ISBN: 978-81-19149-59-9

8. Biochar and its Role in Sustainable Agriculture

Manish Tomar, Kannoj

Department of Agronomy,
CCS Haryana Agricultural University,
Hisar.

Ruchika Choudhary, Narendra Kumar Bhinda

Department of Agronomy,
Rajasthan College of Agriculture,
MPUAT, Udaipur.

Abstract:

Biochar is a carbon-rich material produced through the process of pyrolysis, which involves heating biomass in the absence of oxygen. In recent years, biochar has gained significant attention due to its potential benefits in improving soil fertility, mitigating greenhouse gas emissions and promoting sustainable agricultural practices. It improves soil structure and porosity, enhancing water-holding capacity and reducing erosion. Biochar's permeable structure creates a favourable environment helpful for microorganisms in the soil, enhancing the cycling of nutrients and boosting soil fertility. Furthermore, biochar contributes to climate change mitigation by sequestering carbon in the soil for extended periods. This carbon sequestration potential helps to reduce greenhouse gas emissions and mitigate climate change impacts. So, biochar holds significant promise as a sustainable agricultural tool. Its ability to improve soil fertility, reduce greenhouse gas emissions and enhance crop productivity makes it a valuable resource for achieving sustainable farming practices. Implementing biochar-based strategies requires careful consideration of production methods, application rates and long-term effects, paving the way for a more sustainable and resilient agricultural future.

Keywords:

Sustainable, Greenhouse, Farming, Biochar, Stability.

8.1 Introduction:

As the global population continues to grow, it has become increasingly important to implement sustainable agriculture practices. 'Sustainable agriculture' involves the integration of various sciences, including biology, ecology, chemistry, physics, economics and social sciences (Lichtfouse *et al*., 2009) to develop agricultural practices that are environmentally friendly, socially just and economically viable. These practices aim to produce crops sustainably while minimizing the negative impacts of intensive land use (Hester and Harrison, 2005). In essence, sustainable agriculture is about farming profitably while reducing harm to the environment.

Regardless of being largely seen as unsustainable, environmentally harmful, and unlikely to keep up with rising demand, the green revolution has been successful in feeding the world's population over the past five decades (Barrow, 2012). Conventional farming methods, including conventional tillage and the indiscriminate use of agrochemicals, have degraded natural resources. This has led to an increase in soil degradation and a reduction in their capacity for growing crops. The burning of crop residues further contributes to greenhouse gas emissions, which warm the atmosphere, jeopardise global food security and ultimately lead to climate change.

The adverse effects of the green revolution paved the way for sustainable farming. The utilisation of naturally derived ecologically friendly materials has been a hot subject of investigation in recent years. A recent breakthrough is the creation of biochar from crop residue, which may prove to be a vital and useful element of sustainable agriculture. Biomass is heated with little to no oxygen to form biochar. It has a high percentage of carbon, a chemical structure that is stable and resistant to decay, high porosity and a large specific surface area. Due to its characteristics, it has the potential to effectively store large amounts of carbon in the soil over the long term, improving soil fertility and crop productivity under various biotic and abiotic stresses (Akhtar *et al.*, 2014; Barrow, 2012), reducing global warming, and moving towards achieving global food security.

8.2 Biochar:

Biochar is a carbon-rich, porous solid that is produced when organic materials such as agricultural waste, wood, and manure are heated at high temperatures (between 200 and 800°C) in an oxygen-deprived environment through a process called pyrolysis (Lehmann *et al*., 2006). Various organic materials, including animal manure, municipal sewage sludge, crop and forestry waste products, urban yard waste, industrial biomass byproducts, and crop residues can be used to create biochar. Biochar is composed of ash, labile carbon and recalcitrant carbon. Any nutrients present in biochar are found in the ash, which is the inorganic component. Labile carbon is the fraction of biochar that can be decomposed by soil microorganisms and is lost through respiration as CO_2. Recalcitrant carbon, on the other hand, resists degradation by soil organisms and is incredibly stable and long-lasting.

8.3 Properties of Biochar:

The physicochemical characteristics are essential for governing biochar's biogeochemical interactions in soil environments as well as for determining their agronomic and environmental effects. The two key variables affecting the qualities of biochar are the pyrolysis process's temperature and the initial feedstock's characteristics (Cantrell *et al.*, 2012).

