



REVIEW ARTICLE

Impact of biochar on soil health and plant development: A review

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Abstract

Biochar is a highly stable form of carbon produced by heating organic material (like wood or agricultural waste) in a low-oxygen environment. It improves soil structure by enhancing water retention, aeration and nutrient availability. This is especially helpful in degraded or sandy soils. Biochar is a long-term carbon sink, meaning it can lock carbon in the soil for hundreds or even thousands of years, helping mitigate climate change by reducing the amount of CO₂ in the atmosphere. It can act like a sponge for nutrients, holding them in the soil and releasing them slowly, which can reduce the need for synthetic fertilizers and lower the risk of nutrient leaching into water systems. Biochar supports beneficial soil microbes, improving soil health and potentially leading to better crop yields. It provides a sustainable use for agricultural and forestry waste, reducing landfill waste and improving the overall sustainability of farming practices. Biochar offers a way to enhance soil productivity while addressing environmental concerns like climate change and waste management. Biochar is a highly stable form of carbon produced by heating organic material (like wood or agricultural waste) in a low-oxygen environment. Biochar has the potential to increase conventional agricultural productivity and enhance the ability of farmers to participate in carbon markets beyond the traditional approach by directly applying carbon into the soil. In view of this context, the biochar plays a significant role in crop productivity and improving soil health.

Keywords: amendments; biochar; carbon sequestration; plants; soils

Introduction

India is an agrarian economy, majority of land is used for farming, huge volume of crop residues is produced on-farm. It is estimated that approximately 500-550 million tons of crop residues are produced per year in the country (1). Efficient use of biomass by converting it to a useful source of soil amendment/nutrients to manage soil health and fertility, biochar is a potential soil amendment and carbon sequestration medium improves the soil quality and reduces farm waste. Biochar is a fine-grained charcoal high in organic carbon that is produced from pyrolysis of plant biomass and other waste feedstock. The major crop residues used for biochar production are straws of paddy, wheat, millet, sorghum, pulses (pigeonpea), oilseed crops (castor, mustard), maize Stover and cobs, cotton and jute sticks, sugarcane trash, leaves, fibrous materials, roots, branches and twigs of varying sizes, shapes, forms and densities (2). Similarly, the agro-industrial residues are rice husk, groundnut shell, cotton waste, coconut shell, coir pith, tamarind shell, mustard husk, coffee husk, cassava peels, etc. Some of the common agricultural by-products available in large quantities include bagasse, rice husk, groundnut shell, tea waste, casuarina

leaf litter, silk cotton shell, cotton waste, oil palm fibre and shells, cashew nutshell, coconut shell, coir pith, etc.

Residue burning traditionally provides a fast way to clear the agricultural field of residual biomass and facilitating further land preparation and planting. Other reasons for intentional burning include clearing of fields, fertility enhancement and pest and pasture management (3). It also provides a fast way of controlling weeds, insects and diseases, by both eliminating them directly or by altering their natural habitat. Further, the time gap between rice harvesting and wheat sowing in northwest India is only 15-20 days. Hence, farmers prefer burning the rice stalk in the field instead of harvesting it for other uses. Burning is also perceived to boost soil fertility, although burning has a differential impact on soil fertility (4). It increases the short-term availability of some nutrients (e.g. P and K) and reduces soil acidity but leads to a loss of other nutrients (e.g. N and S), organic matter and microbial activity required for maintaining better soil health. Among the cereal residues, rice and wheat straws are the dominant and the easiest way to clear the field is burning these in the field itself. For example, 23 % of rice straw residue produced is surplus and is either left in the field as

