

**An Overview of the importance of Biochar in Sustainable Agriculture****Abstract:**

Sustainable agriculture is essential for addressing the global food security challenges, environmental degradation, and climate change. Biochar, a carbon-rich material produced through the pyrolysis, has gained significant attention as a promising tool to enhance sustainability of agricultural systems. Biochar serves as a valuable soil amendment by improving soil structure and enhancing its water-holding capacity, nutrient retention, and microbial activity. These improvements translate into increased soil fertility and reduced nutrient runoff, mitigating the risk of water pollution. Furthermore, biochar's porous structure acts as a reservoir for beneficial microorganisms and can potentially contribute to the suppression of soil-borne pathogens. In the context of climate change, biochar plays a dual role. Firstly, it acts as a carbon sink, sequestering carbon in the soil for hundreds to thousands of years, thus mitigating greenhouse gas emissions. Secondly, biochar application can lead to reduced emissions of nitrous oxide, a potent greenhouse gas associated with synthetic fertilizer use. Crop productivity and yield stability are critical factors in sustainable agriculture. Biochar application has been shown to enhance plant growth by improving nutrient availability, root development, and stress tolerance. Additionally, it can increase crop resilience to extreme weather events, helping farmers adapt to changing climatic conditions. However, the successful integration of biochar into agricultural systems requires careful consideration of feedstock selection, pyrolysis processes, and application methods, as well as site-specific factors. Nonetheless, continued research, development, and knowledge dissemination are essential to maximize positive impacts of biochar in diverse agricultural contexts. The current review article aims at understanding the production and applications of biochar for sustainability of agricultural production systems and minimizes the carbon emissions through sequestration.

**Keywords:** Biochar; sustainability; soil fertility; C sequestration; productivity

**1. Introduction:**

The world's population is ever increasing posing challenges to the global agricultural system. In order to feed the expanding population and meet the steadily rising demand for food, the farming system need to be more dependent on technology and chemical inputs (Mueller et al., 2012). Over the years, agricultural soil has seen an increase in the amount of fertilizer and pesticide application to increase crop yields (Pan et al., 2017). During prolonged application, leaching losses of pesticides and fertilizers may occur, reducing soil fertility and polluting the environment. In addition to reducing soil fertility and increasing farming costs, nutrient loss from agricultural soils can also increase soil acidification and reduce crop yields (Laird et al., 2010). In lieu of commercially prepared items, the idea on natural residue and organic substances has focused the attention of the scientific community and farmers (Ilvo et al., 2019). One of the results of scientific research is biochar, which is crucial for establishing sustainable agriculture and the environment (Lu et al., 2020).

An effective way to sequester carbon to combat climate change and global warming is through the use of biochar. When incorporated into the soil, it is extremely long-lasting and can persist there for hundreds to thousands of years (Ayaz et al., 2021). Additionally, it is being investigated for environmental rehabilitation, reducing pollutant mobility in polluted

soils, and lessening the change of dangerous elements to agronomic crops (Jalal et al., 2020). The physical, chemical, and biological qualities of the soil are enhanced by the addition of biochar, which increases the amount of organic matter in the soil. In order to change the agricultural environment, biochar can either positively or negatively impact the microbial growth in the soil (Kavitha et al., 2018).

The Terra Preta, commonly referred to as "Indian black earth," was the first instance of biochar being used to improve soil. Its black hue, high aggregate stability due to the presence of more carbon, and high nutritional content linked to an increase in microbial presence make it easy to identify (Glaser et al., 2012). The Terra Preta has been discovered to have higher levels of nutrients as well as superior soil rigidity and structure, which results in a more secure organization of soil particles (Alling et al., 2014). Flakes from several varieties of mica were found in the soil sub-layers after Lima et al. assessed the Terra Preta's numerous qualities (Lima et al., 2002). There are several types of acido-bacteria, and the Terra Preta has a 25% greater diversity of bacterial species than other soils (Kim et al., 2007).

## 2. Biochar and its Characteristics:

According to Tan et al. (2015, 2016), biochar is a carbon-rich solid produced by heating biomass with minimal or no oxygen. It has a functional group, a porous carbonaceous structure, and an aromatic surface. An efficient waste management solution can be obtained from various origins, including agricultural, kitchen, forest-related, industry-generated, or animal-related waste. The techniques involved in production encompass torrefaction, gasification, pyrolysis, and hydrothermal/flash carbonization (Hu et al., 2021). Among these methods, pyrolysis stands out as the most widely embraced option due to its straightforwardness, substantial output, and economical nature (Uday et al., 2022). Biochar is typically made from waste residues including animal manures, agricultural wastes, and forestry wastes. These feedstocks are important because they have the ability to turn waste into biochar, which is a useful and valuable product (Brewer et al., 2014). The usual pyrolysis temperature is between 200 to 800°C (Hossain et al., 2011; Song et al., 2012). At 300°C, *Lantanacamura* was used to make biochar that was high in accessible P (0.64 mg/kg), Ca (5880 mg/kg), Mg (1010 mg/kg), and Na (1145 mg/kg) (Antonangelo et al., 2019). A large amount of N ranging from 23 to 635 mg/kg and P ranging from 46 to 1664 mg/kg can be released from freshly made biochar, which is a rich source of readily available nutrients (Jiang et al., 2019). After a day, biochar made from mallee wood was easily drainable with double-distilled water (15-20% Ca, 10-60% P, and 2% N) (Wang et al., 2020). These examples show that biochar may have an impact on soil nutrient levels.

Biochar's adsorption capabilities are influenced by its physical and chemical characteristics. Biochar has extremely high specific surface area, oxygen-containing functional group content, and stability (Huang et al., 2016). The major influences on the physicochemical properties of biochar are the feedstock and pyrolysis temperature (Cantrell et al., 2012).

- i. **Surface area-** Biochar's specific surface area is crucial since it aids in the adsorption of chemicals (Inyang et al., 2012; Zhao et al., 2013). When the pyrolysis temperature was raised from 250 to 600°C, the surface area of sugarcane bagasse biochar raised from 0.56 to 14.1 m<sup>2</sup>/g (Ding et al., 2014). The release of volatiles from the biochar increases with the rise in pyrolysis temperature, which could be one explanation (Liu et al., 2014). Additionally, the feedstock used affects the biochar's surface area (Lee et al., 2013). The biochar's specific surface area and pore structure can be improved by increasing the creation of vascular bundle structures as a result of the release of volatile matter, which is mostly created from celluloses and hemicelluloses during pyrolysis (Li et al., 2013).

- ii. **Surface functional group-** The amount of hydrogen and oxygen, as well as the molar hydrogen to carbon (H/C) ratio, decrease as the pyrolysis temperature rises. High temperatures also significantly boost the removal efficiency of polar functional groups (-OH and C-O) (Ahmad et al., 2012). As the pyrolysis temperature rises, the molar oxygen to carbon (O/C) ratio declines, resulting in a greater aromatic and lower hydrophilic surface (Chen et al., 2008).
- iii. **Cation exchange capacity-** Low nutrient loss from soils can be achieved with high biochar CEC (Steiner et al., 2008). When the pyrolysis temperature was raised from 200 to 550°C, the CEC of biochar made from cordgrass appeared to grow from 8.1 to 44.5 cmol(p+)/kg and then fall to 32.4 cmol(p+)/kg (Harvey et al., 2011). The CEC of the sugarcane bagasse biochar increased from 6.40 cmol(p+)/kg at 250°C to 9.66 cmol(p+)/kg at 500°C before decreasing to 4.19 cmol(p+)/kg at 600°C (Ding et al., 2014).
- iv. **pH value-**Applying biochar can increase the pH of the soil due to the pH of the material itself and by enhancing the retention of cations in the soil (Novak et al., 2009; Sohi et al., 2010). Because alkali salts are released from the organic matrix of the feedstock as the temperature of the biochar is increased, the pH of the resulting material is higher (Ahmad et al., 2012). For instance, the pH level of biochar generated from maize straw increased from 9.37 to 11.32 when the pyrolysis temperature was elevated from 300 to 600°C (Yuan et al., 2011). Due to their tendency to be more alkaline, biochar made from agricultural wastes aids in raising the pH of soils (Joseph et al., 2010). Contrarily, because of the functional groups that animal wastes give, biochars made from materials like chicken litter or cow manure are much more acidic (Solaiman et al., 2015).
- v. **Biochar stability-** Increasing pyrolysis temperatures will increase biochar's stability (Rodon et al., 2007; Mašek et al., 2013). For instance, the stability of sugarcane bagasse biochar was significantly increased by increasing the pyrolysis temperature from 350 to 550°C. Additionally, biochar made from chicken manure had less stability than biochar made from sugarcane (Cross and Sohi, 2013). Biochar created at low temperatures can often be easily degraded, however biochar produced at high temperatures is resistant to degrading.
- vi. **Water Holding Capacity-** When biochar and fertilizer were applied together; there was a 14.6% increase in water content, demonstrating the importance of this porosity in increasing soil water capacity (Agegnehu et al., 2017). An average increase in WHC of roughly 18% results from the addition of biochar (Yu et al., 2013). It was interesting to note that 9.52% weight of sunflower husk biochar resulted in a 30% improvement in water retention capacity (Gluba et al., 2021).
- vii. **Electrical Conductivity-** Biochar's EC can range greatly between 0.04 and 54.2 dSm<sup>-1</sup> (Rajkovich et al., 2012; Smider and Singh, 2014). The reaction of biochar with water, which releases soluble chemicals, is thought to be the cause of the rise in EC (Joseph et al., 2021). According to studies, adding biochar causes the electrical conductivity of acidic red colored soil to rise (Pandian et al., 2016). Reduced EC in saline soils may result from the physical entrapment of salts inside the pores of biochar (Thomas et al., 2013).