A. Specific Surface Area:

The specific surface area of biochar typically ranges from 1.5 to 500 $m^2 g^{-1}$ (Li *et al.*, 2018). The pyrolysis temperature can affect the specific surface area and the formation of micropores in biochar. At lower temperatures, the interior pore structure of biochar is filled with tars, volatiles and other products formed as a result of thermal degradation of biomass, reducing the specific surface area. With the increase in temperature, these compounds break down into volatile gases and escape, leading to the formation of more microporous structures and a larger specific surface area (Bansal *et al*., 1988). However, when the temperature reaches a critical value, the specific surface area decreases due to the degradation of the microporous structure and the widening of the micropores (Brown *et al*., 2006). The specific surface area of biochar is important because it affects its adsorption capacity.

B. pH:

Biochar is generally alkaline due to the presence of carbonates, phosphates and ash formed during the process of pyrolysis (Yuan *et al.,* 2011). The pH of biochar can also be affected by the feedstock materials and pyrolysis temperature used. For example, biochar made from legumes has a higher pH than biochar made from non-leguminous materials under the same pyrolysis conditions. As the temperature increases, the pH of biochar increases due to the breakdown of acidic functional groups such as carboxyl and phenolic hydroxyl and the volatilization of organic acids (Chintala *et al.,* 2014).

C. Surface functional groups:

The specific surface area of biochar is an important characteristic because it affects its ability to adsorb metal ions and organic molecules. Increasing the pyrolysis temperature can increase the development of micropores and the specific surface area of biochar. Biochar contains several functional groups, including carboxyl, carbonyl and hydroxyl groups. According to Anton-Herrero *et al*. (2018), most of these functional groups are oxygen or alkaline containing and give biochar good hydrophobicity or hydrophilicity, ion exchange and buffering capabilities.

The number of functional groups on the surface of biochar is closely related to the carbonization temperature. As the carbonization temperature increases, the concentration of C-O, C-H, and O-H bonds in biochar decreases, along with the number of hydroxyl and carboxyl groups and acid groups, while the number of alkaline groups increases. Overall, the number and density of functional groups decrease as the carbonization temperature increases (Gul *et al*., 2015; Wang, 2015).

D. Cation exchange capacity (CEC):

During the process of carbonization, certain oxygen containing functional groups such as carboxyl, hydroxyl and carbonyl are preserved due to the partial degradation of cellulose, increasing the CEC of biochar. The preservation of these functional groups depends on the type of biomass, pyrolysis temperature and carbonization technique used (Lee *et al.*, 2010).

Within a specific temperature range, increasing the temperature reduces the negative charge on the surface of biochar due to the destruction of oxygen-containing functional groups (Lee *et al*., 2010; Suliman *et al*., 2017). However, the content of alkali metals such as Ca, K and Mg in biochar increases with temperature, which can increase CEC (Kalinke *et al*., 2017).

E. Stability:

Biochar is characterized by its high carbon content, low solubility, high boiling point, and structure that includes a high degree of carboxylate esterification and aromatization. A fraction of aromatic C in the biochar rises as the pyrolysis temperature increases as a result of the H/C and O/C ratios decline, and it is thought that the lower the ratio, the more aromaticity and stability there will be (Baldock and Smernik, 2002).

8.4 Effect of Biochar on Soil:

Biochar has unique physical and chemical properties that can improve soil quality and fertility by enhancing nutrient cycling, reducing nutrient loss and increasing soil microbial activity.

8.4.1 Physical Properties:

Biochar's larger surface area and micropores can affect the soil's surface area, pore size distribution, bulk density, water and nutrient holding capacity, and penetration resistance (Chintala *et al*., 2014). Since biochar often has a higher surface area than sand and is comparable to or higher than clay, adding it to the soil as an amendment can increase the soil's total specific surface area. The high porosity of biochar due to its numerous micropores can improve the physical quality of the soil where it is incorporated. Over time, the interaction of biochar with clay and soil organic matter can lead to the formation of micro aggregates, increasing the soil's porosity (Cheng *et al*., 2006). This increased porosity and surface area can allow the soil to retain more moisture and nutrients, reduce its bulk density and decrease penetration resistance.

