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The Basics of Biochar: Mechanisms of Resolving Soil Degradation and Climate Change – A Review

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Abstract: Biochar application as soil amendment has been receiving lot of attention, for many reasons such as creating a carbon (C) sink to mitigate global warming, neutralizing acidity in soil, increasing soil water holding capacity, reducing the losses of nutrients and agricultural chemicals in run-off, reducing greenhouse gas emissions and stabilizing mobile heavy metals, pesticides and other organic pollutants in soil. The aim of this article was to review in depth the effecting mechanism how biochar is used in sustainable agriculture and environmental management. When biochar is applied on the soil, oxidation process is observed on the surface of particles; and the oxidation of aromatic carbon which leads to the formation of carboxyl groups is the reason for high Cation Exchangeable Capacity CEC of soil amended with biochar. Because biochar is highly porous structure it improves water holding capacity of the soil thus helps in water retention for a longer period of time. The carbonate, oxygen-containing functional groups and silicates in biochars are the major components responsible for biochar efficacy in amending acidic soils and resisting soil re-acidification. Biochar amendment transforms the water-soluble and bio accessible fractions of heavy metals into immobilized forms, reducing the bioavailability and the eco toxicity of the toxic elements. The effectiveness of the application of biochar in the control of plant diseases has been attributed to its alkaline pH. Biochar is a promising tool to reduce the atmospheric CO_2 concentration because it slows the return of photo synthetically fixed carbon to the atmosphere. Thus, biochar is posing many benefits to the environment agriculture and economy in the longer run, so it is highly recommended to incorporate it in agriculture practices.

Key words: Biochar · Carbon · Contaminated Soil · C Sequestration · Greenhouse Gas Emission · Pyrolysis · Soil Fertility

INTRODUCTION

The present day agriculture is facing a problem of continuous decline in soil nutrients reserve and decrease in organic matter content of soil. This may be due to intensive cropping system coupled with limited application of farm yard manure (FYM), green manure, vermicompost and crop residue in the field [1]. According to De Meyer *et al*. [2], Long-term cultivation of soils could result in degradation, containing soil acidification, soil organic matter depletion and severe soil erosion. Additionally, the decrease in soil organic matter decreases the aggregate stability of soil [3]. Anthropogenic activities such as land-use change, agriculture and waste management have altered terrestrial biogenic greenhouse gas fluxes and the resulting increases in carbon dioxide, methane and nitrous oxide emissions in particular can contribute to climate change [4]. Reductions in these emissions can be achieved by decreasing the heterotrophic conversion of organic C to carbon dioxide and by better management of agricultural waste streams to minimize release of methane and nitrous oxide. Hence, to reduce the impacts of soil degradation and climate change on agriculture great effort needs to be adding carbon to soil by simple and sustainable methods.

Carbon plays an important role in the soil. It has the potential to influence physical and chemical processes in soil [5, 6]. Carbon has also been shown to affect soil productivity, quality and fertility and nutrient cycling, which all affect crop production [7, 8] so understanding how the addition of carbon may influence the soil is crucial.

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Biochar is becoming one of the major strategy/ technology to add carbon to soil. Biochar is charcoal prepared by pyrolytic processing (i.e., O_2-absent heating at 300–700°C) from natural organic materials (crop and other waste, woodchips, manure) and used as a soil amendment in agricultural and environmental applications [9, 10]. Guo *et al.* [11] and Tan *et al.* [12] reported that biochar is a carbon-rich charcoal, a porous carbonaceous structure, many functional groups and an aromatic surface. It also composed of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S) and ash in different proportions [13]. The relatively high porosity and surface functionality engender biochar with great specific surface area (SSA) and cation exchange capacity (CEC), enabling the material to retain water, nutrients and pollutants in soil [14]. In addition, biochar contains significant portions of labile organic carbon (OC) and possibly plant nutrients (e.g., N, P, K, Ca, Mg and S) [15].

Due to incomplete combustion of biomass, many organic components remain in biochar which are essential as potential fertilizer and soil amendments [16]. As compared with other organic matter, the carbon present in biochar is more stable in soil environment and remains in soil for hundreds to thousand years [17]. The fact that biochar is not easily degradable by the soil microbes favors its use in agricultural soils [18]. Some studies have shown that biochar addition to agricultural soils increases crop production by increasing soil aeration and water-holding capacity (WHC), which in turn enhances microbial activity and plant nutrient status in soil and alteration of some important soil chemical properties.

Several uses and positive effects of biochar amendment have currently been considered as an effective method to reclaim the contaminated soil [19] and to achieve high crop yields without harming the natural environment. By incorporating biochar in soil, NH_3 and N_2O emissions could decrease to a substantial level. This could happen in certain ways including the uptake and adsorption of nitrogenous compounds by biochar. The important aspect of adding biochar into the soil lies in the fact that it improves the nutrient availability level in the soil which can change the plant growth resulting in the microbial activity for the less production of N_2O [20]. The application of biochar to soil can influence a wide range of soil constraints such as high availability of Al [21], soil structure and nutrient availability [17], bioavailability of organic [22] and inorganic pollutants [23]; cation-exchange capacity (CEC) and retention of nutrients [24]. It can also modify the physicochemical properties of the soil [5], decrease gaseous N emission [25], alter soil nutrient availability [26], reduce nutrient leaching [27] and increase crop yields [28]. Moreover, soil microbial properties, such as microbial abundance and activity and mycorrhizal associations were improved after the application of biochar [29, 30].

Biochar is highly efficient as it has the ability to sorb major environmental contaminants for the soil. Many organic pollutants are being sequestered by using biochar to alter their effects on the environment eventually. Due to its resisting nature towards microorganisms and its extraordinary sorption affinity, biochar acts as a critical binding phase for different organic pollutants in the environment. It generally increases carbon sequestration in soil [31], reduces the emission of ammonia and carbon dioxide [32], lowers soil compactness, optimizes compost [33], improves water retention and the sorption of heavy metals, increases the availability of micronutrients for plants and increases the pH of soils [34]. It also stimulates the growth of rhizosphere microorganisms and mycorrhizal fungi [35].

Biochar application has proven to be a very favorable method for simultaneously solving the numerous multipronged issues: creating a carbon (C) sink to mitigate global warming, neutralizing acidity in soil, increasing soil water holding capacity, reducing the losses of nutrients and agricultural chemicals in run-off, reducing greenhouse gas emissions and stabilizing mobile heavy metals, pesticides and other organic pollutants in soil [34, 36-38]. Given these attributes, there is a growing interest for adopting its use in agriculture, soil and land reclamation and climate change mitigation [39, 40]. The application of biochar for both agricultural and environmental benefits has been studied and reviewed extensively. However, the mechanisms' ruling is still poorly understood. This review focused on the current status of knowledge on mechanisms how biochar resolve the most vital issues of the present world: soil degradation and climate change.

Review Methodology: This paper is based on basic information, facts and figures supported by data sources (e.g. secondary data, bibliographic data base, etc.) in recently published journals, annual reports, technical reports and other relevant papers on issues of biochar on soil improvement, waste management, climate change mitigation and energy production. In this review, more than 173 scientific papers have been screened in which only 107 of them were included in the manuscript on the basis of their compatibility.

