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BIOCHAR: A SUPER AMENDMENT FOR SOIL HEALTH AND SUSTAINABILITY

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ABSTRACT

In order to maximize crop output and reduce environmental damage, sustainable agriculture methods are crucial. The pyrolysis of organic materials produces biochar, a carbon-rich byproduct that has generated a lot of attention due to its potential to enhance soil health, boost agricultural productivity, and aid in climate change mitigation. The feedstock supply, pyrolysis conditions, and soil properties all affect how effective biochar is. Waste valorization is possible through the manufacture of biochar from invasive plants like lantana, animal waste, forest litter, and agricultural wastes. Therefore, adding biochar to agricultural systems can reduce environmental issues while increasing crop output and soil sustainability. By decreasing the bulk density of soil, increasing microbial activity, pH, water-holding capacity, and improving nutrient retention, the use of biochar lessens the need for inorganic fertilizers. Biochar greatly increases soil fertility and crop production by enriching the soil with vital elements including phosphorus, potassium, nitrogen, and organic carbon. It is a sustainable way to enhance soil health because it also helps with pollution immobilization and carbon sequestration. The function of biochar in altering the physical, chemical, and biological characteristics of soil and the impact of these modifications on crop productivity are also covered in this study. Ultimately, biochar is demonstrated as a potentially helpful tool for improving soil quality and promoting ecologically friendly farming methods.
***Keywords* :** amendment, biochar, crop productivity, feedstock, microbial activity, pyrolysis.

Introduction

In agriculture, producing enough food while reducing the negative effects on the environment is still a major problem. Applying inputs at the right rates and using sustainable fertilizer management techniques are essential to achieve this (Shanmugavel *et al.*, 2023). Biochar is one such technique that has shown promise in enhancing soil health and raising crop yields. It has gained significant attention in recent years for its potential benefits in agriculture, climate change mitigation, energy production, and environmental sustainability (Bano *et al.*, 2025). Its capacity to adsorb different substances is influenced by factors such as particle size, surface features, and pore structure (Tan *et al.*, 2015). The wide range of biochar applications can be credited to its unique properties, including surface functional groups, high thermal stability, cation exchange capacity, heat retention ability, extensive surface area, good permeability, electrical conductivity, and high fixed carbon content. These characteristics have contributed to its value and use across various fields over time (Wang *et al.*, 2019).

Peter Read coined the word "biochar" to describe a fine-grained, porous substance that is rich in carbon that is created when plant biomass is thermally broken down (Ahmed *et al.*, 2014). This process, called pyrolysis, takes place in an oxygen-limited atmosphere at low temperatures (about 350–600°C) (Zhang *et al.*, 2019). Under these circumstances, organic matter breaks down thermally rather than burning to produce biochar. It is produced artificially utilizing contemporary pyrolysis technologies as well as organically through wildfires (Mohanty *et al*., 2018). A stable, porous substance that affects several soil qualities is the end result. Biochar changes the physical characteristics of soil, including its moisture content, oxygen availability, and ability to retain water. While fostering biological elements like microbial population, diversity, and their activity. Additionally, biochar can raise soil pH (Zhang *et al*., 2019) and improve the soil's ability to retain water and nutrients (Krause *et al*., 2016). Biochar offers advantages such as nutritional enrichment and lessens reliance on inorganic fertilizers by delivering vital nutrients (Bird *et al*., 2011). It also helps in carbon sequestration and pollutant immobilization (Gul *et al*., 2015).

Applying biochar to agricultural soils increases crop output by promoting the storage of necessary elements and improving fertility (Marris, 2006). Because biochar increases the availability of nutrients including phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), sodium (Na), nitrogen (N), total carbon (C), and organic carbon (OC), it is especially advantageous for soils with limited ion-retention capacity (Chan *et al*., 2007).). The kind and extent of these alterations in soil properties affects the growth of crop in biochar amended soils (Jeffery *et al*. 2017).

Crop leftovers, forest litter, animal waste, and invasive weeds like *lantana*, which, despite its quick growth, currently has no useful uses—can all be used as feedstock for the synthesis of biochar. Pyrolysis is an effective technique for turning these organic resources into biochar. The kind of feedstock utilized and the production circumstances determine the particular characteristics of biochar as well as its possible uses.