8.4.2 Chemical Properties:

Due to the combination of its high surface area and porosity, biochar can retain and absorb plant nutrients, hence enhancing soil fertility. Increased cation exchange capacity (CEC), lowered nitrogen leaching, liming and other beneficial effects of biochar amendment to the chemical properties of soil. Biochar can boost soils' CEC, especially for sandy, highly weathered soils that are deficient in nutrients due to the presence of oxidised functional groups (such as carboxyl groups) on the surface of biochar, as well as the exposed organic acids adsorbed by the biochar, contributes to the biochar's negative surface charge, are likely to be responsible for the increase in CEC in biochar amended soil (Liang *et al*., 2006).

However, this depends on the qualities of biochar and how long it has been in the soil after being applied. Ageing increases the amount of acidic functional groups in biochar, particularly carboxylic groups (Cheng *et al*., 2006). It has been found that biochar can hinder both nitrification and ammonification (DeLuca *et al*., 2009). It further decreases nitrate leaching caused by NO_3^- adsorption on the anion exchange surface of the material which might be the result of slower rates of nitrification (Dempster *et al.*, 2012). Due to the biochar's pH and improved cation retention in the soil (such as Ca^{2+}, Mg^{2+} and K^+), the application of biochar can improve soil pH (Novak *et al*., 2009; Sohi *et al*., 2010). This way, by giving plants nutrients, biochar can contribute directly to soil fertility.

8.4.3 Biological Properties:

The composition of flora and fauna in the soil is constantly changing in response to soil conditions and management practices, including the addition of biochar. Biochar can alter the physio-chemical properties of soil, favourably influencing microbial activity and affecting soil microbiological properties.

Soil is home to a complex community of organisms, and biochar has been shown to change the composition of microbial communities while also improving the soil's bulk density, pH, water and nutrient availability (Gul *et al*., 2015; Khodadad *et al*., 2011).

Biochar's high surface area and ability to adsorb nutrients make it an ideal environment for microorganisms such as bacteria, actinomycetes and arbuscular mycorrhizal fungi to colonize, thrive and reproduce (Pietikainen *et al*., 2000).

Its unique pore size properties may also protect these microorganisms from predators such as protozoa and nematodes. Biochar can also significantly influence diazotrophs (N_2-fixing bacteria), leading to increased biological N-fixation (Thies and Rilling, 2009).

Table 1. Effect of Biochar on different soil properties

Parameter	Findings	Reference
Cation exchange capacity	50% increase	Glaser *et al*., 2002
Fertilizer use efficiency	10-30% increase	Gaunt and Cowie, 2009
Liming agent	1 unit pH increase	Lehman and Rondon, 2006
Biological nitrogen fixation	50-72% increase	Lehman and Rondon, 2006
Soil moisture retention	Up to 18% increase	Srinivasarao *et al*., 2012
Bulk density	Soil dependent	Laird, 2008
Methane emission	100% decrease	Rondon *et al*., 2005
Nitrous oxide emissions	50% decrease	Yanai *et al*., 2007
Mycorrhizal fungi	40% increase	Warnock *et al*., 2007

(Bhinda *et al*., 2022)

8.5 Effect of Biochar on Climate Change Mitigation:

Agriculture contributes significantly to anthropogenic global warming. So, lowering agricultural emissions, primarily methane (CH_4) and nitrous oxide (N_2O), could be a vital component of the effort to slow down climate change.

8.5.1 Carbon Sequestration:

Crop residue and soil organic matter microbiological decomposition or burning are the primary sources of carbon dioxide emissions (Smith *et al*., 2008). Through photosynthesis, sequestering carbon in the form of crop growth is a very effective approach for reducing atmospheric CO_2. However, the effectiveness of this method for long-term carbon sequestration is severely constrained since a significant amount of the collected carbon is unstable and will quickly (within months to years) return to the atmosphere as CO_2 through breakdown and respiration. To decrease carbon in the atmosphere and considerably increase long-term C sequestration, moving it into a passive pool is necessary and can be achieved through biomass pyrolysis. Biomass can be pyrolyzed to create a passive pool of stable or inert carbon, which can be used to transport carbon out of the atmosphere and significantly boost long-term C sequestration. A portion of the biomass is converted into a more stable form of carbon called biochar during pyrolysis, which also releases bio-energy. This allows for an easy movement of carbon from the active to the passive pool. The pyrolysis process produces significantly more energy than it uses, resulting in highly positive net energy. By combining the pyrolysis process with the application of biochar in soil, it is possible to sequester atmospheric CO_2 since more carbon is stored than is released. The pyrolysis process has a very positive net energy because substantially more energy is produced than is used. As recalcitrant carbon in biochar is exceptionally stable and long-lasting due to its resistance to microbial breakdown, its application will slow down the return of terrestrial organic carbon as CO_2 to the atmosphere and so reduce climate change.