RESULTS AND DISCUSSION

Biochar Production: Biochar is produced from biomass materials using the thermochemical technique pyrolysis, through which organic residues are heated in O_2-free or highly limited, ambient-pressure environments for a certain time to be carbonized into charcoal, with the generation of pyrolysis bio-oil and syngas as byproducts [41]. As stated by Guo [42], for quality characteristics of biochar three parameters are usually used to manipulate the carbonization (pyrolysis) conditions: pyrolysis (peak) temperature, solid residence time and heating rate, each stretching over a wide range of values. The pyrolysis temperature for biochar production is mostly in the range of 300–700°C. A higher temperature accelerates the carbonization process, allowing the pyrolytic transformation of biomass to reach a deeper level and be completed in a shorter time [15, 43]. Complete pyrolysis is critically important to transform all feedstock OC into carbonized, pyrogenic OC i.e., altered, amorphous C structure. According to Agnieszka *et al.* [44], biochar properties are affected by several technological parameters, mainly pyrolysis temperature and feedstock kind, which differentiation can lead to products with a wide range of values of pH, specific surface area, pore volume, CEC, volatile matter, ash and carbon content. Recently, it has been reported that biochar obtained from the carbonization of organic wastes can be a substitute that not only influences the sequestration of soil carbon but also modifies its physicochemical and biological properties [45].

Physical, Chemical and Biological Properties of Biochars: Biochar has different properties that may vary with different feedstock where biochar quality and attributes are governed by pyrolysis settings such as heating time, maximum temperature, pressure and oxygen [46, 44]. The physical properties of biochar contribute to its function as a tool for managing the environment. In biochar remediation, adsorption is basic mechanism to remove toxic organic and inorganic pollutants, which directly depends on different physiochemical properties such as distribution of pore size, surface area, cation exchange capacity and functional groups. Biochar contains carbon, ash and lower molar H/C ratios, which depends upon the pyrolysis temperature that shows polymerization and ability of biochar to remove different pollutants [47-50]. When biochar is used as a soil amendment, it stimulates soil fertility and improves soil quality by increasing soil pH, increasing the ability to retain moisture, attracting more useful fungi and other microbes, improving the ability of cation exchange and preserving the nutrients in the soil [51].

Studies found that temperature and dwelling time yields biochar rich in nutrient such as Ca, P and K content, while volatile nutrients like N decrease at highest temperature [48, 52]. Pore size range of biochar typically varies from nanopores (< 0.9 nm) to macropores (> 50 nm) depending upon the feedstock, temperature and availability of oxygen and material used for biochar production [53, 54]. Zama *et al.* [55] explained the increases in Mg, Ca, K and P on biochars pyrolysed at high temperatures as being due to increased ash content (ranging from 4.0 to 33.1%). Increased carbon content (ranging from 62.2 to 92.4%) with an increase in pyrolysis temperature occurs due to a higher degree of polymerization [56], leading to a more condensed carbon structure in the biochar [10]. As a result of significant degree of organic matter decomposition, high pyrolysis temperature led to biochars with a high C content, large surface area and high adsorption characteristics [44, 57]. For instance, the increase of acidic functional groups in biochar can increase the adsorption of NH_4^+ [58]. Biochar has a high specific surface area, high amounts of oxygen containing functional groups and a high stability [59]. According to Mohan *et al.*[60] at low temperature and incomplete pyrolysis, pores of different biochar can be moderately blocked reducing the nutrient holding ability and adsorption capacity of biochar. Surface area and porosity of biochar play an important role in cation and anion exchange ability of biochar for nutrient [61]. Biochar reduces soil density and soil hardening, increases soil aeration and cation-exchange capacity. It also helps to reclaim degraded soils. It has shown a greater ability to adsorb cations per unit carbon as compared to other soil organic matters because of its greater surface area, negative surface charge and charge density [47], thereby offering the possibility of improving yields [9].

Effecting Mecanisms of Biochar in Sustainable Agriculture and Environmental Management: Food security, climate change, declining soil fertility and profitability are the burning issues under the present scenario. Soil carbon is important for food security, ecosystem functioning and environmental health, especially in light of global climate change. Owing to its biological origin and physico-chemical properties, biochar has the potential of carbon sequestration. Its higher stability against decay and capability to retain nutrients ensure the nutrient availability according to the crops need for a longer period.

Biochar as Soil Fertility Improvement: The burning issues as food security, climate change, declining soil fertility and profitability act as incentives behind the introduction of latest technologies of new farming systems. To reduce the risk of pollutant transfer to waters or receptor organisms in proximity, the improvement of soils for their remediation has proven a significant role. The extensive use of chemical fertilizers has led to the deterioration of the environment causing infinite problems. It not only lowers the nutrient composition of the crops but also degrades the soil fertility in the long run [62, 63]. As a result of long-term treatment with inorganic fertilizers and/or organic manures, a shift in structural diversity and dominant bacterial groups in agricultural soils has recorded [64]. The organic material such as biochar may serve as a popular choice for this purpose because its source is biological and it may be directly applied to soils with little pretreatment [65].

The application of biochar improves soil fertility through two mechanisms: adding nutrients to the soil (such as K, to a limited extent P and many micronutrients) or retaining nutrients from other sources, including nutrients from the soil itself. However, the main advantage is to retain nutrients from other sources. Biochar increases the availability of C, N, Ca, Mg, K and P to plants, because biochar absorbs and slowly releases fertilizers [30, 66, 67]. According to Cao *et al*.[68] report biochar also helps to prevent fertilizer drainage and leaching by allowing less fertilizer use and reducing agricultural pollution in the surrounding environment.

The addition of biochar to the soil has improve soil quality by raising soil pH of the soil and that leads to improved availability of phosphorous and potassium [69, 70], increasing moisture holding capacity [13], stimulating activity of more beneficial fungi and microbes [71], improving cation exchange capacity [72] and retaining nutrients [73]. Furthermore, application of biochar to soils has been identified as a low-cost technology that can stabilize organic carbon, reduce greenhouse gas emissions [74], improve soil physical and chemical properties and boost crop yield and productivity [75] and farm incomes. Biochar application can also increase CEC by 20 % which in turn reduces the loss of nutrients through leaching [9, 76] and soil electrical conductivity by 124.6 % [77] while reduce soil acidity by 31.9 % [77]. Additionally, biochar has also to increase soil biological community composition [78] and microbial biomass by 125 % [35]. Therefore, biochar is considered to have a great potential for enhancing plant fertilizer use efficiency by increasing nutrient availability in the soil.

The two things which make biochar amendment superior to other organic materials are high stability against decay so that it can last for longer times in soil providing long-term benefits and high capability to retain the nutrients. Various evidences and studies showed that the utilization of biochar can be extremely useful for the improvement of soil organic carbon [21], capacity of water holding [70, 79], stimulating soil microbes, increasing the microbial activity and biomass [80], decreasing in needs and leaching of fertilizers, availability and retention of nutrients, soil aeration [81, 82], bettering the growth and yield of crop growth.