uncollected or open field largely burnt. In Punjab alone, some 70 to 80 million tons of rice and wheat straw are burned annually (5), releasing approximately 140 million tons of CO₂ to the atmosphere, in addition to methane, nitrous oxide and air pollutants. About three fourths of greenhouse gas emissions from agro-residues burning were CH₄ and the remaining one-fourth was N₂O. Burning of wheat and paddy straws alone contribute to about 42 % of GHGs (6). On the other hand, maintenance of a threshold level of organic matter in the soil is crucial for maintaining physical, chemical and biological integrity of the soil and for the soil to perform its agricultural production and environmental functions (7, 8). Hence, conversion of organic waste to produce biochar using the pyrolysis process is one viable option that can enhance natural rates of carbon sequestration in the soil, reduce farm waste and improve the soil quality (8). Biochar has the potential to increase conventional agricultural productivity and enhance the ability of farmers to participate in carbon markets beyond the traditional approach by directly applying carbon into the soil (9). This has led to renewed interest of agricultural researchers to use charcoal/black carbon/biochar as a soil amendment for stabilizing soil organic matter. Converting waste biomass into biochar would transfer very significant amounts of carbon from the active to inactive carbon pool, presenting a compelling opportunity to intervene in the carbon cycle. The use of biochar as soil amendment is proposed as a new approach to mitigate man-induced climate change along with improving soil productivity. The use of biochar in agriculture is not new; in ancient times farmers used it to enhance the production of agricultural crops.

One such example is the slash and burn cultivation, which is still being practiced in some parts of Northeast India. In order to sequester carbon, a material must have long residence time and should be resistant to chemical processes such as oxidation to CO₂ or reduction to methane that the use of biochar as soil amendment meets the above requirements; since the biomass is protected from further oxidation from the material that would otherwise have degraded to release CO₂ into the atmosphere (10). Such partially burnt products, more commonly called pyrogenic carbon or black carbon, may act as an important long-term carbon sink because their microbial decomposition and chemical transformation are probably slow.

Biochar preparation

There are different ways to make biochar, but all of them involve heating biomass with little or no oxygen to drive off volatile gasses, leaving carbon behind. This simple process is called thermal decomposition usually achieved from pyrolysis or gasification. Pyrolysis is the temperature driven chemical decomposition of biomass without combustion. Slow pyrolysis refers to a process in which large biomass particles are heated slowly in the absence of oxygen to produce biochar and fast pyrolysis refers to reactors designed to maximize the yields of bio-oil and typically use powdery biomass as feedstock.

Characteristics of biochar

Physical characterization

Pyrolysis temperature is the main regulating factor, which governs surface area of biochar. It was reported that increase in temperature from 400 to 900 °C increased surface area of biochar from 120 to 460 m²/g (11). However, although low temperature biochar is stronger than high temperature products, it is brittle and prone to abrade

into fine fractions once incorporated into the mineral soil. It may be proposed that the surface area over the long term, that is, of weathered biochar, is not greatly affected by temperature. Increase in pyrolysis temperature from 400 °C to 600 °C decreased the volatile and N component of biochar, while it increased ash and fixed carbon content. Thus, biochar prepared at 60 °C had wider C:N ratio making it more stable in soil. Earlier research reported that the bulk density of rice and wheat biochar prepared at 400 °C was comparatively lower than the maize and pearl millet biochar (12). The water holding capacity of wheat biochar was highest (561 %) followed by maize biochar (456 %).

Chemical characterization

Biochar produced from different feed stock had pH ranged from 8.2 to 13.0. Invariably, total carbon content of biochar increased with the increase in pyrolysis temperature. Total carbon content in biochar materials produced from different feedstock varied from 33.0 % to 82.4 %. Biochar provides a facile flow of carbon from the active pool to the passive pool (13). In comparison to burning, controlled carbonization converts even larger quantities of biomass organic matter into stable C pools which are assumed to persist in the environment over centuries. Apart from carbon sequestration, there are other environmental benefits that can be derived from the application of biochar in soils which include reduction in the emission of non-CO₂ GHGs by soils. Soil is a significant source of nitrous oxide (N₂O) and both a source and sink of methane (CH₄). Biochar is reported to reduce N₂O emission could be due to inhibition of either stage of nitrification and/or inhibition of denitrification, or promotion of the reduction of N₂O and these impacts could occur simultaneously in a soil (14).