In North western part of India, deliberate burying of crop residue *i.e.*, stubble burning is practised in order to remove agricultural crop residue from the field as a short period is available between the harvesting of *kharif* crop and preparing the land for the next winter crop. In India, it has been estimated that 93 million tonnes of crop waste are burned annually. Burning of the stubble not only resulted in the loss of a significant amount of biomass, or organic carbon and plant nutrients, but also had a negative impact on the chemical, biological, physical, and flora and fauna of the soil (Kannoj *et al*. 2023). Burning rice straw is estimated to produce 0.05% of India's overall greenhouse gas emissions (Gadde *et al.*, 2009). According to Lal (2005), India could generate almost 310 million tons of biochar per year from various sources, including crop residues, which could counterbalance about 50 per cent of carbon emissions from fossil fuels.

8.5.2 Greenhouse Gas Emissions:

Soil act as a significant source of nitrous oxide (N_2O) while both a source and sink of methane (CH_4). These gases absorb and emit radiant energy at thermal infrared wavelength, bringing a greenhouse effect. They are responsible for the greenhouse effect as they have a global warming potential of approximately 25 and 300 times more than CO_2. The contribution of agriculture to the overall amount of GHGs produced by anthropogenic actions was about 24% (Smith *et al*., 2007).

Heterotrophic denitrifying bacteria that thrive in anaerobic environments and chemotrophic bacteria that transform ammonium through mineralization processes into soluble NO_3^- are the principal sources of N_2O emission from soil. In the acidic soil of eastern Colombian plains, Rondon *et al*. (2005) reported a 50 per cent reduction in N_2O emissions and an almost complete reduction in CH_4 emissions from soybean plots with biochar application. The possible reason behind the decline of N_2O emission with the application of biochar might be due to slower N cycling, possibly as a result of an increase in the C: N ratio; an increase in soil pH enhances N_2O reductase activity and hence favours completion of NO_3^- reduction to N_2 (DeLuca *et al*., 2009). Increased soil aeration and adsorption of NH_4^+ from biochar addition reduce nitrification and denitrification and increase sink capacity for CH_4. Because N_2O and CH_4 have significantly higher potential for global warming than CO_2, reducing their emissions through biochar is of great interest. The effect of adding biochar on CH_4 and N_2O, however, was erratic and differed depending on the kind of crop and soil, the site and the source of the biochar. (Karhu *et al*., 2011; Kimetu and Lehmann, 2010).

8.6 Improvement of Crop Growth and Yield by Biochar Application:

The impact of biochar on crop yield, seed germination and crop growth depend on the type of soil and the amount of biochar used. Improvements in soil quality due to the use of biochar have often led to improved seed emergence and plant establishment (Solaiman *et al*., 2012; Van Zwieten *et al*., 2010). The plant's root system and the interface between biochar and soil (the rhizosphere) are crucial for crop growth due to their role in nutrient and water uptake, storage, and regulation. The rhizosphere is often larger in soils containing biochar (Zheng *et al*., 2013).

The benefits of biochar on yield and crop biomass have been observed to increase over time. In a multi-year experiment on a maize-soybean rotation system, Major *et al*. (2010) found that applying biochar at a rate of 20 t ha^{-1} did not increase maize yield in the first year, but a significant increase in yield was observed in the following three years compared to the control. Biochar-induced increases in soil specific surface area, CEC, porosity, water holding capacity, nutrient retention, and liming effect are key factors influencing improved crop growth and productivity, in addition to composts and fertilizers (Glaser *et al*., 2002; Lehmann *et al*., 2006). In a study on chickpea under rainfed conditions, Tomar *et al*. (2022) found that biochar application (supported by fertilizer) significantly improved the total nitrogen, phosphorus, and potassium uptake of chickpea compared to the control.