Increase in Crop Yield: The impact of biochar application is more prominent in highly degraded acidic or nutrient depleted soils. Several studies have reported positive responses of biochar on net primary crop production, grain yield and dry matter. Biochar can improve the physical, chemical and biological properties of the soil (pH, surface area, cation exchange capacity (CEC), particle density, humidity and conductivity) [83, 84], reducing the leaching of nutrients, or making a direct or indirect contribution of nutrients that exerts a promoting effect on plant growth and increasing crop yield [85, 86]. The mechanisms involved are: increased soil aeration and water-holding capacity (WHC), enhanced microbial activity and plant nutrient status in soil and alteration of some important soil chemical properties.

Uzoma *et al*. [18] reported that maize grain yield significantly increased by 150 and 98 % after the application of biochar at 15 and 20 t ha^{-1}, respectively. Biochar if applied in combination with inorganic or organic fertilizers can result into increased crop yields, particularly on tropical soils [21].

Better Water Retention and Drainage: Biochar improves water holding capacity of the soil thus helps in water retention for a longer period of time which may be attributed to its highly porous structure [87, 88]. The water retention capacity is mainly due to two factors:

the large internal surface and the high number of residual pores in the biochar, where water is retained by capillarity, improving soil aggregation and structure. This increases the general porosity of the soil and the water content, leading to a decrease in the mobility of water, reducing water stress in plants [89]. The capability of biochar in reducing fertilizer drainage through increasing water retention can improve crop productivity and reduce the nutrient leaching rate in agricultural practices. Biochar has high total porosity therefore it can retain water in small pores and increase soil water holding capacity [90]. This may enhance water availability to crops and prevent from erosion. Some authors suggest that it can be an important tool to manage water in agricultural production, particularly under water stress conditions. Biochar can absorb water up to 5.0 times its own weight [91].

Reduction of Soil Acidity: Biochar has potential benefits in improving the chemical properties of acid soils. Application of biochar to soil may improve nutrient supply to plants. Soil reaction (pH) is an important characteristic of soils in terms of nutrient availability and plant growth. Previous studies reported that soil pH was raised by high-pH biochar at about one-third the rate of lime resulting in increased calcium levels and reduced aluminum toxicity on acid soils [21, 82]. Biochar possess a liming effect on soil as result of high surface charge density, large surface area, internal porosity and the presence of polar and non-polar surface sites [92]. Uchimiya *et al.*[93] pointed out that biochar ameliorate acidic soil with the formation of biochar–metal complexes, Na^+, K^+, Ca^{2+}, Mg^{2+} and other cations released into soil, causing soil pH changes. Nearly all biochars contain carbonates (e.g., K_2CO_3, Na_2CO_3, $CaCO_3$ and $MgCO_3$) that contribute to alkalinity and high pH [94, 39]. The carbonate, oxygen-containing functional groups and silicates in biochars are the major components responsible for their efficacy in amending acidic soils and resisting soil re-acidification by increasing the reaction of the exchangeable basic cations which would cause an increase in the soil pH [95-98].

Numerous studies have demonstrated that biochar can increase soil pH and cation exchange capacity (CEC), which results, in higher nutrient availability [76]. According to SHI Ren-yong *et al.* [99] report the application of crop residue biochars may be a better option than traditional liming to ameliorate acidic soils. Biochar used as neutralizer for acidic soils especially if biomass is a leguminous species [23]. Van Zweiten *et al.* [34] suggested that biochar derived from poultry litter facilitates liming in soil resulting in rise of pH of acidic or neutral soils. He also reported a nearly 30 to 40 percent increase in wheat height when biochar produced from paper mill sludge was applied at a rate of 10 t ha^{-1} to an acidic soil. Glaser *et al*. [21] informed that biochar application reduced aluminium toxicity to plant roots and soil microbiota.

Adsorption of Soil Pollutants: Biochar has the ability to sorb major environmental contaminants which are harmful for the soil. Sequestrations of organic pollutants are being done by using biochar to alter their effects on the environment ultimately. Due to its struggling nature towards microorganisms and its astonishing sorption affinity, biochar acts as a critical binding phase for different organic pollutants in the environment. The applied biochar interacts with heavy metals in the soil, adsorbing heavy metal ions on the pore surfaces and potentially transforming them into hydroxide, carbonate and phosphate precipitates [14]. Biochar amendment does not eradicate but stabilizes heavy metals in soil, transforming the toxic elements into less soluble and less bio accessible forms [100, 101]. In the same way, both Tan *et al*. [12] and O'Connor *et al*. [102] indicated that biochar amendment does not remove heavy metals from soil; instead it transforms the water-soluble and bio accessible fractions of heavy metals into immobilized forms, reducing the bioavailability and the eco toxicity of heavy-metal-contaminated soils. This method offers an approach that may be less environmentally disruptive and less expensive and hence potentially attractive as a future option. Biochar stabilizes cationic heavy metals via electrostatic attraction, ion-exchange-based surface adsorption, surface complexation and chemical precipitation.

Heavy metal ions in the soil solution can be adsorbed to biochar via ion exchange by replacing those cations (e.g., Ca^{2+}, Mg^{2+}, Na+, K^+ and H^+) originally associated with the biochar surface functional groups [103]. This specific interaction (i.e., inner-sphere adsorption) is stronger than electrostatic attraction, yet the adsorbed metal cations are exchangeable, as influenced by the solution pH and ionic strength [104, 103]. For anionic forms of toxic elements, biochar amendment generally improves their mobility in soil, suggesting that biochar may be used to facilitate phytoextraction-based remediation of Cr, As and Sb contaminated soils. The abundance of surface functional groups and the CEC of biochar determine its ability to adsorb heavy metals, while the pH/lime equivalence and the phosphate content control its capacity to precipitate heavy metal contaminants [105, 50].

A notable number of literature data indicate that biochar amendment is capable of effectively sorbing heavy metal cations from water, immobilizing heavy metal elements in soil and mitigating soil contamination. Biochar has been used as a heavy metal sequester and other chemicals such as herbicides, fungicides and insecticides [106, 93, 107, 108]. Chen and Yuan [109] found that applying biochar to the soil contaminated with poly aromatic hydrocarbons (PAHs) can help the sorption of PAHs from the soil. Overall, biochar amendment serves as a promising approach to stabilize soil heavy metals and organic contaminants and mitigate the hazardous soil pollution effects. Biochar alleviates the impact of hazardous pesticides and complex nitrogen fertilizers from the soil, thus reducing the impact on the local environment [105].

Increase in Plant Disease Resistance: The current agricultural scenario faces a range of challenges, with phytosanitary ones being dominant. In most cases, plant diseases are treated with chemicals; however, they cause environmental pollution and face the acquired resistance of pathogens. Alternatively, biochar is a valuable tool for inducing the systemic resistance of plants since it is an effective and widely used resource to improve the physical, chemical and biological attributes of the soil, consequently providing an adequate environment for healthy plant development. The mechanisms by which biochar may protect plants against diseases are varied. They include enhancing plant growth by providing nutrients, increasing soil-microbial diversity, adsorbing toxins produced by pathogens (such as extracellular enzymes and organic acids), stimulating antibiotic or fungi toxic compounds, changing the chemistry of root exudates, or inducing systemic plant defense mechanisms through chemical compounds that act as elicitors, or through microorganisms present in micro-habitats [110, 111]. Biochar has been used effectively against a wide variety of plant pathogens including airborne and soil borne pathogens and pests. In addition, the growth-promoting properties of biochar water-wash extracts have also been confirmed, as they are rich in organic and inorganic compounds [112]. Bonanomi *et al.* [113] reported that biochar is effective against both air-borne and soil borne pathogens.