Soil amendments

Like any other organic amendments, Biochar can be applied to soil by different methods including broadcasting, band application, spot placement, deep banding, etc. However, the method of biochar application in soil depends on the farming system, available machinery and labor. Mixing biochar with composts and manures may reduce odors and improve nutrient performance over time due to slower leaching rates. Experiments have found that rates between 5 and 50 t/ha (0.5-5 kg m⁻²) have often been used successfully. While no recommended application rates for biochar can be given, biochar should be applied in moderate amounts to soil. Rates around 1 % by weight or less have been used successfully so far in field crops (12). Biochar is a high carbon containing material (more than 50 %) produced by heating biomass in absence of oxygen. Biochar can act as a soil conditioner by improving the physical and biological properties of soils such as water holding capacity and soil nutrients retention and enhancing plant growth. Biochar has the potential to: (i) increase soil pH, (ii) decrease aluminum toxicity, (iii) decrease soil tensile strength, (iv) improve soil conditions for earthworm populations and (v) improve fertilizer use efficiency (4).

Effect of biochar on soil properties

The influence of biochar on soil characteristics is provided in Table 1.

Effect of biochar on soil physical properties

A previous findings stated the lowest bulk density was noticed in COMBI + F - 25 t/ha Co composted biochar - compost + F treated plot (0.92 g/cm³) while compared to control (0.97 g/cm³) and the highest water content was noticed in COMBI + F - 25 t/ha Co composted biochar - compost + F treated plot (28.8 %) while

Table 1. Influence of biochar on soil and plants

Parameter	Influence of biochar	Reference
Soil pH	Increases pH in acidic soils, reducing aluminium toxicity and improving nutrient uptake	(27, 76)
Soil organic carbon	Increases SOC due to its high carbon content and stability	(77)
Water holding capacity	Enhances WHC, especially in sandy soils, improving drought resilience	(78)
Cation exchange capacity	Improves CEC, leading to better nutrient retention and availability	(79)
Microbial population	Stimulates microbial biomass and enzymatic activity due to improved habitat structure	(27, 80)
Nitrogen use efficiency	Enhances NUE and reduces nitrate leaching when co-applied with fertilizers	(81)
Plant growth	Increases biomass and yield, especially in degraded or nutrient-poor soils	(77)
Greenhouse gas emissions	Reduces N ₂ O and CH ₄ emissions from soils	(82)
Heavy metal immobilization	Reduces bioavailability of Pb, Cd and Zn in contaminated soils	(83)

compared to control (26.9 %) in Ferralsol soil (15). The reduced bulk density and increased soil water content in biochar treated plots in combination with compost and inorganic fertilizers might be due to the high porous nature and high surface area of biochar might decrease the soil bulk density and increased the aggregate stability by the application of compost thereby increased the soil water retention capacity (16).

Earlier studies reported a field experiment in sandy loam texture (*Typic ustochrept*) at PAU. The results confirmed that the highest infiltration rate was found in biochar applied plot at 8 t/ha with canal water irrigation (3.42 cm³/cm) (17). Irrespective of biochar applied the infiltration rate of soil has been decreased with increase in salinity. However, the interaction effect between biochar applied and saline water irrigation was significant, with the increasing levels of biochar the infiltration rate has been increased irrespective of salinity. The increase in infiltration rate of soil might be attributed to the porous nature of biochar particles has been reported to enhance soil pore space along with the hydraulic properties of soil. The improved infiltration rate along with porous biochar particles may have facilitated the leaching of excess salt below the root zone, particularly during heavy monsoon rains received at the experimental site during the cotton growing season, thus improved infiltration rate of soil. Similar findings have shown by Githinji (18) that most of the salt stored during the preceding wheat season can be leached out from the soil profile with the application of biochar and off-season rains before the next growing season.

Earlier studies stated that there is no improvement in infiltration rate with the application of different sources of compost alone but with the application of biochar at 2 t/ha along with FYM and vermicompost had significantly increased the infiltration rate in sandy clay loam in texture (19). The increased infiltration rate of soil with the biochar application might be due to the porous nature and high surface area of biochar might decrease the soil bulk density and increase the aggregate stability which further increased the infiltration rate and water retention of soil. Previous studies reported that maximum aggregate stability, water holding capacity, infiltration rate and hydraulic conductivity were attained under FYM + VC in combination with the biochar (20-22). Similar findings were also reported consistent with previous findings (23). The biochar (10 t/ha) applied plots resulted in 16.15 kg erosion and 331.56 L runoff which recorded as the lowest erosion and runoff in *Typic kandiodalfs* clay soil while compared to pumice and mycorrhizae plots in corn field (24). The decrease in runoff and erosion in biochar treated plots is due to that biochar has significantly decreased the bulk density, increased the porosity which further increased the water-holding capacity and infiltration capacity in erosion plots. The porous nature of biochar can bind water and nutrients, thereby increasing the ability of the soil to catch water. Addition of biochar has reduced erosion by 50.78 % and runoff by 51.67 %. The decrease in soil erosion due to the addition of biochar was earlier