Biochar has been shown to increase the growth of maize plants in poor sandy soils by improving soil-plant water relations and photosynthesis (Haider *et al*., 2015). According to El-Naggar *et al*. (2019), biochar is generally more effective when applied to soils with low to medium fertility or degraded soils.

8.7 Remediation of Contaminated Soils:

Soil contamination with organic and inorganic toxins is a well-known problem, and there is an urgent need for sustainable, economically feasible, and environmentally friendly remediation methods.

Biochar has the potential to be an environmentally friendly and relatively cost-effective solution for treating contaminated soils due to its high sorption capacity, which can be 10-100 times greater than that of normal soil organic matter (Cornelissen *et al*., 2005).

Biochar through chemisorption and physisorption can alter the bioavailability of heavy metals in the soil. Its high aromatization and porosity allow it to generate a modest electric force when heavy metal ions are nearby, promoting their physisorption (Gomez-Eyles and Ghosh, 2018). The presence of surface functional groups such as carboxylic, alcohol, and hydroxyl groups on biochar allows it to chemisorb heavy metals and form complexes that reduce their bioavailability (Tang *et al*., 2013).

The alkaline properties of biochar can increase soil pH when added to soil, reducing zeta potential and increasing cation exchange capacity. This increases the negative charge on the soil surface, reducing the bioavailability of heavy metals and strengthening the electrostatic attraction between positively charged heavy metals and soil (Peng *et al*., 2011; Chintala *et al*., 2013). Biochar can also affect the soil's redox potential, moisture content, and aeration, altering the toxicity of some charge-sensitive toxic heavy metals such as cadmium (Bogusz *et al*. 2017). However, not all heavy metals are affected by biochar's ability to reduce their bioavailability.

Biochar can also adsorb several organic contaminants, including phenols, polychlorinated biphenyls, naphthalenes, and polycyclic aromatic hydrocarbons. Its ability to adsorb organic pollutants is influenced by factors such as its carbonaceous components, degree of aromatization, elemental composition, pH, pore structure, and surface chemistry (Chen *et al*., 2019). However, the mechanism by which biochar reduces the bioavailability of organic contaminants in soil is complex and involves intricate microbial metabolic activities (Zhu *et al*., 2017). In the present times, there is a lack of in situ or long-term experiments examining the role of biochar in the remediation of inorganic or organic pollutants.

8.8 Conclusion:

Biochar can have a variety of positive effects on crop growth, productivity and soil characteristics. These effects include increased growth and yield, adsorption of heavy metals, improved water holding capacity, and positive plant physiological responses. Biochar has great potential for use in large-scale agricultural production. Initial studies suggest that using biochar can increase crop productivity and soil fertility while mitigating the effects of climate change. However, further research, development, and demonstration of biochar production and use are essential to promote its use as a soil amendment and as a potential solution to combat climate change. Multidisciplinary and site-specific research is needed to better understand the long-term effects of biochar application on soil physical properties, nutrient availability, soil microbial activity, carbon sequestration capacity, crop production and greenhouse gas mitigation.

8.9 References:

1. Akhtar, S.S., Li, G., Andersen, M.N. and Liu, F. 2014. Biochar enhances yield and quality of tomato under reduced irrigation. *Agricultural Water Management* **138**:37-44.
2. Anton-Herrero, R., Garciadelgado, C., Alonsoizquierdo, M., Garciarodriguez, G., Cuevas, J. and Eymar, E. 2018. Comparative adsorption of tetracyclines on biochars and stevensite: looking for the most effective adsorbent. *Applied Clay Science* **160**:162-172.