The pH of the soil was raised and dissolved organic matter was released when biochar made from cacao shell and rice husk was heated to 600 and 500°C, respectively (Mandal et al., 2021). Humic and fulvic acids' carbon content increased when 10% of biochar made from cow and poultry manure was added to a composting mixture (Jain et al., 2018). Corn straw

and mushroom trash can be added to charcoal to hasten the biodegradation of polycyclic aromatic hydrocarbons (Ding et al., 2016). The richness in organic carbon and alkaline nature of biochar also improve CEC, which increases the capacity to adsorb heavy metals (Gul et al., 2015). Biochar could increase porosity by 14 to 64% while reducing soil bulk density by 3 to 31%. Ma et al. (2016) reported a 35% increase in the MWD following the application of 8 Mg ha<sup>-1</sup> biochar derived from corn straw and peanut hulls in China's clay loam soil. Due to its macropores and reduced surface area, it demonstrates a promising behavior of water and nutrient holding capacity in sandy soil (Radwan et al., 2020). Biochar therefore has multifaceted role in agricultural systems (Fig 1).

### 3. Effect of biochar on soil microbes:

The kind of soil and crop has an impact on how biochar affects the activity of soil bacteria (Uzoma et al., 2021). In comparison to untreated soils, the diversity of the soil bacterial population increased by 25% after biochar amendment (Otsuka et al., 2008). The application of rice straw biochar greatly reduced the Actinobacteria and Ascomycota fungal communities (Farrell et al., 2013). When combined with PGPR, rice husk biochar applied at a rate of 3.6 g/kg soil was able to considerably boost rice plant output (Singh et al., 2016). Phosphorus and nitrogen uptake by maize plants were increased by 61.5% and 23.1%, respectively, by biochar in conjunction with *Lysinibacillus fusiformis* (Rafique et al., 2017). Rice plants' susceptibility to root knot nematode (Huang et al., 2017) and *Fusarium* chlamydospore infection in tomato plants (Akhter et al., 2015) were both significantly reduced by biochar. With the help of defence-related gene expression, the biochar amendment may result in systemic resistance to fungi (Harel et al., 2012).

Increased levels of phenol oxidase and  $\beta$ -glucosidase were seen in mangrove sediments after biochar additions, while levels of peroxidase, N-acetyl-glucosaminidase, and acid phosphatase were decreased (Luo and Gu, 2016). Acid phosphatase (32%), alkaline phosphatase (22.8%), and fluorescein hydrolases (50%) showed the greatest increases in soil enzyme activity when *Eichornia* biochar was applied at a concentration of 20 g/kg soil (Masto et al., 2013; Du et al., 2014).

Research initiatives revealed that 88.6% of L-cyfluthrin was degraded within 5 days by *Brevibacterium aureum* DG-12, a novel bacterial strain discovered in active sludge that can breakdown and use cyfluthrin as a growth substrate (Chen et al., 2013).  $\alpha$ -endosulfan,  $\beta$ -endosulfan, and endosulfan sulfate were all digested to 94.1%, 84.5%, and 80.1%, respectively by *Achromobacter xylosoxidans* strain C8B. Microbial consortia may be an environmentally benign technique for pesticide breakdown (Singh and Singh, 2011).

### 4. Integrating biochar with soil fertility:

The incorporation of biochar improves soil fertility (Table 1) by facilitating the biological cycle of phosphorus and nitrogen (Gul and Whalen, 2016). The nitrogen fixation rose from 50% to 72% with the addition of 90 g/kg of biochar (Rondon et al., 2007). It appears that nitrogen, in the form of NH<sub>3</sub>, is less likely to leach when using biochar. The addition of biochar to soil has significant effects on the ammonium (NH<sub>4</sub><sup>+</sup>) concentration through various processes, including NH<sub>4</sub><sup>+</sup> assimilation and conversion to nitrate (NO<sub>3</sub><sup>-</sup>) (Harter et al., 2014). Biochar effectively absorbs NH<sub>4</sub><sup>+</sup> through oxygenated carbonyl and carboxyl groups, reducing its availability for nitrification and leading to higher soil NO<sub>3</sub><sup>-</sup> levels (Abbruzzini et al., 2019). Applying wheat straw biochar at rates of 0.5% to 1% was sufficient to stop various types of N leaching (Sun et al., 2017). It may be simple to increase the organic matter content of soils by using biochar (Laskosky et al., 2020). For crops unable to fix their own nitrogen, biochar also increases the amount of nitrogen available for plant absorption (Zheng et al.,

2013). Biochar improved soil organic matter's physical security by enhancing C storage in macroaggregates of the fine-coarse soil (Zimmerman, 2010). Sandalwood biochars from *Eucalyptus saligna* improved the mineralization of native organic C, but not in soil with a clayey texture (Jien & Wang, 2013). Biochar works as a retaining agent for P and stops P from sandy soil from leaching or running off (Glaser & Lehr, 2019; Dharmakeerthi et al., 2019). Due to the substantial soil nutrient absorption by biochar, it acts as a slow-release fertilizer (Dal et al., 2020). If the soil has a coarse texture and little organic matter, biochar is a viable amendment for stabilizing aggregates (Pituello et al., 2018). When forming aggregates and preventing soil deterioration, biochar may operate as a binding agent for organic materials (Verheijen et al., 2010). The slow oxidation properties of biochar provide the basis for the long-term effects on soil aggregation (Patel et al., 2015). The majority of the time, plants can easily absorb the potassium present in biochar from its original source (Joseph et al., 2010). Biochar application not only enhances soil K availability but also stimulates the proliferation of potassium-dissolving bacteria in Alfisols and Entisols. This, in turn, results in increased K availability, reducing the need for additional mineral K fertilizers (Singh et al., 2019). The number of cyanobacteria associated with nitrogen fixation & saccharibacteria engaged in organic compound breakdown increased due to the usage of biochar-based fertilizers, thereby improving soil fertility (Liao et al., 2020). The result has positive influence in crop yield and production as well (Table 2).

#### **5. Effect of biochar on soil quality:**

Soil quality plays a significant role in improving the status of crop.  $\text{Na}^+$  ions reduce the salinity of the soil; biochar binds to the  $\text{Na}^+$  ions and prevents the plant from absorbing them (Akhtar et al., 2015). In order to increase the development of maize, the excessive salinity of central Chinese soils was reduced using a mixture of wheat straw biochar and poultry manure (Lashari et al., 2013). The use of maize stalk biochar increased partial factor production and agronomic efficiency for nitrogen in calcareous sandy soils with zucchini plants, but had no discernible impacts on phosphorus (Amin and Eissa, 2017). The amount of ammonia-oxidizing bacteria in acidic soils was decreased by biochar (Wang et al., 2015). In acidic red soils, adding 10 g/kg of rice straw biochar raised the pH, P availability, and  $\text{Al}^{3+}$  reduced exchangeable (Zhu et al., 2014).

When biochar was added to soil, the impacts of a higher pH, dispersed metal ions that were liberated, and the active groups on mineral surfaces all worked together to catalyse the hydrolysis of pesticides. According to Zhang et al. (2013), biochar generated from pig manure can hydrolyze carbaryl and atrazine at 350 and 700°C with a result of 59.1% and 90.6%, respectively. Due to the catalytic properties of biochar, pesticide hydrolysis may be enhanced; however, the increased pesticide sorption may impede this improvement. When pig dung biochar produced at 350 °C after 40 days of incubation was applied at a rate of 0.5%, the breakdown efficiency of carbaryl increased from 55.0% to 75.0% in the unsterile soil (Ren et al., 2016). By affecting the sorption and desorption processes, biochar decreased the microbial atrazine mineralization, hence lowering the atrazine's bioavailability (Loganathan et al., 2009). In soil that has been altered with biochar, pesticide mobility, volatilization, leaching, and uptake by plants can all be reduced (Chen et al., 2009). The characteristics of biochar, including its level of organic carbon, fragrance, specific surface area, and ash content, have a significant impact on its capacity to bind pesticides (Fang et al., 2014).

Metals in a soil are immobilized by biochar because of its lower particle size. This immobilization is brought on by the biochar's increased surface area, which finally results in less metal absorption by plant tissues (Zhang et al., 2013). When applied at 5%, tobacco stalk

biochar decreased the uptake of Cd and Zn by 64.2 and 94.9%, respectively (Yang et al., 2017). Rice grain methyl mercury content was decreased by applying biochar made from rice straw and heated to 600 °C at concentrations of 1% to 4% by 49-92% (Shu et al., 2016). Rice plants took up less As when Mn modified biochar was applied to As-contaminated soil, and the amount of amino acids rose by 9% (Yu et al., 2017). Using biochar in conjunction with other chemicals, including limestone, decreased the uptake of Cd in wheat and rice plant straw and grain by more than 80% (Rehman et al., 2017). Plant uptake of metals was frequently decreased by applying biochar at depths of 0 to 15 cm (Forjan et al., 2017). The amount of chlorpyrifos and fipronil that *Allium tuberosum* absorbed after being exposed to soil with 1% straw chip biochar was reduced by 19 and 48%, respectively (Yang et al., 2010). Chinese cabbage plants' uptake of PAHs was reduced when wheat straw biochar was added at a rate of 2% (Peng et al., 2017). The absorption of nanoparticles of cerium oxide by zucchini crops could also be decreased by applying biochar made from pecan shells at a rate of 5% (Servin et al., 2017).