Biochar and Carbon Sequestration: Carbon sequestration is the capture and storage of carbon to prevent it from being released to the atmosphere. Combatting climate change requires a reduction in atmospheric CO_2 concentrations, which can be achieved by both reducing CO_2 emissions and increasing carbon sinks [114]. Through the process of photosynthesis, plants convert carbon dioxide from the air into organic material, or biomass. If that biomass is then used to create biochar and returned to the soil, it has the potential to keep the carbon dioxide from re-entering the atmosphere for an extremely long period of time [115, 116]. Biochar increase the carbon storage in cropland soils [117, 81]. The half-life of biochar in the soil is estimated to range from hundreds to thousands of years [118]. Thus, supplying the soil with biochar is a strategy for long-term carbon sequestration. Biochar sequester carbon from the atmosphere and convert it into a highly stable form thereby decreasing CO_2 emission from soil due to decomposition [119]. Biochar addresses two important sources of environmental problems, by sequestering CO_2 into the soil and by reducing water pollution through enhancing soil nutrient retention [120]. Woolf *et al. [*121] detected that biochar plays important role for emission of carbon and also essential to meeting global climate targets.

Biochar and Greenhouse Gas Emission Reduction: Global warming is among the most urgent global issues nowadays [122]. The Intergovernmental Panel on Climate Change (IPCC) pointed out that carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the major greenhouse gases (GHGs) in the current global climate change process [123]. Greenhouse gases associated with the agriculture sector are nitrous oxide (N_2O) and methane (CH_4). Globally, agriculture accounts for about 14% of the total GHG emissions [124, 125], including 47% of the CH_4 emissions and 84% of the N_2O [126]. On the other hand Karakurt *et al*. [127] stated that agriculture contributes approximately 51% and 58% of the anthropogenic CH_4 and N_2O emissions, respectively. Biochar can reduce greenhouse gas emissions [128, 129] and increase the carbon storage [130-132]. The carbon sequestration and GHG emission reduction effects of biochar on farmland soils come from its high chemical stability and biological stability [115].

Biochar is highly stable and having the capacity to emit less carbon dioxide from organic decomposition significantly. So that it plays an important role in monitoring the release of methane and nitrogen dioxide from the soil [45], which are the major cause of climate change in recent days. Spott *et al*. [133] stated that in terms of N_2O emissions from soil, nitrifier-nitrification, nitrifier-denitrification and denitrification are the principal sources and may occur simultaneously at different microsites within the soil ecosystem. As the result of biochar application, NO and N_2O emissions decreased by

43% and 62%; respectively [134]. Yanai *et al*. [25] also indicated that N_2O emission decreased by 80% after the addition of biochar. Biochar can reduce nitrous oxide (N_2O) emissions from soil [115, 135] and it can alter methane emission or oxidation rates in soil [136]. This reduction in the release of nitrogen dioxide arises because of the capacity of biochar to adsorb and retain the ammonium in soils and then lessen the availability of nitrogen for denitrification process [5]. Zwieten *et al.* [137] stated that soils treated with biochar have showed 40-51% less emissions of nitrogen dioxide than that of those soils not treated with biochar. Thus biochar is being promoted as a climate change mitigation tool as it has the potential to increase soil C sequestration and reduce soil GHG emissions when applied as a soil amendment [115].

CONCLUSION

It is evident that biochar has the potentiality to resolve simultaneously the most vital issues of the present world. Biochar is used as a soil amendment; as a means of remediating contaminated agricultural soil, improving soil fertility by reducing the acidity, increasing the availability of nutrients, repair soils that have been contaminated with toxic heavy metals and improving plant resistance to some pathogens. Biochar increases crop production via increasing soil aeration and water-holding capacity, enhanced microbial activity and plant nutrient status in soil and alteration of some important soil chemical properties. Apart from agricultural benefits biochar also possess some environment benefits like climate change mitigation of GHG, remediation of polluted soil and sequester it (enhanced sinks) in the soil. Biochar is also a promising tool to reduce the atmospheric CO_2 concentration because it slows the return of photo synthetically fixed carbon to the atmosphere. The potential of biochar for carbon sequestration and its ability to reduce greenhouse gas emissions make it a very attractive alternative to counteract the adverse effects of climate change. To sum up, biochar application to soil can sequestrate carbon, adsorb inorganic and organic contaminants and improve soil fertility and quality through increases in pH, macro-nutrients and improved soil water holding capacity. However, the research community should give an emphasis to validate the agricultural and environmental benefits of soil–biochar amendment packages and to develop biochar quality standards. Thus, biochar production and application can be regarded as a viable solution to an array of modern-day problems.

REFERENCES

1. Jatav, H.S., S.K. Singh, Y.V. Singh, A. Paul, V. Kumar and P. Singh, 2016. Effect of Biochar on Yield and Heavy Metals Uptake in Rice Grown on Soil Amended with Sewage Sludge. J. Pure. Appl. Microbio., 10(2): 1367-1377.
2. De Meyer, A., J. Poesen, M. Isabirye, J. Deckers and D. Rates, 2011. Soil erosion rate in tropical villages: a case study from Lake Victoria Basin, Uganda. Catena, 84: 89-98.
3. Annabi, M., Y. Le Bissonnais, M. Le Villio-Poitrenaud and S. Houot, 2011. Improvement of soil aggregate stability by reported applications of organic amendments to a cultivated silty loam soil. Agric Ecosyst Environ, 144: 382-389.
4. Denman, K., G. Brasseur, A. Chidthaisong, P. Ciais, P. Cox, R. Dickinson, D. Hauglustaine, C. Heinze, C. Holland, D. Jacob, U. Lohmann, S. Ramachandran, P. Da Silva Dias, S. Wofsy and X. Zhang, 2007. Couplings Between Changes in the Climate System and Biogeochemistry. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor M and Miller H, (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
5. De Luca, T.H., M.D. Mackenzie, M.J. Gundale and W.E. Holben, 2006. Wildfire-produced charcoal directly influences nitrogen cycling in ponderosa pine forests, Soil Science Society of America Journal, 70(2): 448-453.
6. Glaser, B., L. Haumaier, G. Guggenberge and W. Zech, 2001. The 'Terra Preta'phenomenon: a model for sustainable agriculture in the humid tropics. Naturwissenschaften, 88: 37-41.
7. Skjemstad, JO., D.C. Reicosky, A.R. Wilts and J.A. McGowan, 2002. Charcoal carbon in U.S. agricultural soils. Soil Sci. Soc. Am. J., 66: 1249-1255.
8. Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science, 304: 1623-1627.
9. Lehmann, J., 2007. A handful of carbon. Nature, 447: 143-144.
10. Lehmann, J. and S. Joseph, 2009. Biochar for environmental management science and technology. Earthscan, London.