3. Baldock, J.A. and Smernik, R.J. 2002. Chemical composition and bioavailability of thermally altered *Pinus resinosa* (Red pine) wood. *Organic Geochemistry* **33**:1093-1109.
4. Bansal, R.C., Donnet, J.B. and Stoeckli, F. 1988. Active carbon. Marcel Dekker, New York, pp-158.
5. Barrow, C.J. 2012. Biochar: potential for countering land degradation and for improving agriculture. *Applied Geography* **34**:21-28.
6. Bhinda, N. K., Yogi, A. K., Kumar, M., Choudhary, M. K. and Dhayal, S. 2022. Role of Biochar in Agriculture to Improve Soil Health and Climate Change Mitigation. In Jakhar, R. K., Kumawat, A., Sunda, S. L., Kumar, J., Choudhary, N. K. and Bhawariya, A. (Eds.), *Multifacted Agricultural Research And Extension*, pp. 85-97. Nation Press. India.
7. Bogusz, A., Nowak, K., Stefaniuk, M., Dobrowolski, R. and Oleszczuk, P. 2017). Synthesis of biochar from residues after biogas production with respect to cadmium and nickel removal from wastewater. *Journal of Environmental Management* **201**:268-276.
8. Brown, R.A., Kercher, A.K., Nguyen, T.H., Nagle, D.C. and Ball, W.P. 2006. Production and characterization of synthetic wood chars for use as surrogates for natural sorbents. *Organic Geochemistry* **37**(3):321-333.
9. Cantrell, K.B., Hunt, P. G., Uchimiya, M., Novak, J. M. and Ro, K. S. 2012. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. *Bioresource Technology* **107**:419-428.
10. Chen, Y., Jiang, Z., Wu, D., Wang, H., Li, J., Bi, M. and Zhang, Y. 2019. Development of a novel bio-organic fertilizer for the removal of atrazine in soil. *Journal of Environmental Management* **233**:553-560.
11. Cheng, C.H., Lehmann, J., Thies, J.E., Burton, S.D. and Engelhard, M.H. 2006. Oxidation of black carbon by biotic and abiotic processes. *Organic Geochemistry* **37**:1477-1488.
12. Chintala, R., Mollinedo, J., Schumacher, T.E., Malo, D.D. and Julson, J. 2014. Effect of biochar on chemical properties of acidic soil. *Archives of Agronomy and Soil Science* **60**(3):393-404.
13. Chintala, R., Schumacher, T.E., McDonald, L. M., Clay, D.E., Malo, D.D., Clay, S.A., Papiernik, S.K. and Julson, J. L. 2013. Phosphorus sorption and availability from biochars and soil biochar mixtures. *Clean Soil Air Water* **41**:1-9.
14. Cornelissen, G., Gustafsson, O., Bucheli, T. D., Jonker, M.T.O., Koelmans, A.A. and Van Noort, P.C.M. 2005. Extensive sorption of organic compounds to black carbon, coal, and kerogen in sediments and soils: mechanisms and consequences for distribution, bioaccumulation, and biodegradation. *Environmental Science and Technology* **39**: 6881-6895.
15. DeLuca, T.H., MacKenzie, M.D. and Gundale, M.J. 2009. Biochar effects on soil nutrient transformations. In Lehmann J, Joseph S (eds.) Biochar for Environmental Management: Science and Technology. *Earthscan*, London. pp. 251-270.
16. Dempster, D.N., Gleeson, D.B., Solaiman, Z.M., Jones, D.L. and Murphy, D.V. 2012. Decreased soil microbial biomass and nitrogen mineralisation with eucalyptus biochar addition to a coarse textured soil. *Plant and Soil* **354**:311-324.
17. El-Naggar, A., Sang, S.L., Jorg, R., Muhammad, F., Songe, H., Ajit, K.S., Andrew, R.Z., Mahtab, A., Sabry, M.S. and Yong, S.O. 2019. Biochar application to low fertility soils: a review of current status, and future prospects. *Geoderma* **337**:536-554.