International Biochar Initiative (IBI)

Biochar is a solid that is created by carbonizing biomass, according to the International Biochar Initiative (IBI) (Lehmann, 2007). Biochar may be used as a carbon sink or modification to lower greenhouse carbon dioxide (CO2) emissions from decaying biomass (Brewer *et al*., 2009; Lehmann *et al*., 2011).

One example that made biochar popular was the theory that the Amazonian inhabitants used it, along with other organic and household wastes, over generations to transform the surface soil horizon into Terra Preta, an extremely productive and rich soil. Biochar's role in soil-building processes has piqued the curiosity of many people (Lehmann *et al*., 2011).

Feedstocks for Biochar Production

The kind of the pretreatment procedure and the overall effectiveness of the biochar manufacturing process are greatly impacted by the feedstock type (Amarasinghe *et al*., 2016). Wood, fruit shells, agricultural leftovers such stems, leaves, and seed pods, green manure, sewage sludge, industrial and municipal waste, and farm outputs are just a few of the many biomass feedstocks that may be utilized to make biochar (Duku *et al*., 2011; Wang *et al*., 2018). Algae biomass has also become a sustainable feedstock because of its high nitrogen content and ion exchange capability. It produces biochar, which is a useful soil amendment in agriculture (Yu *et al*., 2017).

Instead of being used directly as fertilizer, biochar made from plant-based feedstocks is frequently appreciated as a soil conditioner (Uchimiya *et al*., 2010). When choosing feedstocks, other factors to take into account include their price, accessibility, and lack of contaminants such heavy metals (Rondon *et al*., 2007). As a result, selecting the appropriate feedstock is essential in guaranteeing that biochar will work as intended.

Features of Biochar

The importance of biochar is significantly influenced by its chemical and physical characteristics. To comprehend its interactions in soil and assess its possible advantages, proper characterisation is crucial. Important characteristics of biochar, including as pH, ash content, water-holding capacity, bulk density, pore volume, and surface area, are greatly influenced by the quality of the feedstock utilized (Hernandez-Mena *et al*., 2014).

Furthermore, two important variables affecting the physicochemical characteristics of biochar are the pyrolysis temperature and time (Tag *et al*., 2016). For example, biochar's surface area increases with increase in pyrolysis temperatures (Ahmad *et al*., 2012; Zhang *et al*., 2015). Accordingly, choosing the right pyrolysis temperature necessitates striking a balance between surface features and chemical properties (Chatterjee *et al*., 2020).

The ideal temperature range for producing biochar is usually 500 to 800°C. Biochar that controls nutrient release is produced at lower pyrolysis temperatures, while biochar that resembles activated carbon is produced at higher temperatures (Day *et al*., 2005; Ogawa *et al*., 2006; Chan *et al*., 2008). It is important to keep in mind, though, that low-temperature biochar could have hydrophobic surfaces, which could lower the soil's ability to retain water.

Biochar Preparation

Biochar is produced and prepared using a variety of procedures (Figure 1), such as (i) pyrolysis, (ii) microwave carbonization, (iii) hydrothermal carbonization, and (iv) torrefaction, all of which make use of various heating methods. The thermochemical breakdown of biomass in a low-oxygen (O_2) atmosphere is known as pyrolysis (Demirbas and Arin, 2002). Three forms of pyrolysis are distinguished by temperature and duration: slow, transitional, and rapid pyrolysis (Tripathi *et al.*, 2016). Slow and transitional pyrolysis have prolonged dwelling durations, spanning from minutes to many hours or even days, which makes them appropriate for producing biochar, whereas rapid pyrolysis has a relatively limited retention time.