11. Guo, M., Z. He and S. Uchimiya, 2016. "Introduction to biochar as an agricultural and environmental amendment," in Agricultural and Environmental Applications of Biochar: Advances and Barriers. Vol. 63, eds Guo, M., He, Z., Uchimiya, S., (Madison, WI: Soil Science Society of America), pp: 1-14.
12. Tan, X., Y. Liu, G.Zeng, X. Wang, X. Hu and Y. Gu, 2015. Application of biochar for the removal of pollutants from aqueous solutions. Chemosphere, 125: 70-85.
13. Duku, M.H., S. Gu and E.B. Hagan, 2011. Biochar production potential in Ghana-a review. Renew Sust Energ Rev., 15: 3539-3551.
14. Ahmad, M., A. Rajapaksha, J. Lim, M. Zhang, N. Bolan and D. Mohan, 2014. Biochar as a sorbent for contaminant management in soil and water - a review. Chemosphere, 99: 19-33.
15. Song, W. and M. Guo, 2012. Quality variations of poultry litter biochars generated at different pyrolysis temperatures. J. Anal. Appl. Pyrolysis, 94: 138-145.
16. Tammeorg, P., A. Simojoki, P. Mäkelä, F.L. Stoddard, L. Alakukku and J. Helenius, 2013. Biochar application to a fertile sandy clay loam in boreal conditions: effects on soil properties and yield formation of wheat, turnip rape and faba bean. Plant Soil, 374: 89-107.
17. Lehmann, J., M.C. Rilig, J. Thies, C.A. Masiello, W.C. Hockaday and D. Crowley, 2011. Biochar effects on soil biota-a review. Soil Biol Biochem., 43: 1812-1836.
18. Uzoma, K.C., M. Inoue, H. Andry, H. Fujimaki, A. Zahoor and E. Nishihara, 2011. Effect of cow manure biochar on maize productivity under sandy soil condition. Soil Use Manag., 27: 205-212.
19. Placek, A., A. Grobelak and M. Kacprzak, 2016. Improving the phytoremediation of heavy metals contaminated soil by use of sewage sludge. International Journal of Phytoremediation, 18(6): 605-618.
20. Smith, J.L., H.P. Collins and V.L. Bailey, 2010. The effect of young biochar on soil respiration. Soil Biol Biochem, 42: 2345-2347.
21. Glaser, B., J. Lehmann and W. Zech, 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal-a review. Biol. Fert. Soils, 35: 219- 230.
22. Rajkovich, S., A. Enders, K. Hanley, C. Hyland, A.R. Zimmerman and J. Lehmann, 2012. Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. Biol Fertil Soils, 48: 271-284.
23. Yuan, J.H. and R.K. Xu, 2011. The amelioration effects of low temperature biochar generated from nine crop residues on an acidic Ultisol, soil Use Manage., 27: 110-115
24. Mengel, K. and E.A. Kirkby, 2001. Principles of plant nutrition, 5^{th} edn. Kluwer Academic Publishers, Dordrecht.
25. Yanai, Y., K. Toyota and M. Okazaki, 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(2): 181-188.
26. Chan, K.Y., L. Van Zwieten, I. Meszaros, A. Downie and S. Joseph, 2008a. Agronomic values of green waste biochar as a soil amendment. Soil Res., 45: 629-634.
27. Zheng, H., Z. Wang, X. Deng, J. Zhao, Y. Luo, J. Novak, S. Herbert and B. Xing, 2013. Characteristics and nutrient values of biochars produced from giant reed at different temperatures. Bioresour Technol., 130: 463-471.
28. Major, J., M. Rondon, D. Molina, S.Riha and J. Lehmann, 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. Plant Soil., 333: 117-128.
29. Warnock, D.D., J. Lehmann, T.W. Kuyper and M.C. Rillig, 2007. Mycorrhizal responses to biochar in soil-concepts and mechanisms. Plant Soil, 300: 9-20.
30. Steiner, C., K.C. Das, M. Garcia, B. Forster and W. Zech, 2008. Charcoal and smoke extract stimulate the soil microbial community in a highly weathered xanthic Ferralsol, Pedobiologia, 51: 359-366.
31. Sohi, S., E. Krull, E. Lopez-Capel and R. Bol, 2010. A review of biochar and its use and function in soil. Adv Agron, 105: 47-82.
32. Cabeza, I., T. Waterhouse, S. Sohi and J.A. Rooke, 2018. Effect of biochar produced from different biomass sources and at different process temperatures on methane production and ammonia concentrations *in vitro*. Anim Feed Sci. Technol., 237: 1-7.
33. Liang, B., J. Lehmann, S.P. Sohi, J.E. Thies, B. O'Neill, L. Trujillo, J. Gaunt, D. Solomon, J. Grossman, E.G.Neves and F.J. Luizão, 2010. Black carbon affects the cycling of non-black carbon in soil. Org Geochem, 41: 206-213.
34. Van Zwieten, L., S. Kimber, S. Morris, K.Y. Chan and A. Downie, 2010. Effects of biochar from slow pyrolysis of paper mill waste on agronomic performance and soil fertility. Plant and Soil., 327: 235-246.