reported (25) that biochar had reduced the surface runoff rate by 50 % and increased the total water availability by up to 32 %. Furthermore, the lowest bulk density of soil has recorded in biochar treated plot (1.14 g/cm³) the highest porosity of 44.48 % was recorded in biochar treated plot. The decrease in bulk density and increase in porosity of soil might be due to the high porous nature and high surface area of biochar might increase the soil aggregation which further decreased the soil bulk density and increased the porosity of soil.

Earlier study concluded that the lowest bulk density (0.85 and 0.79 mg/m³), highest porosity (67.9 % and 70.2 %) and highest moisture content (24.9 % and 26.5 %) was recorded in biochar (30 t/ha) with poultry manure (10 t/ha) treated plots of site A and B during 2019 and 2020, respectively (26). The improvement in soil bulk density, porosity and moisture content might be due to the application of biochar which has the low bulk density (<0.6 Mg m⁻³) than field soil (1.2 Mg m⁻³). Hence biochar application reduces the density of the bulk soil through the dilution or mixing effect and by interacting with soil particles and improving aggregation and porosity thereby increased the soil moisture content. The fact that overall, biochar and poultry manure applications reduced bulk density, highlighted their potential to improve soil structural development and stability led to increased moisture content (27-30).

Effect of biochar on soil chemical properties

The earlier research evaluated the influence of biochar (10 t/ha) in combination with compost (25 t/ha), inorganic fertilizers (26.6:31.6:66.2 kg NPK/ha) and COMBI (25 t/ha) on soil NH₄-N and NO₃-N content in groundnut field (15). The results revealed that the highest NH₄-N was noticed in B + F - 10 t/ha biochar + F and COMBI + F - 25 t/ha Co composted biochar - compost + F treated plot (16.7 and 16.0 mg/kg respectively) and the highest NO₃-N was noticed in COMBI + F - 25 t/ha Co composted biochar - compost + F treated plot (6.0 mg/kg). The increase in NH₄-N and NO₃-N is due to the use of COMBI implying that co-composted biochar-compost has been more effective in the retention of N during the composting process and in making the N plant available in the soil resulted in the highest soil NH₄-N and NO₃-N. And the increased N content also might be due to the reduced bulk density and increased soil water content which enhanced the N mineralization and availability. Co-composting of poultry manure and farmyard manure with biochar has previously been shown to reduce the losses of N in the mature composts (31, 32).

Biochar addition increased available K, which is possibly due to direct K⁺ addition from biochar ashes and the application of biochar in combination with organic and inorganic fertilizers may have a synergistic effect, enhance soil microbial activities and make nutrients (P and K) bioavailable (33, 34).

The lowest EC was recorded as 0.4 dS/m in canal water

irrigated plots along with biochar and the EC has been gradually increased with the increased application rates of saline water irrespective of biochar application, however the interaction effect of saline water along with biochar is significant, with the application of biochar in saline water irrigated plots has significantly reduced the EC of soil (*Typic ustochrept*) (17). The decrease in EC of soil from those of biochar amended plots might have shown the possible mechanisms which are retention of salts on the surface of biochar with high CEC, increased hydraulic conductivity of soil and providing soil surface cover which reduced evaporation and decreased upward movement of salt and it is expected that salts entrapped in the pores of biochar are released back with time that further leach down as infiltration rate increases. Similar findings have been reported consistent with earlier studies (35, 36).