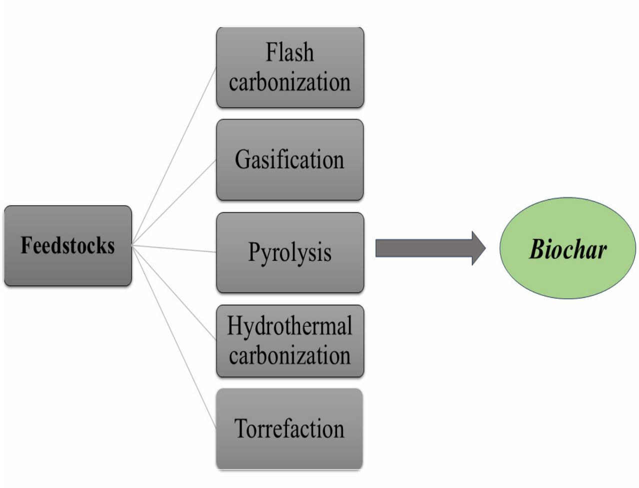

Fig. 1 : Biochar Preparation Techniques

The stability of biochar is significantly influenced by the temperature during pyrolysis. Biochar produced at temperatures higher than 500°C usually has half-lives of more than a millennium (Ippolito *et al.*, 2020). As the pyrolysis temperature rises, changes in elemental composition may be seen, including the ratios of carbon (C), hydrogen (H), oxygen (O), and nitrogen (N) (Wang *et al.*, 2018). According to Domingues *et al.* (2017), increasing the pyrolysis temperature from 350°C and 450°C to 750°C lowers the cation exchange capacity (CEC), which in turn lowers the nutrient-rich biochar's adsorptive ability.

Furthermore, it has been discovered that greater pyrolysis temperatures increase the amount of ash in biochar while decreasing its surface area and pore volume (Rafiq *et al.*, 2016). In conclusion, temperature has a significant impact on the content, structure, and functional groups of biochar. Thus, choosing the right pyrolysis temperature is crucial for preparing biochar of superior quality.

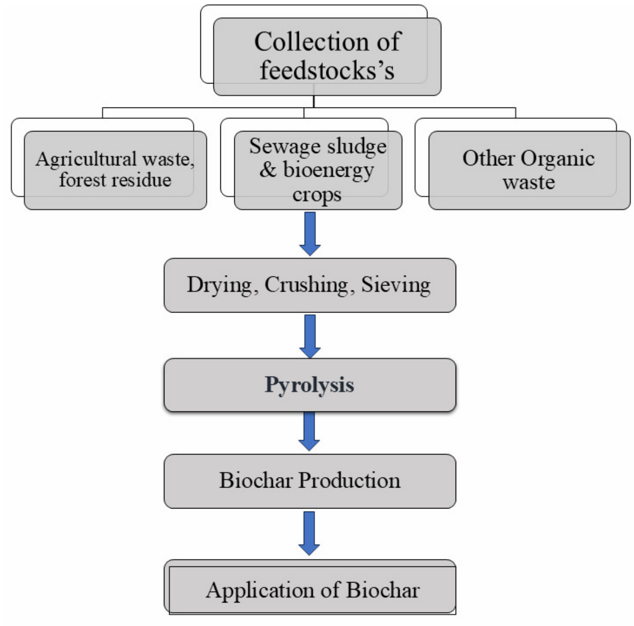

Fig. 2 : Diagram of the pyrolysis process

The physical, chemical, and biological characteristics of biochar

Physical Characteristics

According to Shenbagavalli and Mahimairaja (2012), biochar is a stable, carbon-rich substance that may persist in soil for thousands of years. Its effectiveness as a soil amendment for enhancing soil health and sequestering carbon is determined by the kind of feedstock utilized and the pyrolysis method, both of which have a substantial impact on its characteristics. The physical characteristics of biochar have several positive effects on the environment, such as raising the pH of the soil, improving moisture retention, encouraging the growth of helpful microbes, boosting cation exchange capacity (CEC), and conserving soil nutrients (Sohi *et al.*, 2010). All of these procedures work together to enhance the fertility and condition of the soil (Ajema, 2018).

Biochar changes the physical and chemical characteristics of soil, reducing bulk density and compaction, improving aeration and CEC, and changing the texture and structure of the soil. Additionally, it makes it easier to restore deteriorated soils. In comparison to other organic components in soil, its large surface area, negative surface charge, and charge density make it more efficient at absorbing cations per unit of carbon, which can increase crop yields (Liang *et al.*, 2006; Lehmann, 2007).