35. Compant, S., S.Cle´ment and A. Sessitsch, 2010. Plant growth-promoting bacteria in the rhizo- and endosphere of plants: their role, colonization, mechanisms involved and prospects for utilization. Soil Biol. Biochem., 42: 669-678.
36. Inyang, M., 2011. Enhanced lead sorption by biochar derived from anaerobically digested sugarcane bagasse. Sep. Sci. Technol., 46: 1950-1956.
37. Abdul Halim, N., 2018. Influence of soil amendments on the growth and yield of rice in acidic soil. Agronomy, 8, 165.
38. Berek, A., N. Hue, T. Radovich and A. Ahmad, 2018. Biochars improve nutrient phyto-availability of Hawai'i's highly weathered soils. Agronomy 8, 203.
39. Jiang, T.Y., J. Jiang, R.K. Xu and Z. Li, 2012. Adsorption of Pb (II) on variable charge soils amended with rice-straw derived biochar. Chemosphere, 89: 249-256.
40. Liu, X., J. Qu, L. Li, A. Zhang, Z. Jufeng, J. Zheng and G. Pan, 2012. Can biochar amendment be an ecological engineering technology to depress N_2O emission in rice paddies? A cross site field experiment from South China. Ecol. Eng., 42: 168-173.
41. Guo, M., Z. He and S.M. Uchimiya, 2016. Introduction to biochar as an agricultural and environmental amendment. In Agricultural and Environmental Applications of Biochar: Advances and Barriers; Guo, M., He, Z., Uchimiya, S.M., Eds.; SSSA Spec. Publ. 63; Soil Science Society of America: Madison, WI, USA, 2016, pp: 1-14.
42. Guo, M., 2020. The 3R principles for applying biochar to improve soil health. Soil Syst. 4: 9.
43. Chen, Y., X. Zhang, W. Chen, H. Yang and H. Chen., 2017. The structure evolution of biochar from biomass pyrolysis and its correlation with gas pollutant adsorption performance. Bioresour. Technol., 246: 101-109.
44. Agnieszka Tomczyk, Zofia Sokołowska and Patrycja Boguta, 2020. Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. Rev Environ Sci Biotechnol., 19: 191-215.
45. Zhang, M., G. Cheng, H. Feng, B. Sun, Y. Zhao, H. Chen, J. Chen, M. Dyck, X. Wang, J. Zhang and A.Zhang, 2017. Effects of straw and biochar amendments on aggregate stability, soil organic carbon and enzyme activities in the Loess Plateau, China. Environmental Science and Pollution Research. 24(11): 10108-10120.
46. Kalinke Cristiane, Paulo Roberto Oliveira, Geovane Arruda Oliveira, Antonio SálvioMangrich and Luiz H.Marcolino-Junior, 2017. Activated biochar: Preparation, characterization and electro analytical application in an alternative strategy of nickel determination Analytica Chimica Acta, 983(29): 103-111
47. Liang, J.J., T.W. Crowther, N. Picard, S. Wiser, M. Zhou, G.Alberti and E.D. Schulze, 2016. Positive biodiversity-productivity relationship predominant in global forests. Science, 354:aaf8957
48. Li, F., K. Shen, X. Long, J. Wen, X. Xie, X. Zeng, Y. Liang, Y. Wei, Z. Lin, W. Huang and R. Zhong, 2016. Preparation and characterization of biochars from Eichornia crassipes for cadmium removal in aqueous solutions. PLoS One [Internet];11(2):Article e0148132 [p.13].
49. Abdulaha-Al Baquy, M., J.Y. Li, C.Y. Xu, K. Mehmood and RK. Xu, 2017. Determination of critical pH and Al concentration of acidic Ultisols for wheat and canola crops. Solid Earth, 8: 149-159.
50. Sun, X., X. Han, F. Ping, L. Zhang, K. Zhang, M. Chen and W. Wu, 2018. Effect of rice-straw biochar on nitrous oxide emissions from paddy soils under elevated CO2 temperature. Sci. Total Environ., 628-629: 1009-1016.
51. Ajema, L., 2018. Effects of biochar application on beneficial soil organism review. International Journal of Research Studies in Science, Engineering and Technology, 5(5): 9-18.
52. Jha, P., A.K. Biswas, B.L. Lakaria and A. Subba Rao, 2010. Biochar in agriculture—prospects and related implications. Curr. Sci., 99: 1218-1225.
53. Bruun, E.W., C.T. Petersen, E. Hansen, J.K. Holm and H. Hauggaard-Nielse, 2014. Biochar amendment to coarse sandy subsoil improves root growth and increases water retention. Soil Use and management.
54. Li, H., X. Dong, E.B. Da Silva, L.M. De Oliveira, Y. Chen and L.Q. Ma, 2017. Mechanisms of metal sorption by biochars: Biochar Characteristics.
55. Zama, E.F., Y.G. Zhu, B.J. Reid and G.X. Sun, 2017. The role of biochar properties in influencing the sorption and desorption of Pb(II), Cd(II) and As(III) in aqueous solution. J. Clean Prod., 148: 127-136
56. Domingues, R., P. Trugilho, C. Silva, I. Melo, L. Melo, Z. Magriotis and M. Sanchez-Monedero, 2017. Properties of biochar derived from wood and high-nutrient biomasses with the aim of agronomic and environmental benefits. PLoS ONE 12, e0176884.
57. Mahdi, Z., A. Hanandeh and Q. Yu, 2017. Influence of Pyrolysis Conditions on Surface Characteristics and Methylene Blue Adsorption of Biochar Derived from Date Seed Biomass. Waste Biomass Valorization, 8: 2061-2073.

58. Spokas, K., J. Novak and R. Venterea, 2012. Biochar's role as an alternative N-fertilizer: ammonia capture. Plant Soil., 350: 35-42.
59. Huang, X., Y. Liu, S. Liu, X. Tan, Y. Ding, G. Zeng, Y. Zhou, M. Zhang, S. Wang and B.Zheng, 2016. Effective removal of Cr (VI) using β-cyclodextrin-chitosan modified biochars with adsorption/reduction bifuctional roles. RSC Adv., 6: 94-104.
60. Mohan, D., A. Sarswat, Y.S. Ok and C.U. Pittman Jr, 2014. Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent-a critical review. Bioresource Technology, 160: 191-202.
61. Shu, R., Y. Wang and H. Zhong, 2016. Biochar amendment reduced methylmercury accumulation in rice plants. J. Hazard, Mater., 313: 1-8
62. Hariprasad, N.V. and H.S. Dayananda, 2013. Environmental impact due to agricultural runoff containing heavy metals- A review. International Journal of Scientific and Research Publications, 3(5): 1-6.
63. Yargholi, B. and S. Azarneshan, 2014. Long term effects of pesticides and chemical fertilizers usage on some soil properties and accumulation of heavy metals in the soil (case study of Moghan plain's (Iran) irrigation and drainage network). International Journal of Agriculture and Crop Sciences, 7: 518-523.
64. Wu, F., Y. Gai, Z. Jiao, Y. Liu, X. Ma and L. An, 2012. The community structure of microbial in arable soil under different long-term fertilization regimes in the Loess Plateau of China. African Journal of Microbiology Research, 6: 6152-6164.
65. Beesley, L., E. Moreno-Jiménez, J. Gomez-Eyles, E. Harris, B. Robinson and T. Sizmur, 2011. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. Environ. Pollut., 159: 3269-3282.
66. DeLuca, T.H., M.J. Gundale, M.D. MacKenzie and D.L. Jones, 2015. Biochar effects on soil nutrient transformation. In: Lehmann J., Joseph S., editors. Biochar for Environmental Management: Science and Technology. 2nd ed. Routledge, pp: 421-454.
67. Dume, B., T. Mosissa and A. Nebiyu, 2016. Effect of biochar on soil properties and lead (Pb) availability in a military camp in South West Ethiopia. African Journal of Environmental Science and Technology, 10(3): 77-85.
68. Cao, Y., Y. Gao, Y. Qi and J. Li, 2018. Biochar enhanced composts reduce the potential leaching of nutrients and heavy metals and suppress plant-parasitic nematodes in excessively fertilized cucumber soils. Environmental Science and Pollution Research International, 25(8): 7589-7599.
69. Rodriguez, L., P. Salazar and T. Preston, 2009. "Effects of biochar and digester effluent on growth of maize in acid soils, " Livestock Research for Rural Development, 21(7): 110.
70. Atkinson, C.J., J.D. Fitzgerald and N.A. Hipps, 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant Soil, 337: 1-18.
71. Zheng, W., B. Sharma and N. Rajagopalan, 2010. "Using biochar as a soil amendment for sustainable agriculture, " Field Report, Illinois Department of Agriculture, Illinois, USA.
72. Lehmann, J. and M. Rondon, 2006. Biochar soil management on highly weathered soils in the humid tropics. In: Uphoff N (ed.), Biological approaches to sustainable soil systems. Boca Raton, FL: CRC Press, pp: 517-530.
73. Paz-Ferreiro, J., H. Lu, S. Fu, A. Mendez and G. Gasc´o, 2014. "Use of ´ phytoremediation and biochar to remediate heavy metal polluted soils: a review," Solid Earth, 5(1): 65-75.
74. De Gryze, S., M. Cullen, L. Durschinger, J. Lehmann, D. Bluhm and J. Six, 2010. "Evaluation of opportunities for generating carbon offsets from soil sequestration of biochar, " in An issues paper commissioned by the Climate Action Reserve, 2010.
75. Jeffery, S., D. Abalos and M. Prodana, 2017. "Biochar boosts tropical but not temperate crop yields, " Environmental Research Letters, 12(5): 053001.
76. Laird, D., P. Fleming, B. Wang, R. Horton and D. Karlen, 2010. Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma, 158(3-4): 436-442.
77. Oguntunde, P., M. Fosu, A. Ajayi and N. Giesen, 2004. Effects of charcoal production on maize yield, chemical properties and texture of soil. Biol Fertil Soils, 39: 295-299.
78. Grossman, J.M., B.E. O'Neill, S.M. Tsai, B. Liang, E. Neves, J. Lehmann and J.E. Thies, 2010. Amazonian anthrosols support similar microbial communities that differ distinctly from those extant in adjacent, unmodified soils of the same mineralogy. Microb. Ecol., 60: 192-205.