The application of biochar along with manure and NPK had a positive effect on total organic carbon content in sandy clay loam, Ferralsol (37). The improvement in total organic carbon content with the application of biochar was because of the abundance of aromatic compounds in the biochar that are resistant to biological degradation and the higher amount of carbon present in biochar, resulted in increased the carbon content of the soil. Similar results were reported in the previous studies (38, 39). The influence of biochar (10 t/ha) alone and biochar with different combinations such as cattle manure (20 t/ha), poultry manure (5 t/ha), cattle urine (10000 L/ha), commercial biofertilizers (5 kg/ha), urea (100 kg N/ha) on soil pH, organic matter, total nitrogen, available phosphorus and available potassium in a raddish field (40). The experiment confirmed that the optimum pH was noticed under biochar + urea, treated plot (6.5) while compared to control, highest organic matter content was recorded under biochar + cattle manure treated plot (4.0 %), highest total N was recorded under biochar + cattle urine and urea treated plots, highest available phosphorus and potassium was recorded under biochar + poultry manure treated plot (80.1 and 203.6 kg/ha, respectively). The increase in soil pH and OM upon biochar addition could be due to the alkaline nature (high pH) and higher organic carbon content of biochar. Biochar acts as an absorbent of applied organic fertilizers and inorganic fertilizers and retains nutrients such as N, P and K due to its larger porous surface area and functional groups and increased the N, P and K status of soil. Similar findings were reported consistent with earlier study (41). The highest total carbon (1.41 %) and total nitrogen (0.45 %) were recorded in the soil + 2 % enriched biochar treated plot (42). The higher carbon content and total N in soil with the application of enriched biochar is due to its more stable organic form which reduced the gaseous fluxes of C and N and biochar has high carbon content which directly adds carbon to soil and due to its high retaining capacity, it aids in slow release of nutrients which improved total N content in soil. Soil enriched biochar application increased the soil adsorption capacity to retain the nutrients (43, 44).

The highest OC (1.36 %) and CEC (7.20 meq/100g) were observed in the biochar-treated plot of *Typic kandudalfs* (24). The increase in OC might be due to application of biochar contains highly stable form of carbon, as not easily degradable up to hundreds of years. Soil organic matter plays a vital role to improve the fertility of soil and sequester the carbon, thus enhancing the soil organic carbon contents (45-47). The CEC increased in biochar plots was because of the porous nature of biochar, porosity becomes a reservoir that binds cation elements. Biochar has an empty C bond due to pyrolysis; therefore, biochar easily binds to cations in the soil,

thereby increasing the soil CEC. Due to the increase in soil bulk density, porosity, reduced soil erosion and increased soil OC and CEC (48), the nutrient uptake increases further improved the corn growth and yield by 47%.

Effect of biochar on soil biological properties

The application of biochar along with carpet waste, FYM and PGPR has significantly increased the soil microbial population. The highest bacterial, actinomycetes and fungal count at 40 and 120 DAT were recorded as 30.0, 41.0 cfu $\times 10^5$ /g soil, 21.33, 22.0 cfu $\times 10^4$ /g soil and 16.0, 19.33 cfu $\times 10^3$ /g soil respectively under biochar + carpet waste + FYM (2 + 1 + 1) t/ha + PGPR treated plots in Inceptisol with sandy clay loam (49). The increased microbial biomass may be due to the addition of biochar along with organic substances to the soil served as a carbon source that enhanced microbial biomass such as bacteria, actinomycetes and fungi which may further thereby increased the crop yield by 60 %. Similar findings showed that below ground microbes play an essential role in nutrient cycling and organic matter turnover and influence the growth and yield of plants (50).

The highest bacterial population (23 CFU g^{-1} soil) and the highest acid phosphatase activity (920 μg PNP released $g\ soil^{-1}\ h^{-1}$) were recorded under the red gram stalk biochar 5 t/ha + phosphobacteria 2 kg/ha treated plot (45). Applying biochar with or without phosphobacteria resulted in higher bacteria colony forming units than other treatments. The increased carbon content in soil due to biochar application and porous nature of applied biochar provides an ideal environment for soil microbial growth by optimizing soil moisture and temperature. The results showed that maximum acid phosphatase activity was noticeable under biochars with phosphobacteria followed by biochar alone and least in control plots. Interestingly, phosphobacteria alone treatment showed less acid phosphatase activity suggesting the presence soluble carbon is more important for improving microbial count and enzymatic activities in soil. Similar results were consistent with previous findings (51-55).