18. Gadde, B., Menke, C. and Wassman, R. 2009. Rice straw as a renewable energy source in India, Thailand and the Philippines: Overall potential and limitations for energy contribution and greenhouse gas migration. *Biomass and Bioenergy* **33**:11.
19. Gaunt, J. and Cowie, A. 2009. Biochar greenhouse gas accounting and emission trading. In: *Biochar for environmental management* (J. Lehmann and S. Joseph eds.), Science and Technology, Earthscan, London. pp 317-340.
20. Glaser, B., Lehmann, J. and Zech, W. 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. *Biology and Fertility Soils* **35**(4):219-230.
21. Gomez-Eyles, J.L. and Ghosh, U. 2018. Enhanced biochars can match activated carbon performance in sediments with high native bioavailability and low final porewater PCB concentrations. *Chemosphere* **203**:179-187.
22. Gul, S., Whalen, J.K., Thomas, B.W., Sachdeva, V. and Deng, H. 2015. Physico-chemical properties and microbial responses in biochar-amended soils: mechanisms and future directions. *Agriculture Ecosystems and Environment* **206**(1):46-59.
23. Haider, G., Koyro, H.W., Azam, F., Steffens, D., Muller, C. and Kammann, C. 2015. Biochar € but not humic acid product amendment affected maize yields via improving plantsoil moisture relations. *Plant and Soil* **395**:141-157.
24. Hester, R.E. and Harrison, R.M. 2005. Sustainability in Agriculture. Royal Society of Chemistry.
25. Kalinke, C., Oliveira, P.R.D., Oliveira, G.A.D., Mangrich, A.S., Marcolino-junior, L.H. and Bergamini, M.F. 2017. Activated biochar: preparation, characterization and electroanalytical application in an alternative strategy of nickel determination. *Analytica Chimica Acta* **983**:103-111.
26. Kannoj., Tomar, M., Choudhary. R. and Bhardwaj, S. 2023. Crop residue management Agriculture Science: Research and Review Volume XIV. Bhumi Publishing, India, pp 1-9.
27. Karhu, K., Mattila, T., Bergstrom, I. and Regina, K. 2011. Biochar addition to agricultural soil € increased CH_4 uptake and water holding capacity. Results from a short-term pilot field study. *Agriculture Ecosystems and Environment* **140**:309-313.
28. Khodadad, C.L.M., Zimmerman, A.R., Green, S.J., Uthandi, S. and Foster, J.S. 2011. Taxa-specific changes in soil microbial community composition induced by pyrogenic carbon amendments. *Soil Biology & Biochemistry* **43**:385-392.
29. Kimetu, J.M. and Lehmann, J. 2010. Stability and stabilisation of biochar and green manure in soil with different organic carbon contents. *Australian Journal of Soil Research* **48**: 577-585.
30. Laird, D.A. 2008. The charcoal vision: A win-win-win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agronomy Journal* **100**:178-181.
31. Lal, M. 2005. Climate change-implications for India's water resources. In: Mirza, M.M.Q., Ahmad, Q.K., Balkema, A.A. (Eds.), Climate Change and Water Resources in South Asia. Taylor and Francis Group, UK, pp. 15-193.
32. Lee, J.W., Kidder, M. and Evans, B.R. 2010. Characterization of biochars produced from cornstovers for soil amendment. *Environmental Science and Technology* **44**(20):7970-7974.
33. Lehmann, J. 2007. A handful of carbon. *Nature* **447**:143-144.

34. Lehmann, J. and Rondon, M. 2006. Biochar soil management on highly weathered soils in the humid tropics. *Biological Approaches to Sustainable Soil Systems*, (N. Uphoff *et al*. eds), Boca Raton, FL: CRC Press. pp 517-530.
35. Lehmann, J., Gaunt, J. and Rondon, M. 2006. Biochar sequestration in terrestrial ecosystems-a review. *Mitigation and Adaptation Strategies Global Change* **11**:403-427.
36. Li, J.M., Cao, L.R., Yuan, Y., Wang, R.P., Wen, Y.Z. and Man, J.Y. 2018. Comparative study for microcystin-LR sorption onto biochars produced from various plant and animal-wastes at diferent pyrolysis temperatures: influencing mechanisms of biochar properties. *Bioresource Technology* **247**:794-803.
37. Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., Skjemstad, J.O., Thies, J., Luizao, F.J., Petersen, J. and Neves, E.G. 2006. Black carbon increases cation ~ exchange capacity in soils. *Soil Science Society of America Journal* **70**:1719-1730.
38. Lichtfouse, E., Navarrete, M., Debaeke, P., Souchere, V., Alberola, C. and Menassieu, J. 2009. Agronomy for sustainable agriculture: a review. *Agronomy for Sustainable Development* **29**:1-6.
39. Major, J., Rondon, M., Molina, D., Riha, S.J. and Lehmann, J. 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant and Soil* **333**:117-128
40. Novak, J.M., Busscher, W.J., Laird, D.L., Ahmedna, M., Watts, D.W. and Niandou, M.A.S. 2009. Impact of biochar amendment on fertility of a southeastern coastal plain soil. *Soil Science* **174**:105-112.
41. Peng, X., Ye, L.L., Wang, C.H., Zhou, H. and Sun, B. 2011. Temperature and duration-dependent rice straw-derived biochar: characteristics and its effects on soil properties of an Ultisol in southern China. *Soil Tillage Research* **112**:159-166.
42. Pietika¨inen, J., Kiikkila¨, O. and Fritze, H. 2000. Charcoal as a habitat for microbes and its effect on the microbial community of the underlying humus. *Oikos* **89**:231-242.
43. Rondon, M., Ramirez, J.A. and Lehmann, J. 2005. Charcoal additions reduce net emissions of greenhouse gases to the atmosphere. In: *Proceedings of the 3rd USDA Symposium on Greenhouse Gases and Carbon Sequestration*, Baltimore, USA, March 21-24, 2005.
44. Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B. and Sirotenko, O. 2007. Agriculture, in: climate change 2007: mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, pp. 497-540.
45. Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M. and Smith, J. 2008. Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B :Biology Science **363**:789-813.
46. Sohi, S.P., Krull, E., Lopez-Capel, E. and Bol, R. 2010. A review of biochar and its use and function in soil. *Advance Agronomy* **105**:47-82.
47. Solaiman, Z.M., Murphy, D.V. and Abbott, L.K. 2012. Biochars influence seed germination and early growth of seedlings. *Plant and Soil* **353**:273-287.
48. Srinivasarao, Ch., Vankateswarlu, B., Lal, R., Singh, A.K., Sumanta Kundu, Vittal, K.P.R., Balaguruvaiah, G., Vijaya Shankar Babu, M., Ravindra Chary, G., Prasadbabu,