Polar gases, water-soluble metals, and different organic contaminants are normally all absorbed by biochar (Ahmad et al., 2014; Tan et al., 2015). Generally speaking, biochars with greater aromatic qualities and greater C condensation are more resilient (Lehmann et al., 2015). Biochar efficiently binds heavy metal cations from water and immobilizes elements of heavy metal in soil (Guo et al., 2010; Ahmad et al., 2014; Tan et al., 2015; O'Connor et al., 2018). By interacting with the applied biochar and adhering to the pore surfaces, heavy metal ions in the soil may be changed into hydroxides, carbonates, and phosphate precipitates (Fig 2). As a result of this process, the proportion of heavy metals those are water-soluble and bioactive in soil drops, which diminish their potential for uptake and bioaccumulation by soil organisms, including plant roots (Ahmad et al., 2014). By exchanging the cations that were previously connected to its surface functional units through ion exchange, biochar is able to adsorb heavy metal ions from the soil solution (Fidel et al., 2018). Biochar sorbs Cd, Cu, Ni, and Pb mostly through surface complexation, which makes use of ligand-like surface functional elements like carboxylic, hydroxyl, and phenolic groups (Uchimiya et al., 2011). The addition of alkalinity from biochar often results in an increase in soil pH. Increased pH promotes heavy metal hydrolysis, which results in the creation of metal hydroxide precipitates. This lowers the amount of metal ions that is soluble in water and helps minimize soil heavy metal contamination (Ippolito et al., 2017). Organic non-ionic compounds are adsorbable on biochar via surface adsorption along with partitioning. Because of their higher surface energy, biochar micropores are where the adsorption of organic pollutants begins (Uchimiya et al., 2011). Metal ions can combine with polar and charged organic molecules to produce complexes that can either be deposited on the surface of the biochar or precipitate in the soil (Tan et al., 2015).

## **6. Effect of biochar on greenhouse gases:**

Biochar is also considered as a boon as it is possible to reduce CO<sub>2</sub> emissions by 1.67 tonnes of CO<sub>2</sub> equivalent every tonne of feedstock utilized during application (Tisserant and Cherubini, 2019). It is important to note that woody biomass-derived biochar delivers greater emission reductions because of its increased energy content, which can counteract GHG emissions created during the biomass burning process (Lehmann et al., 2021). The concentration of soil organic carbon (SOC) is also affected by the maturation of biochar in the soil. For instance, Zhang et al. (2016) found that the application of wheat straw biochar (40 Mg ha<sup>-1</sup>) in rice fields led to a 57% increase in SOC concentrations. In calcareous soil with low OC, Zhang et al. (2013) reported that addition of biochar at 20 and 40 Mg ha<sup>-1</sup> integrated with nitrogen fertilizers increased SOC by 25 to 42.2%. It was proposed that biochar might deliver a maximum of 15-35% of the carbon dioxide reduction target by using

residue biomass and growing additional crops expressly for biochar production (Tisserant and Cherubini, 2019). Additionally, iron- or calcium-treated biochar demonstrated its value in increasing the stability of soil aggregates and lowering carbon emissions with improved carbon sequestration abilities (Liu et al., 2020). Because biochar decomposes organic carbon more slowly than straw biomass, applying it to paddy fields minimizes CH<sub>4</sub> emissions from those areas (Lehmann et al., 2021). The addition of biochar leads in less CH<sub>4</sub> being released from the carbonaceous substances than straw biomass and inhibits the spread of methanogenic bacteria by providing a comfortable environment in its porous structure (Jeffery et al., 2016; Wu et al., 2019).

Additionally, biochar enhances the production of N<sub>2</sub>O reductase genes in denitrifying bacteria and encourages microbial N immobilization (Lehmann et al., 2021). This makes it easier for N<sub>2</sub>O to be converted to N<sub>2</sub> during denitrification, which lowers emissions of N<sub>2</sub>O from soil (Cayuela et al., 2013). N<sub>2</sub>O emissions dropped by 50% after the addition of wood biochar formed at 350 °C and 700 °C biochar, respectively (Ameloot et al., 2013). Utilizing biochar made from pine, willow, and corn, which were all created at 550 °C, decreased N<sub>2</sub>O emissions by around 40%, 46%, and 60%, accordingly (Nelissen et al., 2014). Higher-temperature biochars were more effective at lowering the release of N<sub>2</sub>O than NO emissions, and lower-temperature biochars are more effective at lowering NO emissions. Crop yields increased and N<sub>2</sub>O emissions decreased after straw-derived biochar was added to sandy-loam soils for a five-year wheat and maize crop rotation, but total GWP did not change (Liu et al., 2020). It is believed that biochar will have the ideal characteristics for preventing global warming and changing the climate (Downie et al., 2012). Numerous research support the idea that applying biochar to areas used for cultivating vegetables will significantly reduce emissions of carbon dioxide, N<sub>2</sub>O, and methane gasses (Sun et al., 2014; Hale et al., 2020).

## **7. Effect of biochar in sustainability:**

Littfouse et al. (2009) revealed the concept of "sustainable agriculture" as the combination of socioeconomic research with biological, chemical, physical, and ecological functions in order to create new agricultural techniques that are secure and ecologically sound. By conserving and upholding all of its natural resources, such as conserving soil fertility, protecting surface and below-ground assets, creating renewable energy sources, and looking for ways to adapt farming practices to climate change, sustainable agriculture enables agro farming to sustain itself over an extended period of time (Jala et al., 2020; Akhtar et al., 2020). Agro farming needs to take social groupings and the environment's sustainability into account.

The main challenges facing the existing agrofarming methods are to increase crop yield in a way that is environmentally sound and sustainable (Hamilton et al., 2016; Srivastav, 2020). A more sustainable approach to farming will lessen the need for organic fertilizers and maintain the productivity of agriculture. The majority of current biochar research focuses on modifying the material's characteristics to improve its ability to remove both organic as well as inorganic contaminants (De Boer & Kowalchuk, 2001). Biochar exhibits amazing efficacy in decreasing contaminants including antibacterial agents, herbicides, pigments, pesticides, and heavy metals due to its outstanding surface properties, and it is essential in addressing the effects of climate change (Schiermeier, 2006). The extraordinary ability of biochar to immobilize rhizospheric heavy metals and agricultural pesticides on its vast surface and prevent their uptake by crops increases crop production (Bolan et al., 2013). It has been demonstrated that adding biochar reduces the soil's maximum hydraulic conductivity, particularly in light-textured soils (Brockhoff et al., 2010; Lehmann et al., 2003).

## **8. Limitations of the use of biochar:**

There are several restrictions even if the majority of research data demonstrated the advantages of biochar treatments. Additionally, *Oryza sativa* and *Solanum lycopersicum*'s subsurface root biomass decreased in response to aged biochar (Anyanwu et al., 2018). It has been demonstrated that biochar has favourable soil-specific impacts (Zhu et al., 2015). Using biochar at a high level in lentil cultivation caused the development of weeds to rise by 200% (Safaei Khorram et al., 2018). Implementation of biochar may also cause plants to blossom later (Hol et al., 2017). **In saline and sodic soil**, applying biochar and phosphorus fertilizer together may speed up the phosphate precipitation/sorption processes. This interaction may ultimately result in the plants' access to phosphorus being reduced (Xu et al., 2016). It has been demonstrated that the biochar source's contamination is harmful for crop development (Jones and Quilliam, 2014). Based on the kind, quantity, kind of soil, crop variety, etc. of the biochar amendment, beneficial as well as detrimental impacts on crop production and fertility fluctuations might occur.

### **9. Future line of research: use of nano biochar:**

**Recently a number of studies have been done on the sustainable production of nano-biochar for land and agricultural use.** A micro-sized biochar known as "dissolve" and "nano-biochar" is created during the carbonization process. It has dimensions less than or equal to a micrometer and up to a nanometer. Recent research produced nano-biochar with a diameter <5 nm. The structural modifications and physico-chemical properties of bulk biochar and nanobiochar differ from one another. The elemental compositions, aromatic/polar nature, pH, CEC, specific surface area (SSA), pore properties, and zeta potential of nano-biochar can all vary. Nano-biochar is also available in soluble and insoluble forms. Dairy manure biochar generally has **a soluble carbon concentration of 14% at 100°C to about 0.2% at 700°C**, with the soluble carbon content usually rising according to rising solvent pH and decreasing with rising pyrolysis temperature. As a result of rising instances of environmental degradation and decreased crop productivity caused by shifting climatic circumstances, nano-biochar becomes increasingly intriguing (Chen et al., 2015; Liu et al., 2018; Rajput et al., 2022).

### **10. Conclusions:**

**Biochar shines as a ray of hope in our pursuit of sustainable farming, improved soil health, vigorous cultivation, and efficient climate change management.** Its many advantages, including increased nutrient retention, less release of greenhouse gases, and greater soil capacity to hold water, offer a positive vision for a more robust and environmentally conscientious agricultural destiny. We can lessen our impact on our surroundings, repair damaged soils, and equip farmers to meet the hurdles of a changing climate by incorporating biochar into our farming practices. With the use of biochar, we may conserve nature without sacrificing crop output by delaying the release of resources. Biochar must be seen as more than just a fix—it must be seen as a road toward a more peaceful living with our planet as we work to fully realize its potential through continued study and creative use. We can make a big step towards sustainable farming, better ecosystems, and a more sustainable planet for future generations by embracing biochar.