Depending on the makeup and interactions of minerals and organic matter, biochar can have both direct and indirect effects on soil processes. It changes the physical properties of soil, including density, packing, particle size, surface area, and pore size distribution. These modifications affect the texture, structure, porosity, and consistency of the soil, which affects the passage of water and air in the root zone and, in turn, the development of plants (Blanco-Canqui, 2017). In addition to improving soil permeability, aggregation, and workability, biochar's porous structure helps retain moisture, which makes it especially helpful in areas that are prone to drought. Acidic soils are neutralized by its alkaline properties, which removes restrictions on plant development (Hammes and Schmidt, 2009).

Furthermore, biochar may trap CO_2 and O_2 in its porous structure or adsorb them on its surface, allowing gasses, microorganisms, and nutrients to be retained. By doing this, nutrient leakage into water bodies is decreased, protecting the ecosystem and maintaining soil health.

Chemical Properties By enhancing nutrient retention and lowering acidity through its liming activity, which elevates soil pH, biochar improves soil fertility (Lehmann *et al*., 2006). It increases soil productivity by adding minerals like potassium (K), phosphorus (P), and micronutrients, or by retaining nutrients from other sources. Even though biochar by itself doesn't always have enough nutrients, it can help crops perform better when combined with either organic or inorganic fertilizers.

The delayed release of nutrients like carbon (C), nitrogen (N), calcium (Ca), magnesium (Mg), potassium (K), and phosphorus (P) that biochar provides is one of its most advantageous qualities since it enables plants to obtain nutrients over a longer period of time (DeLuca *et al*., 2015). This gradual release lowers nutrient leaching, lessens agricultural contamination, and eliminates the need for regular fertilizer treatments. The negative environmental consequences of chemical fertilizers and pesticides are also lessened by biochar's capacity to store nutrients (Cao *et al*., 2018).

A wide variety of species, such as bacteria, fungus, protozoa, nematodes, arthropods, and earthworms, are supported by healthy soil. These species find a home in biochar, which boosts biodiversity and soil microbial activity (Slapakova *et al*., 2018). By providing a haven for beneficial fungi like arbuscular mycorrhizal fungi and microbial communities, the micropores of biochar lessen saprophyte competition and improve nutrient exchange between fungus and plants (Saito and Marumoto, 2002).

According to Krull *et al*. (2003), biochar's stubborn character allows it to endure in soil for thousands of years, with estimations ranging from 1,000 to 10,000 years and an average of about 5,000 years. However, because of its intricate structure, evaluating its long-term stability is challenging (Lehmann *et al*., 2006).

Additionally, biochar offers a haven for microbial inoculants such Bacillus thuringiensis, *Azospirillum* sp., *Azotobacter* sp., and *Glomus fasciculatum*, *Rhizobium* sp., *Trichoderma viride*, *Pseudomonas fluorescens*, and mosseae (Hazarika and Ansari, 2007). Biochar increases nutrient absorption and stimulates plant development by cultivating symbiotic interactions between fungus and plants, especially mycorrhizal fungi. It is a useful tool for sustainable soil management because of its porous nature, which facilitates these interactions (Glaser, 2007).

Biochar's Impact on Soil Properties

Effects of biochar on various soil properties viz., physical, chemical and biological is illustrated in figure 3.

Impact on soil physical properties

Impact on Soil Porosity

It has been demonstrated that applying biochar improves soil porosity; however, the degree of improvement varies depending on the kind of biochar and the soil (Herath *et al*., 2013). Soil aeration, heat transmission, and water flow are all improved by increased porosity (Omondi *et al*., 2016). Overall soil porosity is influenced by the relative contributions of macro, micro, and mesopores, which differ based on the type of soil and biochar (Githinji, 2014). Biochar decreases saturated hydraulic conductivity (*Ksat*) and enhances water retention in sandy soils while increasing *Ksa*t in clayey soils to minimize runoff (Edeh *et al*., 2020).

Impact on Bulk Density of Soil (BD)

Applying biochar has been shown to dramatically lower soil bulk density; the more biochar applied, the larger the reductions (Herath *et al*., 2013; Githinji, 2014). According to Liu *et al*. (2016), there is a negative association between the addition of biochar and soil BD, meaning that BD falls as biochar concentration rises. Reducing BD can have positive agronomic effects as it has a direct impact on soil health, crop productivity, and plant development (Githinji, 2014).