M.B.B. and Yellamanda Reddy, T. 2012. Soil carbon sequestration and agronomic productivity of an Alfisol for a groundnut-based system in a semiarid environment in southern India. *European Journal of Agronomy* **43**: 40-48.

49. Suliman, W., Harsh, J.B., Fortuna, A., Garciaperez, M. and Abulail, N.I. 2017. Quantitative effects of biochar oxidation and pyrolysis temperature on the transport of pathogenic and nonpathogenic Escherichia coli in biochar-amended sand columns. *Environmental Science and Technology* **51**:5071-5081.
50. Tang, J.C., Zhu, W.Y., Kookana, R. and Katayama A. 2013. Characteristics of biochar and its application in remediation of contaminated soil. *Journal of Bioscience and Bioengineering* **116**:653-659.
51. Thies, E., and Rilling, M. C. 2009. Characteristics of biochar: Biological properties. In "Biochar for Environmental Management. Science and Technology" (J. Lehmann and S. Joseph, Eds.), Earthscan, London.
52. Tomar, M., Chaplot, P.C., Choudhary, J., Meena, R.H., Patidar, R. and Samota, A.K. 2022. Effect of Salicylic Acid and Biochar on Nutrient content and Uptake of chickpea (*Cicer arietinum* L.) under Rainfed Condition. *Biological Forum - An International Journal* **14**(3):613-616.
53. Van Zwieten, L., Kimber, S., Morris, S., Chan, K.Y., Downie, A., Rust, J., Joseph, S. and Cowie, A. 2010. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant and* Soil **327**:235-246.
54. Wang, H. 2015. Removal of Pb (II), Cu (II), and Cd (II) from aqueous solutions by biochar derived from $KMnO_4$ treated hickory wood. *Bioresource Technology* **197**(9):356-362.
55. Warnock, D.D., Lehmann, J., Kuyper, T.W. and Rillig, M.C. 2007. Mycorrhizal responses to biochar in soil - concepts and mechanisms. *Plant and Soil* **300**:9-20.
56. Yanai, Y., Toyota, K. and Okazani, M. 2007. Effects of charcoal addition on N_2O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments. *Soil Science and Plant Nutrition* **53**:181-188.
57. Yuan, J.H., Xu, R.K. and Zhang, H. 2011. The forms of alkalis in the biochar produced from crop residues at different temperature. *Bioresource Technology* **102**:3488-3497.
58. Zheng, H., Wang, Z., Deng, X., Herbert, S. and Xing, B. 2013. Impacts of adding biochar on nitrogen retention and bioavailability in agricultural soil. *Geoderma* **206**:32-39.
59. Zhu, X.M., Chen, B.L, Zhu, L.Z. and Xing, B.S. 2017. Effects and mechanisms of biochar-microbe interactions in soil improvement and pollution remediation: a review. *Environmental Pollution* **227**:98-115.