### **Reference**

- Abbruzzini, T.F., Davies, C.A., Toledo, F.H., & Cerri, C.E.P. (2019). Dynamic biochar effects on nitrogen use efficiency, crop yield and soil nitrous oxide emissions during a tropical wheat-growing season. *Journal of Environmental Management*, 252, 109638.**
- Agegnehu, G., Srivastava, A. K., & Bird, M. I. (2017). The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Applied soil ecology*, 119, 156-170.

- Ahmad, M., Lee, S. S., Dou, X., Mohan, D., Sung, J. K., Yang, J. E., & Ok, Y. S. (2012). Effects of pyrolysis temperature on soybean stover-and peanut shell-derived biochar properties and TCE adsorption in water. *Bioresource technology*, *118*, 536-544.
- Ahmad, M., Rajapaksha, A. U., Lim, J. E., Zhang, M., Bolan, N., Mohan, D., ... & Ok, Y. S. (2014). Biochar as a sorbent for contaminant management in soil and water: a review. *Chemosphere*, *99*, 19-33.
- Akhtar, K., Wang, W., Ren, G., Khan, A., Enguang, N., Khan, A., ... & Wang, H. (2020). Straw mulching with inorganic nitrogen fertilizer reduces soil CO<sub>2</sub> and N<sub>2</sub>O emissions and improves wheat yield. *Science of the Total Environment*, *741*, 140488.
- Akhtar, S. S., Andersen, M. N., & Liu, F. (2015). Residual effects of biochar on improving growth, physiology and yield of wheat under salt stress. *Agricultural Water Management*, *158*, 61-68.
- Akhter, A., Hage-Ahmed, K., Soja, G., & Steinkellner, S. (2015). Compost and biochar alter mycorrhization, tomato root exudation, and development of *Fusarium oxysporum* f. sp. *lycopersici*. *Frontiers in Plant Science*, *6*, 529.
- Alling, V., Hale, S. E., Martinsen, V., Mulder, J., Smebye, A., Breedveld, G. D., & Cornelissen, G. (2014). The role of biochar in retaining nutrients in amended tropical soils. *Journal of Plant Nutrition and Soil Science*, *177*(5), 671-680.
- Ameloot, N., De Neve, S., Jegajeevagan, K., Yildiz, G., Buchan, D., Funkuin, Y. N., ... & Sleutel, S. (2013). Short-term CO<sub>2</sub> and N<sub>2</sub>O emissions and microbial properties of biochar amended sandy loam soils. *Soil Biology and Biochemistry*, *57*, 401-410.
- Amin, A. E. E. A. Z., & Eissa, M. A. (2017). Biochar effects on nitrogen and phosphorus use efficiencies of zucchini plants grown in a calcareous sandy soil. *Journal of soil science and plant nutrition*, *17*(4), 912-921.
- Antonangelo, J. A., & Zhang, H. (2019). Heavy metal phytoavailability in a contaminated soil of northeastern Oklahoma as affected by biochar amendment. *Environmental Science and Pollution Research*, *26*, 33582-33593.
- Anyanwu, I. N., Alo, M. N., Onyekwere, A. M., Crosse, J. D., Nworie, O., & Chamba, E. B. (2018). Influence of biochar aged in acidic soil on ecosystem engineers and two tropical agricultural plants. *Ecotoxicology and environmental safety*, *153*, 116-126.
- Ayaz, M., Feizienė, D., Tilvikienė, V., Akhtar, K., Stulpinaitė, U., & Iqbal, R. (2021). Biochar role in the sustainability of agriculture and environment. *Sustainability*, *13*(3), 1330.
- Azeem, M., Hayat, R., Hussain, Q., Ahmed, M., Pan, G., Tahir, M. I., ... & Irfan, M. (2019). Biochar improves soil quality and N<sub>2</sub>-fixation and reduces net ecosystem CO<sub>2</sub> exchange in a dryland legume-cereal cropping system. *Soil and Tillage Research*, *186*, 172-182.
- Boersma, M., Wrobel-Tobiszewska, A., Murphy, L., & Eyles, A. (2017). Impact of biochar application on the productivity of a temperate vegetable cropping system. *New Zealand Journal of Crop and Horticultural Science*, *45*(4), 277-288.
- Bolan, N. S., Choppala, G., Kunhikrishnan, A., Park, J., & Naidu, R. (2013). *Microbial transformation of trace elements in soils in relation to bioavailability and remediation* (pp. 1-56). Springer New York.
- Brewer, C. E., Chuang, V. J., Masiello, C. A., Gonnermann, H., Gao, X., Dugan, B., ... & Davies, C. A. (2014). New approaches to measuring biochar density and porosity. *Biomass and bioenergy*, *66*, 176-185.
- Brockhoff, S. R., Christians, N. E., Killorn, R. J., Horton, R., & Davis, D. D. (2010). Physical and mineral- nutrition properties of sand- based turfgrass root zones amended with biochar. *Agronomy Journal*, *102*(6), 1627-1631.

- Cantrell, K. B., Hunt, P. G., Uchimiya, M., Novak, J. M., & Ro, K. S. (2012). Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. *Bioresource technology*, *107*, 419-428.
- Cayuela, M. L., Jeffery, S., & van Zwieten, L. (2015). The molar H: Corg ratio of biochar is a key factor in mitigating N<sub>2</sub>O emissions from soil. *Agriculture, Ecosystems & Environment*, *202*, 135-138.
- Chen, B., Zhou, D., & Zhu, L. (2008). Transitional adsorption and partition of nonpolar and polar aromatic contaminants by biochars of pine needles with different pyrolytic temperatures. *Environmental science & technology*, *42*(14), 5137-5143.
- Chen, H., He, X., Rong, X., Chen, W., Cai, P., Liang, W., ... & Huang, Q. (2009). Adsorption and biodegradation of carbaryl on montmorillonite, kaolinite and goethite. *Applied clay science*, *46*(1), 102-108.
- Chen, S., Dong, Y. H., Chang, C., Deng, Y., Zhang, X. F., Zhong, G., ... & Zhang, L. H. (2013). Characterization of a novel cyfluthrin-degrading bacterial strain *Brevibacterium aureum* and its biochemical degradation pathway. *Bioresource technology*, *132*, 16-23.
- Chen, T., Zhou, Z., Xu, S., Wang, H., & Lu, W. (2015). Adsorption behavior comparison of trivalent and hexavalent chromium on biochar derived from municipal sludge. *Bioresource technology*, *190*, 388-394.
- Cross, A., & Sohi, S. P. (2013). A method for screening the relative long-term stability of biochar. *Gcb Bioenergy*, *5*(2), 215-220.
- Dai, Y., Wang, W., Lu, L., Yan, L., & Yu, D. (2020). Utilization of biochar for the removal of nitrogen and phosphorus. *Journal of Cleaner Production*, *257*, 120573.
- De Boer, W., & Kowalchuk, G. A. (2001). Nitrification in acid soils: micro-organisms and mechanisms. *Soil Biology and Biochemistry*, *33*(7-8), 853-866.
- Dharmakeerthi, R. S., Kumaragamage, D., Goltz, D., & Indraratne, S. P. (2019). Phosphorus release from unamended and gypsum- or biochar- amended soils under simulated snowmelt and summer flooding conditions. *Journal of environmental quality*, *48*(4), 822-830.
- Ding, W., Dong, X., Ime, I. M., Gao, B., & Ma, L. Q. (2014). Pyrolytic temperatures impact lead sorption mechanisms by bagasse biochars. *Chemosphere*, *105*, 68-74.
- Ding, Y., Liu, Y., Liu, S., Li, Z., Tan, X., Huang, X., ... & Zheng, B. (2016). Biochar to improve soil fertility. A review. *Agron Sustain Dev* *36*: 36.
- Downie, A., Munroe, P., Cowie, A., Van Zwieten, L., & Lau, D. M. (2012). Biochar as a geoengineering climate solution: hazard identification and risk management. *Critical reviews in environmental science and technology*, *42*(3), 225-250.
- Du, Z., Wang, Y., Huang, J., Lu, N., Liu, X., Lou, Y., & Zhang, Q. (2014). Consecutive biochar application alters soil enzyme activities in the winter wheat-growing season. *Soil Science*, *179*(2), 75-83.
- Fang, Q., Chen, B., Lin, Y., & Guan, Y. (2014). Aromatic and hydrophobic surfaces of wood-derived biochar enhance perchlorate adsorption via hydrogen bonding to oxygen-containing organic groups. *Environmental science & technology*, *48*(1), 279-288.
- Farrell, M., Kuhn, T. K., Macdonald, L. M., Maddern, T. M., Murphy, D. V., Hall, P. A., ... & Baldock, J. A. (2013). Microbial utilisation of biochar-derived carbon. *Science of the Total Environment*, *465*, 288-297.
- Fidel, R. B., Laird, D. A., and Spokas, K. A. (2018). Sorption of ammonium and nitrate to biochars is electrostatic and pH-dependent. *Sci. Rep.* *8*:17627. doi: 10.1038/s41598-018-35534-w