79. Abel, S., A. Peters, S. Trinks, H. Schonsky, M. Facklam and G. Wessolek, 2013. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil, Geoderma 202-203, 183-191.
80. Thies, J.E. and M. Rillig, 2009. Characteristics of biochar: biological properties. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology. Earthscan, London, 85-105.
81. 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. Agron J., 100: 178-181.
82. Steiner, C., W. Teixeira, J. Lehmann, T. Nehls, J. De Macedo, W. Blum and W. Zech, 2007. Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. Plant and Soil, 291(1-2): 275-290.
83. Burrell, L., D. Zehetner, F. Rampazzo, N. Wimmer and G. Soja, 2016. Long-term effects of biochar on soil physical properties. Geoderma, 282: 96-102.
84. Zwart, K., 2020. Effects of biochar produced from waste on soil quality. In Meers E, Velthof G, Michels E and Rietra R, (Eds.), Biorefinery of Inorganics: recovering mineral nutrients from biomass and organic waste (pp. 283-299). John Wiley & Sons Ltd.
85. Ouyang, L., Q. Tang, L. Yu and R. Zhang, 2014. Effects of amendment of different biochars on soil enzyme activities related to carbon mineralization. Soil Research, 52(7): 706-716.
86. Sun, H., H. Zhang, W. Shi, M. Zhou and X. Ma, 2019. Effect of biochar on nitrogen use efficiency, grain yield and amino acid content of wheat cultivated on saline soil. Plant, Soil and Environment, 65(2): 83-89.
87. Keech, O., C. Carcaillet and M.C. Nilsson, 2005. Adsorption of allopathic compounds by wood-derived charcoal; the role of wood porosity. Plant and Soil, 272: 291-300.
88. Liang, B., J. Lehmann, D. Solomon, J. Kinyangi, J. Grossman, B. O'Neill, J.O. Skjemstad, J. Thies, F.J. Luizão, J. Petersen and E.G. Neves, 2006. Black carbon increases cation exchange capacity in soils. Soil Sci. Soc. Am. J., 70: 1719-1730.
89. Batista, E., M. Shultz, J. Matos, T. Fornari, M. Ferreira, T. Szpoganicz, B. de Freitas and A. Mangrich, 2018. Effect of surface and porosity of biochar on water holding capacity aiming indirectly at preservation of the Amazon biome. Scientific Reports, 8(1), Article 10677.
90. Asai, H., B.K. Samson and H.M. Stephan, 2009. Biochar amendment techniques for upland rice production in northern Laos. Field Crops Research, 111: 81-84.
91. Gasior, D. and W.J. Tic, 2017. Application of the biochar-based technologies as the way of realization of the sustainable development strategy. Econ Environ Stud, 17: 597-611.
92. Shetty, R. and N. Prakash, 2020. Effect of different biochars on acid soil and growth parameters of rice plants under aluminium toxicity. Scientific Reports, 10(1), Article 12249.
93. Uchimiya, M., K. Klasson, L. Wartelle and I. Lima, 2011. Influence of soil properties on heavy metal sequestration by biochar amendment: 1. Copper sorption isotherms and the release of cations. Chemosphere, 82(10): 1431-1437.
94. Cao, X., L. Ma, Y. Liang, B. Gao and W. Harris, 2011. Simultaneous immobilization of lead and atrazine in contaminated soils using dairy-manure biochar. Environ. Sci. Technol., 45: 4884-4889.
95. Lehmann, J., J. Pereira da Silva, C. Steiner, T. Nehls, W. Zech and B. Glaser, 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant Soil, 249: 343-357.
96. Hansen, V., D. Múller-Stõver, L. Munkholm, C. Peltre, H. Haug-gaard-Nielsen and L. Jensen, 2016. The effect of straw and wood gasification biochar on carbon sequestration, selected soil fertility indicators and functional groups in soil: an incubation study. Geoderma, 269: 99-107.
97. Dai, Z., X. Zhang, C. Tang, N. Muhammad, J. Wu, P. Brookes and J. Xu, 2017. Potential role of biochars in decreasing soil acidification - A critical review. Science of the Total Environment, 581-582, 601-611.
98. Zong, Y., Y. Wang, Y. Sheng, C. Wu and S. Lu, 2018. Ameliorating soil acidity and physical properties of two contrasting texture Ultisols with waste water sludge biochar. Environmental Science and Pollution Research, 25: 25726-25733.
99. Ren-yong , S.H.I., L.I. Jiu-yu, N.I. Ni and X.U. Ren-Kou, 2019. Understanding the biochar's role in ameliorating soil acidity, Journal of Integrative Agriculture, 18(7): 1508-1517.
100. Zhou, Q. and Y. Song, 2004. Contaminated soil remediation: principles and methods. Science Press, Beijing.

