar is a rich form of stable carbon and a suitable option as soil amendment for sustainable agriculture due to the improvement in soil physical, chemical and biological properties. Apart from carbon storage, biochar also provides a solution for managing the large volume of crop residue without burning and thus prevent air pollution and reduce greenhouse gas emission and thereby climate change. Production of renewable energy and heat during biochar production and an increase in nutrient and water use efficiency when applied to soil further help in mitigating climate change through reduction in emission of $CO_2$. The yield, characteristics and rate of biochar application significantly vary depending on the feedstock quality and pyrolysis temperature. Further, most of the studies are confined to laboratory or institute-level field trials and the application of biochar in agricultural fields by farmers is less. Therefore, there is a need to formulate polices for promoting the use of biochar as a soil amendment so as to exploit its potential for enhancing soil quality and for mitigating climate change.

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