- Forján, R., Rodríguez-Vila, A., Cerqueira, B., & Covelo, E. F. (2017). Comparison of the effects of compost versus compost and biochar on the recovery of a mine soil by improving the nutrient content. *Journal of Geochemical Exploration*, 183, 46-57.
- Glaser, B., & Birk, J. J. (2012). State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de Índio). *Geochimica et Cosmochimica acta*, 82, 39-51.
- Glaser, B., & Lehr, V. I. (2019). Biochar effects on phosphorus availability in agricultural soils: A meta-analysis. *Scientific reports*, 9(1), 9338.
- Gluba, Ł., Rafalska-Przysucha, A., Szewczak, K., Łukowski, M., Szlązak, R., Vitková, J., ... & Usowicz, B. (2021). Effect of fine size-fractionated sunflower husk biochar on water retention properties of arable sandy soil. *Materials*, 14(6), 1335.
- Güereña, D., Lehmann, J., Hanley, K., Enders, A., Hyland, C., & Riha, S. (2013). Nitrogen dynamics following field application of biochar in a temperate North American maize-based production system. *Plant and soil*, 365, 239-254.
- Gul, S., & Whalen, J. K. (2016). Biochemical cycling of nitrogen and phosphorus in biochar-amended soils. *Soil Biology and Biochemistry*, 103, 1-15.
- Gul, S., Whalen, J. K., Thomas, B. W., Sachdeva, V., & Deng, H. (2015). Physico-chemical properties and microbial responses in biochar-amended soils: mechanisms and future directions. *Agriculture, Ecosystems & Environment*, 206, 46-59.
- Guo, M., Qiu, G., and Song, W. (2010). Poultry litter-based activated carbon for removing heavy metal ions in water. *Waste Manage.* 30, 308–315. doi: 10.1016/j.wasman.2009.08.010
- Hale, S. E., Nurida, N. L., Mulder, J., Sørmo, E., Silvani, L., Abiven, S., ... & Cornelissen, G. (2020). The effect of biochar, lime and ash on maize yield in a long-term field trial in a Ultisol in the humid tropics. *Science of the Total Environment*, 719, 137455.
- Hamilton, C. E., Bever, J. D., Labbé, J., Yang, X., & Yin, H. (2016). Mitigating climate change through managing constructed-microbial communities in agriculture. *Agriculture, ecosystems & environment*, 216, 304-308.
- Harter, J., Krause, H.M., Schuettler, S., Ruser, R., Fromme, M., Scholten, T., Kappler, A., & Behrens, S. (2014). Linking N<sub>2</sub>O emissions from biochar-amended soil to the structure and function of the N-cycling microbial community. *The ISME Journal*, 8(3), 660-674.
- Harvey, O. R., Herbert, B. E., Rhue, R. D., & Kuo, L. J. (2011). Metal interactions at the biochar-water interface: energetics and structure-sorption relationships elucidated by flow adsorption microcalorimetry. *Environmental science & technology*, 45(13), 5550-5556.
- Hol, W. G., Vestergård, M., ten Hooven, F., Duyts, H., van de Voorde, T. F., & Bezemer, T. M. (2017). Transient negative biochar effects on plant growth are strongest after microbial species loss. *Soil Biology and Biochemistry*, 115, 442-451.
- Hossain, M. K., Strezov, V., Chan, K. Y., Ziolkowski, A., & Nelson, P. F. (2011). Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar. *Journal of environmental management*, 92(1), 223-228.
- Hu, F., Xu, C., Ma, R., Tu, K., Yang, J., Zhao, S., Yang, M., & Zhang, F. (2021). Biochar application driven change in soil internal forces improves aggregate stability: Based on a two-year field study. *Geoderma*, 403, 115276.
- Huang, X., Liu, Y., Liu, S., Tan, X., Ding, Y., Zeng, G., ... & Zheng, B. (2016). Effective removal of Cr (VI) using  $\beta$ -cyclodextrin–chitosan modified biochars with adsorption/reduction bifunctional roles. *RSC advances*, 6(1), 94-104.

- Huang, Z., Lu, Q., Wang, J., Chen, X., Mao, X., & He, Z. (2017). Inhibition of the bioavailability of heavy metals in sewage sludge biochar by adding two stabilizers. *PloS one*, *12*(8), e0183617.
- Ilvo, P.; Uog, P.; Slu, P.; Inra, P.; Upm, P.; Unitus, P.; Iamo, P.; Iea-ar, P. D5.2 Participatory Impact Assessment of Sustainability and Resilience of EU Farming Systems. 2019. No. June 2017
- Inyang, M., Gao, B., Yao, Y., Xue, Y., Zimmerman, A. R., Pullammanappallil, P., & Cao, X. (2012). Removal of heavy metals from aqueous solution by biochars derived from anaerobically digested biomass. *Bioresource technology*, *110*, 50-56.
- Ippolito, J. A., Berry, C. M., Strawn, D. G., Novak, J. M., Levine, J., and Harley, A. (2017). Biochars reduce mine land soil bioavailable metals. *J. Environ. Qual.* *46*, 411–419. doi: 10.2134/jeq2016.10.0388
- Jain, M. S., Jambhulkar, R., & Kalamdhad, A. S. (2018). Biochar amendment for batch composting of nitrogen rich organic waste: Effect on degradation kinetics, composting physics and nutritional properties. *Bioresource Technology*, *253*, 204-213.
- Jalal, F., Arif, M., Akhtar, K., Khan, A., Naz, M., Said, F., ... & Wei, F. (2020). Biochar integration with legume crops in summer gape synergizes nitrogen use efficiency and enhance maize yield. *Agronomy*, *10*(1), 58.
- Jeffery, S., Verheijen, F. G., Kammann, C., & Abalos, D. (2016). Biochar effects on methane emissions from soils: a meta-analysis. *Soil Biology and Biochemistry*, *101*, 251-258.
- Jiang, X., Tan, X., Cheng, J., Haddix, M. L., & Cotrufo, M. F. (2019). Interactions between aged biochar, fresh low molecular weight carbon and soil organic carbon after 3.5 years soil-biochar incubations. *Geoderma*, *333*, 99-107.
- Jien, S. H., & Wang, C. S. (2013). Effects of biochar on soil properties and erosion potential in a highly weathered soil. *Catena*, *110*, 225-233.
- Jones, D. L., & Quilliam, R. S. (2014). Metal contaminated biochar and wood ash negatively affect plant growth and soil quality after land application. *Journal of hazardous materials*, *276*, 362-370.
- Joseph, S. D., Camps-Arbestain, M., Lin, Y., Munroe, P., Chia, C. H., Hook, J., ... & Amonette, J. E. (2010). An investigation into the reactions of biochar in soil. *Soil Research*, *48*(7), 501-515.
- Joseph, S., Cowie, A. L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., ... & Lehmann, J. (2021). How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *Gcb Bioenergy*, *13*(11), 1731-1764.
- Kahil, A. A., Issa, A. A., Al-Sodany, Y. M., & Ali, E. F. (2018). Effects of Biochar Amended Saline Soil on Growth and Some Metabolic Activities of Two Soybean Cultivars in Saudi Arabia. *Annual Research & Review in Biology*, *25*(6), 1–14. <https://doi.org/10.9734/ARRB/2018/41126>
- Kavitha, B., Reddy, P. V. L., Kim, B., Lee, S. S., Pandey, S. K., & Kim, K. H. (2018). Benefits and limitations of biochar amendment in agricultural soils: A review. *Journal of environmental management*, *227*, 146-154.
- Kim, J. S., Sparovek, G., Longo, R. M., De Melo, W. J., & Crowley, D. (2007). Bacterial diversity of terra preta and pristine forest soil from the Western Amazon. *Soil Biology and Biochemistry*, *39*(2), 684-690.
- Lai, W. Y., Lai, C. M., Ke, G. R., Chung, R. S., Chen, C. T., Cheng, C. H., ... & Chen, C. C. (2013). The effects of woodchip biochar application on crop yield, carbon sequestration and greenhouse gas emissions from soils planted with rice or leaf beet. *Journal of the Taiwan Institute of Chemical Engineers*, *44*(6), 1039-1044.