101. Liu, L., W. Li, W. Song and M. Guo, 2018. Remediation techniques for heavy metal-contaminated soils: principles and applicability. Sci. Total Environ., 633: 206-219.
102. O'Connor, D., T.Peng, J. Zhang, D. Tsang, D. Alessi and Z. Shen, 2018. Biochar application for the remediation of heavy metal polluted land: a review of in situ field trials. Sci. Total Environ., 619-620, 815-826.
103. Fidel, R.B., D.A. Laird and K.A. Spokas, 2018. Sorption of ammonium and nitrate to biochars is electrostatic and pH-dependent. Sci. Rep., 8: 17627.
104. Ding, W., X. Dong, I. Ime, B. Gao and L. Ma, 2014. Pyrolytic temperatures impact lead sorption mechanisms by bagasse biochars. Chemosphere, 105: 68-74.
105. Mingxin Guo, Weiping and Jing Tian, 2020. Biochar-Facilitated Soil Remediation: Mechanisms and Efficacy Variations. Front. Environ. Sci., 21 October 2020.
106. Yang, X., J. Liu, K. McGrouther, H. Huang, K. Lu, X. Guo, 2016. Effect of bio-char on the extractability of heavy metals (Cd, Cu, Pb and Zn) and enzyme activity in soil. Environ. Sci. Pollut. Res., 23: 974-984. doi: 10.1007/s11356-015-4233-0.
107. Lu, H., W. Zhang and Y. Yang, 2012. Relative distribution of Pb^{2+} sorption mechanisms by sludge-derived biochar. Water Res., 46(3): 854-862
108. Jiang, J. and R. Xu, 2013. Application of crop straw derived biochars to Cu (II) contaminated Ultisol: Evaluating role of alkali and organic functional groups in Cu (II) immobilization. Bioresource Technology, 133: 537-545.
109. Chen, B. and M. Yuan, 2011. Enhanced Sorption of Polycyclic Aromatic Hydrocarbons by Soil Amended with Biochar. J. Soils Sediments, 11: 62-71.
110. Graber, E. and Y. Elad, 2013. Biochar Impact on Plant Resistance to Disease. In: Ladygina N, Rineau F, (eds.). Biochar and Soil Biota., pp: 41-68. CRC Press, Boca Raton.
111. Bonanomi, G., F. Ippolito and F. Scala, 2015. A" black" future for plant pathology? Biochar as a new soil 350 amendment for controlling plant diseases. J. Plant Pathol., 97: 223-234.
112. Lou, Y., S. Joseph, L. Li, E. Graber, X. Liu and G. Pan, 2016. Water extract from straw biochar used for plant growth promotion: an initial test. Bio Resources, 11: 249-266.
113. Bonanomi, G., F. Ippolito, G. Cesarano, B. Nanni, N. Lombardi and A. Rita, 2017. Biochar as plant growth promoter: Better off alone or mixed with organic amendments? Frontiers in Plant Science, 8: 1570.
114. Paustian, K., J. Lehmann, S. Ogle, D. Reay, G.P. Robertson and P.Smith, 2016. Climate-Smart Soils. Nature, 532: 49-57.
115. Woolf, D., J.E. Amonette, F.A. Street-perrott, J. Lehmaan and S. Joseph, 2010. Sustainable biochar to mitigate global climate change. Nat.Commun. 1, 56.
116. Xu, G., Y. Lv, J. Sun, H. Shao and L. Wei, 2012. Recent advances in biochar applications in agricultural soils: Benefits and environmental implications. CLEAN - Soil, Air, Water, 40: 1093-1098.
117. Gaunt, J. and J. Lehmann, 2008. "Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production, " Environmental Science and Technology, 42: 4152-4158.
118. Zimmerman, A.R., 2010. Abiotic and microbial oxidation of laboratory produced black carbon (biochar). Environ. Sci. Technol., 44: 1295-1301.
119. Kataki, R., M. Das, R. Chutia and M. Borah, 2012. Biochar for C sequestration and soil amelioration. In: Renewable Energy Technology: Issues and Prospects, (eds Shankar G, Das R Blange). Excell India Publishers, New Delhi, pp: 131-137.
120. Shackley, S., S. Sohi, P. Brownsort, S. Carter, J. Cook, C. Cunningham, J. Gaunt, J. Hammond, R. Ibarrola, O. Mašek and K. Sims, 2010. An assessment of the benefits and issues associated with the application of biochar to soil. Department for Environment, Food and Rural Affairs, UK Government, London.
121. Woolf, D., J. Lehmann and D.R. Lee, 2016. Optimal bioenergy power generation for climate change mitigation with or without carbon sequestration. Nature Communications, 7(1): 1-11.
122. Stocker, T., IPCC, 2013. Technical Summary. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013, 159-254.
123. Solomon, S. IPCC, 2007. Climate Change. The Physical Science Basis. Am. Geophys. Union 2007, 9: 123-124.
124. Bouwman, A., 2001. Global Estimates of Gaseous Emissions from Agricultural Land. FAO, Rome, 106.

125. Rice, C.W., 2006. Introduction to special section on greenhouse gases and carbon sequestration in agriculture and forestry. Journal of Environmental Quality 35:1338-1340.
126. US-EPA, 2006a. Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990 - 2020. United States Environmental Protection Agency, EPA 430-R-06-003, June 2006. Washington, DC. Available at: http://www.epa.gov/nonco2/econ-inv/international.html.
127. Karakurt, I., G. Aydin and K. Aydiner, 2012. Sources and mitigation of methane emissions by sectors: A critical review. Renew. Energy, 39: 40-48.
128. Schmidt, H.P., S. Abiven, C. Kammann, B. Glaser, T. Bucheli, J. Leifeld and S. Shackley, 2016. European Biochar Certificate-Guidelines for a Sustainable Production of Biochar; European Biochar Foundation (EBC): Arbaz, Switzerland.
129. Hagemann, N., E. Subdiaga, S. Orsetti, J.M.D.L. Rosa, H. Knicker, H P. Schmidt, A. Kappler and S. Behrens, 2018. Effect of biochar amendment on compost organic matter composition following aerobic compositing of manure. Sci. Total Environ., 613-614, 20-29.
130. Zhang, A., Y. Liu, G. Pan, Q. Hussain, L. Li, J. Zheng and X. Zhang, 2012. Effect of biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon poor calcareous loamy soil from Central China Plain. Plant Soil, 351: 263-275.
131. Stewart, C.E., J.Y. Zheng, J. Botte and M.F. Cotrufo, 2013.Co-generated fast pyrolysis biochar mitigates green-house gas emissions and increases carbon sequestration in temperate soils. Glob. Chang. Biol. Bioenergy, 5: 153-164.
132. Kim, J., G. Yoo, D. Kim, W. Ding and H. Kang, 2017. Combined application of biochar and slow-release fertilizer reduces methane emission but enhances rice yield by different mechanisms. Appl. Soil Ecol., 117-118, 57-62.
133. Spott, O., R. Russow and C.F. Strange, 2011. Formation of hybrid N_2O and hybrid N_2 due to codenitrification: first review of a barely considered process of microbially mediated N-nitrosation Soil Biol. Biochem., 43(10): 1995-2011.
134. Nelissen, V., B. Saha, G. Ruysschaert and P. Boeckx, 2014. Effect of different biochar and fertilizer types on N_2O and NO emissions. Soil Biol. Biochem., 70: 244-255.
135. Cayuela, M.L., L. Van Zwieten, B.P. Singh, S. Jeffery, A. Roig and M.A. Sanchez-Monedero, 2013. Biochar's role in mitigating soil nitrous oxide emissions: a review and meta-analysis. Agriculture Ecosystems and Environment, 191: 5-16.
136. Jeffery, S., F.G. Verheijen, C. Kammann and D. Abalos, 2016. Biochar effects on methane emissions from soils: a meta-analysis. Soil Biol. Biochem, 101: 251-258.
137. Zwieten, L., B. Singh, S. Joseph, S. Kimber, A.Cowie and K.Y. Chan, 2009. Biochar and emissions of non-CO_2 greenhouse gases from soil. In: J. Lehmann, S. Joseph (ed) Biochar for Environmental Management: Science and Technology. Earthscan, London, pp: 227-249.