Impact on the Aggregation of Soils

Because of its interactions with soil mineral particles, biochar especially when produced at lower temperatures plays a critical role in encouraging the development of soil aggregates (Brodowski *et al.*, 2005). According to Briggs *et al.* (2012), biochar carbon affects soil aggregation and associated processes by interacting with both organic and inorganic soil components. It has been demonstrated that biochar improves wet aggregate stability, especially in sandy soils. According to Burrell *et al.* (2016), its organic particles enhance the bonding of bigger particles, which leads to soil aggregation in coarse-textured soils as opposed to fine-textured soils. Furthermore, biological, chemical, and physical processes can cause biochar particles to surround inorganic soil aggregates with a carbon-rich core (Hua *et al.*, 2014).

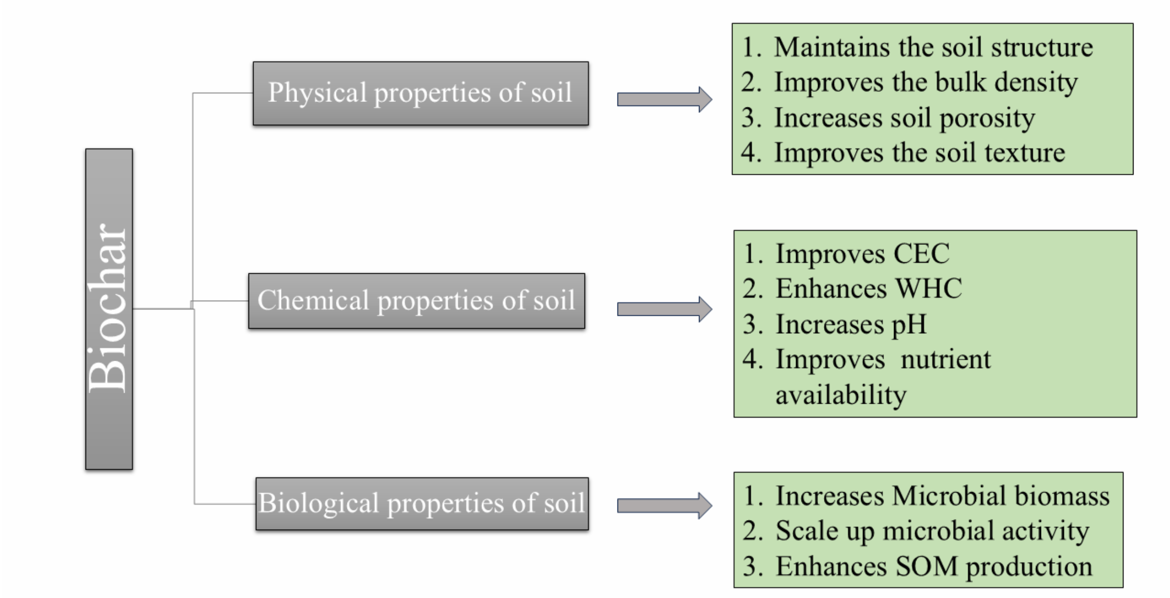

Fig. 3 : Biochar's impact on different soil characteristics

Impact of Applying Biochar on Chemical Characteristics

Biochar is a good soil amendment because it significantly affects the chemical characteristics of the soil (Lehmann *et al.*, 2011). Biochar's high pH makes it an excellent way to improve the pH of soil, especially in acidic soils (Song *et al.*, 2018). Ash content is the main cause of this pH rise as it raises the pyrolysis temperature and mineral makeup of the feedstock used to make biochar (Rafiq *et al.*, 2016).