- Laird, D., Fleming, P., Wang, B., Horton, R., & Karlen, D. (2010). Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma*, 158(3-4), 436-442.
- Lashari, M. S., Ye, Y., Ji, H., Li, L., Kibue, G. W., Lu, H., ... & Pan, G. (2015). Biochar–manure compost in conjunction with pyroligneous solution alleviated salt stress and improved leaf bioactivity of maize in a saline soil from central China: a 2- year field experiment. *Journal of the Science of Food and Agriculture*, 95(6), 1321-1327.
- Laskosky, J. D., Mante, A. A., Zvomuya, F., Amarakoon, I., & Leskiw, L. (2020). A bioassay of long- term stockpiled salvaged soil amended with biochar, peat, and humalite. *Agrosystems, Geosciences & Environment*, 3(1), e20068.
- Lee, Y., Park, J., Ryu, C., Gang, K. S., Yang, W., Park, Y. K., ... & Hyun, S. (2013). Comparison of biochar properties from biomass residues produced by slow pyrolysis at 500 C. *Bioresource technology*, 148, 196-201.
- Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. E., ... & Whitman, T. (2021). Biochar in climate change mitigation. *Nature Geoscience*, 14(12), 883-892.
- Lehmann, J., Czimczik, C., Laird, D., and Sohi, S. (2015). “Stability of biochar in soil,” in *Biochar for Environmental Management: Science, Technology and Implementation*. 2nd Edn, J. Lehmann, and S. Joseph (London: Routledge), 183–198.
- Lehmann, J., Pereira da Silva, J., Steiner, C., Nehls, T., Zech, W., & Glaser, B. (2003). Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. *Plant and soil*, 249, 343-357.
- Li, M., Liu, Q., Guo, L., Zhang, Y., Lou, Z., Wang, Y., & Qian, G. (2013). Cu (II) removal from aqueous solution by *Spartina alterniflora* derived biochar. *Bioresource technology*, 141, 83-88.
- Liao, J., Liu, X., Hu, A., Song, H., Chen, X., & Zhang, Z. (2020). Effects of biochar-based controlled release nitrogen fertilizer on nitrogen-use efficiency of oilseed rape (*Brassica napus* L.). *Scientific reports*, 10(1), 11063.
- Lichtfouse, E., Navarrete, M., Debaeke, P., Souchère, V., Alberola, C., & Ménessieu, J. (2009). Agronomy for sustainable agriculture: a review. *Sustainable agriculture*, 1-7.
- Lima, H. N., Schaefer, C. E., Mello, J. W., Gilkes, R. J., & Ker, J. C. (2002). Pedogenesis and pre-Colombian land use of “Terra Preta Anthrosols”(“Indian black earth”) of Western Amazonia. *Geoderma*, 110(1-2), 1-17.
- Liu, H., Xu, G., & Li, G. (2020). The characteristics of pharmaceutical sludge-derived biochar and its application for the adsorption of tetracycline. *Science of The Total Environment*, 747, 141492.
- Liu, X., Zhang, Y., Li, Z., Feng, R., & Zhang, Y. (2014). Characterization of corncob-derived biochar and pyrolysis kinetics in comparison with corn stalk and sawdust. *Bioresource technology*, 170, 76-82.
- Liu, Y., Bi, Y., Xie, Y., Zhao, X., He, D., Wang, S., ... & Xing, G. (2020). Successive straw biochar amendments reduce nitrous oxide emissions but do not improve the net ecosystem economic benefit in an alkaline sandy loam under a wheat–maize cropping system. *Land Degradation & Development*, 31(7), 868-883.
- Liu, Y., Lonappan, L., Brar, S. K., & Yang, S. (2018). Impact of biochar amendment in agricultural soils on the sorption, desorption, and degradation of pesticides: a review. *Science of the total environment*, 645, 60-70.
- Loganathan, V. A., Feng, Y., Sheng, G. D., & Clement, T. P. (2009). Crop- residue- derived char influences sorption, desorption and bioavailability of atrazine in soils. *Soil Science Society of America Journal*, 73(3), 967-974.

- Lu, L., Yu, W., Wang, Y., Zhang, K., Zhu, X., Zhang, Y., ... & Chen, B. (2020). Application of biochar-based materials in environmental remediation: from multi-level structures to specific devices. *Biochar*, 2, 1-31.
- Luo, L., & Gu, J. D. (2016). Alteration of extracellular enzyme activity and microbial abundance by biochar addition: Implication for carbon sequestration in subtropical mangrove sediment. *Journal of environmental management*, 182, 29-36.
- Ma, N., Zhang, L., Zhang, Y., Yang, L., Yu, C., Yin, G., ... & Ma, X. (2016). Biochar improves soil aggregate stability and water availability in a mollisol after three years of field application. *PLOS ONE*, 11(5), e0154091.
- Mandal, S., Pu, S., Adhikari, S., Ma, H., Kim, D. H., Bai, Y., & Hou, D. (2021). Progress and future prospects in biochar composites: Application and reflection in the soil environment. *Critical reviews in environmental science and technology*, 51(3), 219-271.
- Mašek, O., Brownsort, P., Cross, A., & Sohi, S. (2013). Influence of production conditions on the yield and environmental stability of biochar. *Fuel*, 103, 151-155.
- Masto, R. E., Kumar, S., Rout, T. K., Sarkar, P., George, J., & Ram, L. C. (2013). Biochar from water hyacinth (*Eichornia crassipes*) and its impact on soil biological activity. *Catena*, 111, 64-71.
- Meller Harel, Y., Elad, Y., Rav-David, D., Borenstein, M., Shulchani, R., Lew, B., & Graber, E. R. (2012). Biochar mediates systemic response of strawberry to foliar fungal pathogens. *Plant and Soil*, 357, 245-257.
- Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature*, 490(7419), 254-257.
- Muhammad, N., Aziz, R., Brookes, P. C., & Xu, J. (2017). Impact of wheat straw biochar on yield of rice and some properties of Psammaquent and Plinthudult. *Journal of soil science and plant nutrition*, 17(3), 808-823.
- Nansubuga I, Banadda N, Ronsse F, Verstraete W, Rabaey K. Digestion of high rate activated sludge coupled to biochar formation for soil improvement in the tropics. *Water research*. 2015 Sep 15;81:216-22.
- Nelissen, V., Saha, B. K., Ruyschaert, G., & Boeckx, P. (2014). Effect of different biochar and fertilizer types on N<sub>2</sub>O and NO emissions. *Soil Biology and Biochemistry*, 70, 244-255.
- Novak, J. M., Busscher, W. J., Laird, D. L., Ahmedna, M., Watts, D. W., & Niandou, M. A. (2009). Impact of biochar amendment on fertility of a southeastern coastal plain soil. *Soil science*, 174(2), 105-112.
- O'Connor, D., Peng, T., Zhang, J., Tsang, D. C. W., Alessi, D. S., Shen, Z., et al. (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. doi: 10.1016/j.scitotenv.2017.11.132
- Otsuka, S., Sudiana, I., Komori, A., Isobe, K., Deguchi, S., Nishiyama, M., ... & Senoo, K. (2008). Community structure of soil bacteria in a tropical rainforest several years after fire. *Microbes and Environments*, 23(1), 49-56.
- Pan, D., Kong, F., Zhang, N., & Ying, R. (2017). Knowledge training and the change of fertilizer use intensity: Evidence from wheat farmers in China. *Journal of environmental management*, 197, 130-139.
- Pandian, K., Subramaniyan, P., Gnasekaran, P., & Chitraputhirapillai, S. (2016). Effect of biochar amendment on soil physical, chemical and biological properties and

- groundnut yield in rainfed Alfisol of semi-arid tropics. *Archives of Agronomy and Soil Science*, 62(9), 1293-1310.
- Patel, J. S., Singh, A., Singh, H. B., & Sarma, B. K. (2015). Plant genotype, microbial recruitment and nutritional security. *Frontiers in plant science*, 6, 608.
- Peng, B., Liu, M., Sui, F., Pan, Z., Li, L., Pan, G., & Cheng, K. (2017). Effects of biochar on polycyclic aromatic hydrocarbons (PAHs) bioaccumulation in Chinese cabbage. *Journal of Agro-Environment Science*, 36(4), 702-708.
- Pituello, C., Dal Ferro, N., Francioso, O., Simonetti, G., Berti, A., Piccoli, I., ... & Morari, F. (2018). Effects of biochar on the dynamics of aggregate stability in clay and sandy loam soils. *European Journal of Soil Science*, 69(5), 827-842.
- Radwan, N. M., Marzouk, E. R., El-Melegy, A. M., & Hassan, M. A. (2020). Improving soil properties by using biochar under drainage conditions in North Sinai. *Sinai Journal of Applied Sciences*, 9(2), 157-168.
- Rafique, M., Sultan, T., Ortas, I., & Chaudhary, H. J. (2017). Enhancement of maize plant growth with inoculation of phosphate-solubilizing bacteria and biochar amendment in soil. *Soil science and plant nutrition*, 63(5), 460-469.
- Rajkovich, S., Enders, A., Hanley, K., Hyland, C., Zimmerman, A. R., & Lehmann, J. (2012). Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. *Biology and Fertility of Soils*, 48, 271-284.
- Rajput, V. D., Minkina, T., Ahmed, B., Singh, V. K., Mandzhieva, S., Sushkova, S., ... & Wang, B. (2022). Nano-biochar: A novel solution for sustainable agriculture and environmental remediation. *Environmental Research*, 210, 112891.
- Ren, X., Zhang, P., Zhao, L., & Sun, H. (2016). Sorption and degradation of carbaryl in soils amended with biochars: influence of biochar type and content. *Environmental Science and Pollution Research*, 23, 2724-2734.
- Rondon, M. A., Lehmann, J., Ramírez, J., & Hurtado, M. (2007). Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with bio-char additions. *Biology and fertility of soils*, 43, 699-708.
- Safaei Khorram, M., Fatemi, A., Khan, M. A., Kiefer, R., & Jafarnia, S. (2018). Potential risk of weed outbreak by increasing biochar's application rates in slow- growth legume, lentil (*Lens culinaris* Medik.). *Journal of the Science of Food and Agriculture*, 98(6), 2080-2088.
- Schiermeier, Q. (2006). Putting the carbon back: The hundred billion tonne challenge. *Nature*, 442(7103), 620-624.
- Servin, A. D., De la Torre-Roche, R., Castillo-Michel, H., Pagano, L., Hawthorne, J., Musante, C., ... & White, J. C. (2017). Exposure of agricultural crops to nanoparticle CeO<sub>2</sub> in biochar-amended soil. *Plant Physiology and Biochemistry*, 110, 147-157.
- Shiyal, V., Patel, V. M., Patel, H. K., Rathwa, M., & Patel, P. (2022). Biochar: An Emerging Soil Amendment for Sustaining Soil Health and Black Gold for Indian Agriculture. *Journal of Experimental Agriculture International*, 44(12), 6-12. <https://doi.org/10.9734/jeai/2022/v44i122072>
- Shu, R., Wang, Y., & Zhong, H. (2016). Biochar amendment reduced methylmercury accumulation in rice plants. *Journal of hazardous materials*, 313, 1-8.
- Singh, A., Singh, A. P., & Purakayastha, T. J. (2019). Characterization of biochar and their influence on microbial activities and potassium availability in an acid soil. *Archives of Agronomy and Soil Science*, 65(9), 1302-1315.
- Singh, A., Singh, A. P., Singh, S. K., Rai, S., & Kumar, D. (2016). Impact of Addition of Biochar Along with PGPR on Rice Yield, Availability of Nutrients and their Uptake in Alluvial Soil. *Journal of Pure & Applied Microbiology*, 10(3).