Effect of biochar on carbon sequestration

The effect of biochar from different sources (5 t/ha), phosphobacteria (2 kg/ha) and enriched FYM (750 kg/ha) on soil carbon stock was examined in a black gram field and the experimental site was situated on southern plain at Dryland Agricultural Research Station, Tamil Nadu Agricultural University, Chettinad, Tamil Nadu, India (45). The soil is acidic (5.67) with sandy loam texture and classified as *Typic hapludalf*. The study revealed that the red gram stalk biochar in combination with phosphobacteria has significantly influenced the carbon stock of soil. The results revealed that the highest carbon stock was recorded as 20.5 Mg/ha under RSB 5 t/ha + PB 2 kg/ha treated plot followed by AAB 5 t/ha + PB 2 kg/ha recorded 20.3 Mg/ha followed by RSB 5 t/ha recorded 20.0 Mg/ha. The increased carbon content in soil is primarily due to the greater carbon content of biochar which directly added carbon to the soil. Similar results have been reported in previous (46-48).

Effect of biochar on soil enzymatic activity

An experiment was conducted to study the influence of different soil amendments viz., feedstock, 2 % biochar, fertilizer (30:21:41mg/kg) and 2 % enriched biochar on different soil enzymatic activities in wheat pot experiment which was conducted in Pakistan in loamy soil (42). Date palm residues including leaves, small twigs and small

branches were used as feedstock for biochar production. The results revealed that the enriched biochar has performed better and showed highest enzymatic activities while compared to other soil amendments. The highest β gs ($3.91 \text{ mol PNF g}^{-1} \text{ h}^{-1}$), APH ($34.78 \text{ g p-NP g}^{-1} \text{ 24 h}^{-1}$), CL ($0.81 \text{ Vol. of KMnO}_4 \text{ g}^{-1} \text{ soil}$), DHG ($0.66 \text{ g TFP g}^{-1} \text{ h}^{-1}$), PHE (1.68) and UE ($2.91 \text{ gn-NH}_4 \text{ kg}^{-1} \text{ h}^{-1}$) were recorded under soil with 2 % enriched biochar treated plot. Higher β -glucosidase, APH, CL, PHE and UE activities in the SEB treatment were strongly correlated to organic compound cycling. The higher volatile compounds in the biochar treatments may enhance the activities of the enzymes in the soil and the increased total organic carbon and total nitrogen in soil improved the soil enzymatic activities (56, 57). Moreover, biochar increases the N transformation which might be due to UE activities (58, 59).

Effect of biochar on crop production

The influence of biochar on wheat yield was examined in Australia (15). The outcome of the study revealed that the highest seed and pod yield were noticed in COMBI + F - 25 t/ha Co composted biochar - compost + F treated plot (5096 and 6946 kg/ha, respectively). The increase in seed and pod yield with COMBI applied along with inorganic fertilizers is attributed to the improved nutrient availability and water retention capacity due to the organic amendments and associated nutrient input relative to that in fertilizer only treated soil. Similarly, a significant increase in peanut yield up to 50 % following the application of 10 t/ha charred bark of Acacia biochar with 75 kg/ha of each NPK for an infertile soil in Indonesia (60). The highest grain yield of wheat was recorded in canal water irrigated plot along with biochar application at 8 t/ha, the saline water irrigated plots recorded reduced grain yield irrespective of biochar application, however saline water irrigated plots along with biochar application has significantly increased the grain yield of wheat counteracting the salinity in *Typic ustochrept* (sandy loam texture) (17). The increase in grain yield of wheat might be attributed to the application of biochar increased the infiltration rate of soil, reduced the EC of soil thereby reduced the osmotic and ion toxicity effect which further improves nutrient uptake and increased the grain yield of wheat. Similar findings were also observed in previous studies (19, 61), that there is no improvement in crop yield with the application of different sources of compost alone but with the application of biochar at 2 t/ha along with FYM and vermicompost had significantly increased the Knol Khol yield in sandy clay loam soil. The increased crop yield is attributed to the application of biochar had significantly increased the soil physical properties such as infiltration rate and biochar addition with compost have positive effect on soil hydro-physical properties, water use efficiency which further improves soil nutrient retention capacity thereby increased the crop yield. Previous studied showed that biochar addition in coarse textured and degraded soils has the potential to increase the crop yield (62-64).