Additionally, the use of biochar has been associated with increased soil carbon reserves, which can improve soil fertility, promote carbon sequestration, improve nutrient retention, and temporarily stimulate native organic carbon mineralization (positive priming) all of which can result in increased crop yields (Ouyang *et al.*, 2014). After applying biochar for four years, Zhan *et al.* (2015) found that the soil's total nitrogen (N) increased by 27.5%, its carbon (C) content grew by 75.5%, and its peanut yield improved by 50.5%. According to a number of studies, biochar can increase nitrogen retention, decrease N leaching, and raise the total amount of nitrogen in soil (Major *et al.*, 2012). Because of its porous structure, nitrate and ammonium may be adsorbed, enhancing nitrogen immobilization and decreasing ammonium volatilization, which increases the amount of nitrogen available for plant development (Rondon *et al.*, 2007).

Additionally, biochar contributes to the recycling of phosphorus (P) from sewage sludge and manure, two agricultural wastes. Increased soil P availability is a result of the high phosphorus concentration of biochar's ash (Major *et al.*, 2012; Zhai *et al.*, 2015). Nevertheless, the type of soil affects the availability of phosphorus; biochar increases P availability in acidic soils but may decrease it in alkaline soils because of enhanced sorption (Chintala *et al.*, 2014).

Furthermore, it has been discovered that applying biochar improves the cation exchange capacity (CEC) of soil. According to Major *et al.* (2012), this improvement is usually followed by a decrease in acidic cations and an increase in basic cations, which influences nutrient availability and may result in increased soil productivity.

Impact of Applying Biochar on Biological Characteristics

Microbial activity has been a major focus of the extensive research on the effects of biochar on soil microbial populations. Biochar can improve microbial populations by interacting with minerals and soil organic matter (Zhang *et al*., 2014; Pokharel *et al*., 2020). It is also a useful technique for enhancing soil carbon sinks because to its resilience to degradation and capacity to lower CO_2 emissions from soil organic matter. By altering the availability of carbon, nitrogen, and other soil characteristics, biochar changes the biomass composition and microbial population (Zhang *et al*., 2014).

Although the effects of biochar might differ based on the kind of soil and application rate, its enormous surface area creates an environment that encourages enzymatic activity. Biochar, a labile carbon source, stimulates microbial activity, which raises the activity of soil enzymes (Ouyang *et al*., 2014). However, research has indicated that phosphomonoesterase activity can be decreased by applying biochar that contains a large amount of inorganic phosphorus (Zhai *et al*., 2015). According to Karhu *et al*. (2011), biochar generally creates an environment that is conducive to microbial populations, which increases the biological activity of soil.

Four main ways that biochar affects mycorrhizal associations were described by Warnock *et al*. (2007): (i) changing nutrient availability by modifying soil properties; (ii) affecting interactions between soil microbes; (iii) detoxifying allelochemicals; and (iv) offering defense against soil predators. Numerous studies have reported increased mycorrhizal colonization (Yamato *et al*., 2006; Solaiman *et al*., 2010; Shen *et al*., 2016). Applying biochar has been demonstrated to improve soil fertility and agricultural yield, especially in nutrient-deficient soils (Xie *et al*., 2013). The impacts on production in extremely rich soils, however, vary; some studies even show growth restriction. The kind of biochar feedstock and the properties of the soil both affect how biochar affects mycorrhizal relationships.

Soil fauna is also impacted by biochar. The precise consequences of ingested biochar inside earthworm systems are yet unknown, although earthworms, for instance, may consume it while they dig and eat. Depending on the kind of soil and the properties of the feedstock, the reactions of soil fauna to the addition of biochar might range from neutral to positive or negative (Lehmann *et al*., 2011).

Effect of Biochar on Crop Productivity

The forms of biochar dust, fine particles, and coarse grains as well as the application techniques surface application, top dressing, and drilling are the two primary factors affecting the influence of biochar on crop productivity. When assessing how biochar affects crop performance and soil health, these variables are crucial. Different levels of ash, which is high in minerals that promote plant development, are present in fresh biochar. This offers a temporary benefit, allowing ash-rich biochar to be used as fertilizer in the early phases until the mineral content is exhausted. Research has indicated that the use of biochar has a considerable impact on grain yield, dry matter output, and net primary crop production (Chan *et al*., 2008). The kind of soil and how biochar is modified determine how successful it is. According to El-Naggar *et al*. (2019), biochar typically exhibits higher efficiency in medium-to-low fertility soils compared to extremely fertile soils, leading to considerable improvements in agricultural output.