- Singh, N. S., & Singh, D. K. (2011). Biodegradation of endosulfan and endosulfan sulfate by *Achromobacter xylosoxidans* strain C8B in broth medium. *Biodegradation*, 22, 845-857.
- Smider, B., & Singh, B. (2014). Agronomic performance of a high ash biochar in two contrasting soils. *Agriculture, Ecosystems & Environment*, 191, 99-107.
- Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. (2010). A review of biochar and its use and function in soil. *Advances in agronomy*, 105, 47-82.
- Solaiman, Z. M., & Anawar, H. M. (2015). Application of biochars for soil constraints: challenges and solutions. *Pedosphere*, 25(5), 631-638.
- Song, W., & Guo, M. (2012). Quality variations of poultry litter biochar generated at different pyrolysis temperatures. *Journal of analytical and applied pyrolysis*, 94, 138-145.
- Srivastav, A. L. (2020). Chemical Fertilizers and Pesticides: Role in Groundwater Contamination in Agrochemicals Detection, Treatment and Remediation. *Butterworth-Heinemann*, 143-159.
- Steiner, C., Glaser, B., Geredes Teixeira, W., Lehmann, J., Blum, W. E., & Zech, W. (2008). Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. *Journal of plant nutrition and soil science*, 171(6), 893-899.
- Sun, H., Lu, H., Chu, L., Shao, H., & Shi, W. (2017). Biochar applied with appropriate rates can reduce N leaching, keep N retention and not increase NH<sub>3</sub> volatilization in a coastal saline soil. *Science of the Total Environment*, 575, 820-825.
- Sun, L., Li, L., Chen, Z., Wang, J., & Xiong, Z. (2014). Combined effects of nitrogen deposition and biochar application on emissions of N<sub>2</sub>O, CO<sub>2</sub> and NH<sub>3</sub> from agricultural and forest soils. *Soil Science and Plant Nutrition*, 60(2), 254-265.
- Tan, X. F., Liu, Y. G., Gu, Y. L., Xu, Y., Zeng, G. M., Hu, X. J., ... & Li, J. (2016). Biochar-based nano-composites for the decontamination of wastewater: a review. *Bioresourcetechnology*, 212, 318-333.
- Tan, X., Liu, Y., Zeng, G., Wang, X., Hu, X., Gu, Y., & Yang, Z. (2015). Application of biochar for the removal of pollutants from aqueous solutions. *Chemosphere*, 125, 70-85.
- Thomas, S. C., Frye, S., Gale, N., Garmon, M., Launchbury, R., Machado, N., ... & Winsborough, C. (2013). Biochar mitigates negative effects of salt additions on two herbaceous plant species. *Journal of Environmental Management*, 129, 62-68.
- Tisserant, A., & Cherubini, F. (2019). Potentials, limitations, co-benefits, and trade-offs of biochar applications to soils for climate change mitigation. *Land*, 8(12), 179.
- Uchimiya, M., Chang, S., and Klasson, K. T. (2011). Screening biochars for heavy metal retention in soil: role of oxygen functional groups. *J. Hazard. Mater.* 190, 432-441. doi: 10.1016/j.jhazmat.2011.03.063
- Uday, V., Hari Krishnan, P. S., Deoli, K., Zitouni, F., Mahlkecht, J., & Kumar, M. (2022). Current trends in production, morphology, and real-world environmental applications of biochar for the promotion of sustainability. *Bioresourcetechnology*, 359, 127467.
- Ur Rehman, M. Z., Khalid, H., Akmal, F., Ali, S., Rizwan, M., Qayyum, M. F., ... & Azhar, M. (2017). Effect of limestone, lignite and biochar applied alone and combined on cadmium uptake in wheat and rice under rotation in an effluent irrigated field. *Environmental Pollution*, 227, 560-568.
- Uzoma, K. C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A., & Nishihara, E. (2011). Effect of cow manure biochar on maize productivity under sandy soil condition. *Soil use and management*, 27(2), 205-212.

- Verheijen, F., Jeffery, S., Bastos, A. C., Van der Velde, M., & Diafas, I. (2010). Biochar application to soils. *A critical scientific review of effects on soil properties, processes, and functions. EUR, 24099(162)*, 2183-2207.
- Wang, H., Gao, B., Wang, S., Fang, J., Xue, Y., & Yang, K. (2015). Removal of Pb (II), Cu (II), and Cd (II) from aqueous solutions by biochar derived from KMnO<sub>4</sub> treated hickory wood. *Bioresource Technology*, 197, 356-362.
- Wang, J., Pan, X., Liu, Y., Zhang, X., & Xiong, Z. (2012). Effects of biochar amendment in two soils on greenhouse gas emissions and crop production. *Plant and soil*, 360, 287-298.
- Wang, K., Peng, N., Lu, G., & Dang, Z. (2020). Effects of pyrolysis temperature and holding time on physicochemical properties of swine-manure-derived biochar. *Waste and Biomass Valorization*, 11, 613-624.
- Wu, P., Ata-Ul-Karim, S. T., Singh, B. P., Wang, H., Wu, T., Liu, C., ... & Chen, W. (2019). A scientometric review of biochar research in the past 20 years (1998–2018). *Biochar*, 1, 23-43.
- Xu, G., Sun, J., Shao, H., & Chang, S. X. (2014). Biochar had effects on phosphorus sorption and desorption in three soils with differing acidity. *Ecological engineering*, 62, 54-60.
- Xu, G., Zhang, Y., Sun, J., & Shao, H. (2016). Negative interactive effects between biochar and phosphorus fertilization on phosphorus availability and plant yield in saline sodic soil. *Science of the Total Environment*, 568, 910-915.
- Yang, X. B., Ying, G. G., Peng, P. A., Wang, L., Zhao, J. L., Zhang, L. J., ... & He, H. P. (2010). Influence of biochars on plant uptake and dissipation of two pesticides in an agricultural soil. *Journal of agricultural and food chemistry*, 58(13), 7915-7921.
- Yang, X., Lu, K., McGrouther, K., Che, L., Hu, G., Wang, Q., ... & Wang, H. (2017). Bioavailability of Cd and Zn in soils treated with biochars derived from tobacco stalk and dead pigs. *Journal of soils and sediments*, 17, 751-762.
- Yang, Y., Ma, S., Zhao, Y., Jing, M., Xu, M., & Chen, J. (2015). A field experiment on enhancement of crop yield by rice straw and corn stalk-derived biochar in Northern China. *Sustainability*, 7: 13713–13725.
- Yao, Y., Gao, B., Zhang, M., Inyang, M., & Zimmerman, A. R. (2012). Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. *Chemosphere*, 89(11), 1467-1471.
- Yu, O. Y., Raichle, B., & Sink, S. (2013). Impact of biochar on the water holding capacity of loamy sand soil. *International Journal of Energy and Environmental Engineering*, 4, 1-9.
- Yu, Z., Qiu, W., Wang, F., Lei, M., Wang, D., & Song, Z. (2017). Effects of manganese oxide-modified biochar composites on arsenic speciation and accumulation in an indica rice (*Oryza sativa* L.) cultivar. *Chemosphere*, 168, 341-349.
- Yuan, J. H., Xu, R. K., & Zhang, H. (2011). The forms of alkalis in the biochar produced from crop residues at different temperatures. *Bioresource technology*, 102(3), 3488-3497.
- Zhang, F., Chen, X., & Vitousek, P. (2013). An experiment for the world. *Nature*, 497(7447), 33-35.
- Zhang, H., Chen, C., Gray, E.M., Boyd, S.E., Yang, H., Zhang, D. (2016). Roles of biochar in improving phosphorus availability in soils: A phosphate adsorbent and a source of available phosphorus. *Geoderma*, 276, 1-6.
- Zhang, P., Sun, H., Yu, L., & Sun, T. (2013). Adsorption and catalytic hydrolysis of carbaryl and atrazine on pig manure-derived biochars: impact of structural properties of biochars. *Journal of hazardous materials*, 244, 217-224.