The application of biochar along with manure and NPK has significantly increased the yield of cucumber (37). The highest fruit yield/plant and fruit yield/ha was recorded under the treatments applied biochar-NPK and biochar-manure treated plots (2.31 kg/plant, 6.97 t/ha and 2.21 kg/plant, 6.66 t/ha, respectively). The increased cucumber yield in the biochar and NPK addition than the combined biochar and manure plot was due to the higher nutrient concentration in the inorganic NPK fertilizer, which was adsorbed onto the surface biochar and restricted the nutrient from leaching. The interaction of the biochar and the NPK may lead to high

fertilizer use efficiency and decreased plant nutrient loss, resulting in cell division and physiological performance. And increase in total organic carbon promotes soil structure, physical stability and water and nutrient retention in soils which improved crop growth and yield (65, 66).

The highest seed black gram yield (262 kg/ha) and dry matter production (618 kg/ha) were recorded under red gram stalk biochar 5 t/ha + phosphobacteria 2 kg/ha treated plot when compared to control and other treatments (45). Application of biochar in combination with phosphobacteria increased the carbon pool of soil, bacterial population and enzymatic activities of soil thereby improves the nutrient availability and uptake by crops which resulted in higher yields (67-69).

The application of biochar mixed with cattle manure stood out and showed the highest marketable yield compared with other organic and urea-N fertilizers (40). The increased yield of radish might be due to the application of biochar along with various organic and inorganic fertilizers increased the soil pH, organic matters and NPK status of soil and further improvement in yield could be attributed to the formation of organic coatings in biochar pores when mixed with manure, which can retain a higher amount of nutrients (nitrate and phosphate) and release slowly to plants as and when needed by the plants (70, 71).

The highest N uptake by wheat was 12.18 mg/kg DW, P uptake was 5.14 mg/kg DW and K uptake was 4.11 mg/kg DW were noticed under 2 % enriched biochar treated plot (42). The higher NPK uptake by wheat crop with the application of enriched biochar is attributed to the increased total organic carbon, total nitrogen in soil which improved the nutrient availability to crop and further it improved different enzyme activities in soil which improved nutrient mineralization and improved the uptake of nutrients by crops which further improved the crop yield by 73 % (72, 73).

The highest tuber yield of sweet potato was recorded in biochar (30 t/ha) with poultry manure (10 t/ha) treated plots in Alfisols at Nigeria (26). The increased tuber yield of sweet potato might be attributed to that the application of biochar along with poultry manure had significantly improved the soil physical properties such as bulk density, porosity and moisture content there by increases the nutrient availability to the crop which further improved the yield of sweet potato (74, 75). The influence of biochar on plant is presented in Table 1.

Conclusion

Biochar is a promising, sustainable material with significant environmental and agricultural benefits. Biochar can be beneficial to a wide range of crops, but the specific benefits depend on the soil and climate conditions, as well as how biochar is applied. Different crops may require varying amounts and types of biochar to maximize benefits. Biochar represents a valuable solution for improving soil health, reducing greenhouse gas emissions and promoting sustainable agriculture. Biochar has demonstrated significant potential as sustainable soil amendment, improving soil structure, water retention, nutrient availability and microbial activity. Its application can enhance plant growth, increase crop yields and contribute to long-term soil fertility, particularly in degraded or nutrient-poor soils. Moreover, biochar's ability to sequester carbon makes it a valuable tool in climate change mitigation. However, its effectiveness can vary depending on factors

such as feedstock type, pyrolysis conditions, soil type and crop species. Therefore, while biochar holds promise for both agricultural and environmental benefits, its application should be guided by site-specific research to maximize its positive impact. As research advances, tailored biochar formulations and application methods are expected to emerge, optimizing its performance for specific soil types and crops. Innovations in production technology could make biochar more cost-effective and scalable for widespread agricultural and environmental use. Furthermore, biochar is gaining attention in carbon markets for its ability to sequester carbon over the long term, potentially offering financial incentives for farmers and land managers. Integration with other organic amendments, such as compost and manure, may further amplify its benefits. Overall, biochar stands at the intersection of environmental sustainability and regenerative agriculture, positioning it as a key tool in future climate-smart farming systems.

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Authors' contributions

KSR and DG wrote the original manuscript; PKK and RB revised the manuscript. All the authors read and approved the final manuscript.

Compliance with ethical standards

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