In a multi-year study using a soybean (*Glycine max* L.) and maize (*Zea mays* L.) cropping system, Major *et al*. (2010) found that applying 20 t ha^{-1} of biochar did not increase maize yield in the first year. In contrast to the control, yield increases of 28%, 30%, and 140% were seen in the following three years. Similar findings were made by Park *et al*. (2011), who discovered that adding biochar at a rate of 1% (w/w) considerably raised the dry biomass of Indian mustard by 672% for roots and 452% for shoots. Chemically modified chicken manure was the source of the biochar that was utilized. These gains were ascribed to improved nutritional availability, especially potassium (K) and phosphorus (P), and decreased toxicity from lead (Pb) and copper (Cu).

Biochar for Carbon Sequestration and Climate Change Mitigation

Capturing and storing carbon to stop its escape into the atmosphere is known as carbon sequestration (Duku *et al*., 2011; Hu *et al*., 2020). Long-term carbon storage and soil improvement are two advantages of applying biochar to soils (Tenenbaum, 2009; Ennis *et al*., 2012). Biochar is a promising tool for carbon sequestration due to its ability to remain stable in the soil for hundreds or even thousands of years (Yin *et al*., 2022). Additionally, biochar helps mitigate climate change by lowering emissions of nitrous oxide (N_2O) and methane (CH_4) from agricultural soils (Gupta *et al*., 2020). Compared to combustion (3%) and biological degradation (10–20% after 5–10 years), biochar maintains more than 50% of the carbon from its initial biomass (Lehmann *et al*., 2006).

The lifespan and nutrient-retention qualities of biochar make it unique. Because it doesn't break down, it improves soil fertility and structure over time. Furthermore, according to Mensah and Frimpong (2018), biochar dramatically improves soil pH, moisture retention, cation exchange capacity (CEC), and microbial activity.

Zhang *et al*. (2010) showed how biochar can lower emissions of CH_4 and N_2O, two major causes of global warming. Additionally, biochar applications (2% to 60% by weight) decreased CO_2 emissions, lowered N_2O generation (beyond 20% application rates), and enhanced methane oxidation, according to Spokas *et al*. (2009).

Additionally, biochar has disease-suppressive qualities that may help reduce pathogen-caused soil-borne illnesses. This suppression process is aided by calcium compounds and enhancements to the physical, chemical, and biological characteristics of the soil (Ogawa, 2009). Research has demonstrated the efficacy of biochar in combating airborne and soil-borne illnesses such powdery mildew, *Botrytis cinerea*, and *Rhizoctonia solani*, as well as *Fusarium* species and *Phytophthora* (Bonanomi *et al*., 2015). For example, using biochar made from citrus wood improved crops like strawberries (*Fragaria* × *ananassa*), peppers (*Capsicum annuum*), and tomatoes (*Lycopersicon esculentum*) resistance to gray mold (*Botrytis cinerea*).

Despite the paucity of studies on biochar's ability to inhibit soil-borne pathogens, Elmer *et al*. (2010) found that it may be able to manage certain illnesses. For instance, at treatment rates of 0.32%, 1.60%, and 3.20% (w/w), biochar decreased root rot disease and enhanced plant biomass in asparagus soils afflicted with Fusarium. Likewise, Fusarium root rot in asparagus crops has been successfully prevented by using charcoal enhanced with mycorrhizal fungus (Thies and Rillig, 2009).

Biochar is a promising and versatile approach to improving soil health, encouraging sustainable agriculture, and tackling environmental issues like climate change. By improving soil fertility, structure, and water retention, its application increases crop yields while lowering the demand for inorganic fertilizers. Furthermore, biochar is an essential strategy for reducing greenhouse gas emissions because of its capacity to store carbon in the soil. However, addressing obstacles pertaining to production prices, application methods, and regional variations in efficacy is necessary before it can be widely used. To maximize biochar synthesis and application techniques for various agricultural systems, more research and development is required. All things considered, biochar has a great deal of promise for incorporating into sustainable farming methods and enhancing agricultural and environmental resilience over the long run.

Disclosure statement

No potential conflict of interest was reported by the authors.

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