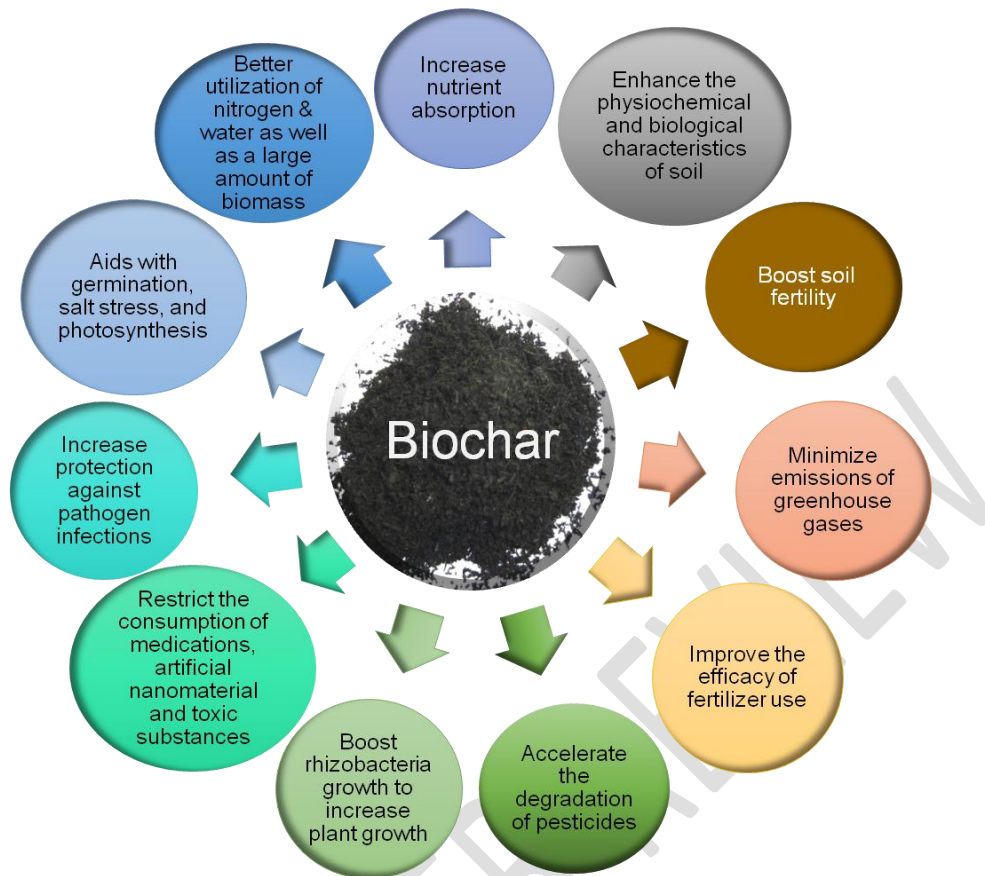
- Zhao, X., Ouyang, W., Hao, F., Lin, C., Wang, F., Han, S., & Geng, X. (2013). Properties comparison of biochars from corn straw with different pretreatment and sorption behaviour of atrazine. *Bioresource technology*, *147*, 338-344.
- Zheng, H., Wang, Z., Deng, X., Herbert, S., & Xing, B. (2013). Impacts of adding biochar on nitrogen retention and bioavailability in agricultural soil. *Geoderma*, *206*, 32-39.
- Zheng, H., Wang, Z., Deng, X., Zhao, J., Luo, Y., Novak, J., ... & Xing, B. (2013). Characteristics and nutrient values of biochars produced from giant reed at different temperatures. *Bioresource Technology*, *130*, 463-471.
- Zhu, Q., Peng, X., & Huang, T. (2015). Contrasted effects of biochar on maize growth and N use efficiency depending on soil conditions. *International Agrophysics*, *29*(2).
- Zhu, Q., Wu, J., Wang, L., Yang, G., & Zhang, X. (2014). Effect of biochar on heavy metal speciation of paddy soil. *Water, Air, & Soil Pollution*, *226*, 1-10.
- Zimmerman, A. R. (2010). Abiotic and microbial oxidation of laboratory-produced black carbon (biochar). *Environmental science & technology*, *44*(4), 1295-1301.
- Kahil, A. A., Issa, A. A., Al-Sodany, Y. M., & Ali, E. F. (2018). Effects of Biochar Amended Saline Soil on Growth and Some Metabolic Activities of Two Soybean Cultivars in Saudi Arabia. *Annual Research & Review in Biology*, *25*(6), 1-14. <https://doi.org/10.9734/ARRB/2018/41126>
- Shiyal, V., Patel, V. M., Patel, H. K., Rathwa, M., & Patel, P. (2022). Biochar: An Emerging Soil Amendment for Sustaining Soil Health and Black Gold for Indian Agriculture. *Journal of Experimental Agriculture International*, *44*(12), 6-12. <https://doi.org/10.9734/jeai/2022/v44i122072>
- Nansubuga I, Banadda N, Ronsse F, Verstraete W, Rabaey K. Digestion of high rate activated sludge coupled to biochar formation for soil improvement in the tropics. *Water research*. 2015 Sep 15;81:216-22.

**Table 1: Nutrient retention by biochar and their effect of feedstock, pyrolysis temperature and application rate**

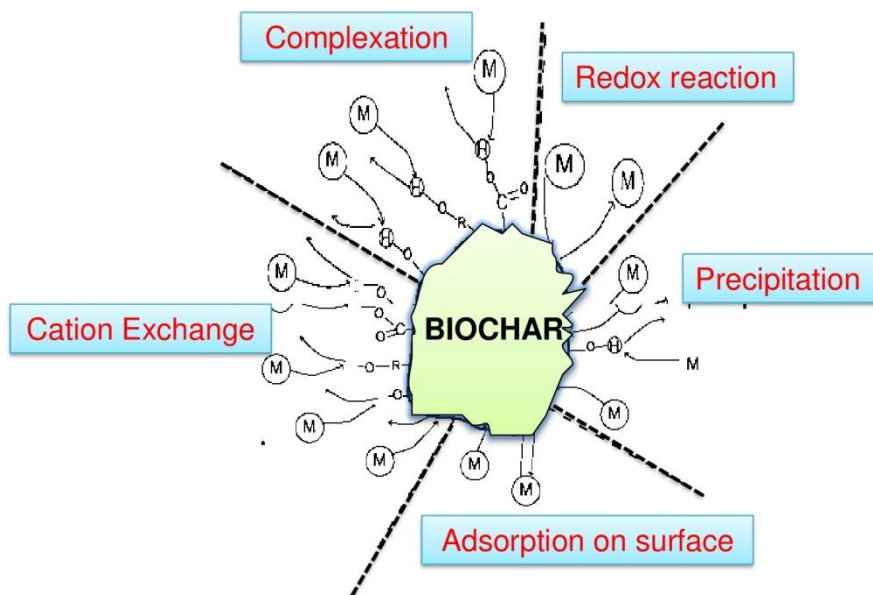
Nutrient	Feedstock	Pyrolysis temperature (°C)	Rate of biochar application	Adsorption capacity (mg/kg)	Reference
NH <sub>4</sub> <sup>+</sup>	Brazilian pepperwood	300	0.1g 50m/L	190	Yao <i>et al.</i> , 2012
		450		785	
		600		595	
	<i>Arundo donax</i> L.	300	0.35g 12m/L	2101.9	Zheng <i>et al.</i> , 2013
		350		1432.6	
		400	0.8g 12m/L	1043.4	
		500		362.8	
600	371.8				
NO <sub>3</sub> <sup>-</sup>	Brazilian pepperwood	600	0.1g 50m/L	20.6	Yao <i>et al.</i> , 2012
	<i>Arundo donax</i> L.	500	0.3g 8m/L	171.8	Zheng <i>et al.</i> , 2013
		600		533.5	
PO <sub>4</sub> <sup>3-</sup>	Wheat straw	350-550	1%	333	Xu <i>et al.</i> , 2014
			5%	625	
			10%	769	
	Sugarcane bagasse	450	0.1g 50m/L	477.4	Yao <i>et al.</i> , 2012
	K <sup>+</sup>	<i>Spartina spartinae</i>	300	A solution flow rate of 0.30–0.35 mL/min; 50–60 mg of biochar	19.5
350			20.3		
550			12.5		
<i>Pinus taeda</i>		300	A solution flow rate of 0.30–0.35 mL/min; 50–60 mg of biochar	6.6	Harvey <i>et al.</i> , 2011
		350		10.9	
		650		1.2	

**Table 2: Dynamics of biochar and its effects on crop**

Sl No	Type of biochar	Temperature	Area of study	Rate of application	Soil type	Effect on crop yield	Reference
1	Wheat Straw	300–500°C	China	3% w/w	Psammaquent and Plinthudult	Rice	Muhammad et al., 2017
2	Rice Straw and Corn Stalk	450°C	China	1, 2& 4 t/ha	Inceptisol	Corn, Peanut Sweet potato	Yang et al., 2015
3	Cow Manure	600°C	Japan	0, 10, 15 and 20 t/ha	Sandy soil	Maize	Azeem et al., 2019
4	Rice Husks	450 °C	China	0, 10, 25 and 50 t/ha	Upland soil and paddy soil	Rice, Wheat	Wang et al., 2012
5	Maize Stover	600 °C	USA	0, 1, 3, 12 & 30 t/ha	Kendaia silt loam	NA	Güereña et al., 2012
6	Woodchips	700°C	USA	5% w/w	Clay texture and sandy loam texture	NA	Lai et al., 2013
7	<i>Eucalyptus polybractea</i>	550°C	UK	10 t/ha	Ferrosol Soil	Cauliflower, peas, Broccoli- no significant effect	Boersma et al., 2017



**Fig 1. Benefits of the use of biochar in soil-plant systems**



**Fig 2. Reaction of biochar in retention of nutrients and heavy metals**