Biochar: A Comprehensive Overview of Its Role in Soil Health

ABSTRACT

Soil health plays a crucial role in agricultural productivity, environmental sustainability, and global food security. In recent years, biochar has emerged as a promising soil amendment due to its ability to enhance soil fertility, nutrient retention, water holding capacity, and overall soil health. From an agricultural standpoint, using biochar as a soil conditioner has various advantages, including improved physical, chemical, and biological qualities of soils, which leads to enhanced crop output. Biochar can be utilised for soil carbon sequestration, reducing the bioavailability of pollutants impacting living organisms, and water treatment due to its physicochemical qualities This review paper aims to provide an in-depth analysis of the role of biochar in improving soil health. It discusses the production methods and its impact on soil health.

KEYWORDS- Biochar, nutrient retention, soil conditioner, soil health.

INTRODUCTION

Agriculture has a significant impact on the global economy. Food security is a serious concern these days. Despite great improvements in agricultural practises following World War II, the global food supply remains insufficient to meet actual demand. Furthermore, new challenges such as soil degradation, climate change, and desertification must yet be addressed in the agriculture sector (Pullagurala *et al.*, 2018). With a growing population, worldwide food consumption is expected to rise by 70% by 2050 (Samantarai and Achakzai 2014), and achieving this demand without jeopardising soil health and the agroecosystem has become a major problem in the agriculture industry. To fulfil the increasing need for food, the indiscriminate use of fertilisers, plant growth regulators, pesticides, and other chemicals has become common practise. Because of the negative impact on the ecology and the entire food chain, their over use is a severe concern. Depletion of soil organic matter and nutrients, reduction in agricultural output due to overuse of artificial fertilisers, and climate change caused by anthropogenic activities all pose significant concerns to the sustainability of tropical agricultural production. As a result, it is becoming increasingly vital to utilise organic fertiliser alongside inorganic fertiliser to improve sustainability and soil health. Biochar, along with organic manures and composts, is a viable solution.

Biochar is a carbon-rich solid substance produced by the anoxic pyrolysis of bio-organic materials at intermediate to low temperatures (700°C) (Lehmann *et al.,* 2006). Biochar is mostly made from biomass waste (straw, faeces, or sludge), which not only promotes waste resource utilisation but also efficiently mitigates environmental deterioration (Chen and Chen 2009). This renewable organic substance is generated from plants and animals and is used as an energy source (Abioye and Ani FN 2015). The improper disposal of biomass generated by the agriculture industry is a serious global concern (Siddiqui *et al.,* 2019). As the world population expands, so does the demand for energy and food security. Energy is critical for every country's industrial, agricultural, and transportation sectors to thrive (Enweremadu and Mbarawa 2009). To meet global energy needs, fossil fuels are widely employed. Environmental and economic challenges are constantly emphasising the importance of finding environmentally acceptable renewable energy sources (Yaman, 2004) (Smets *et al.,* 2013).

Biochar is a fine-grained, carbon-rich, porous substance that remains after plant biomass is subjected to a thermo-chemical conversion process (pyrolysis) at low temperatures (350-600°C) in an oxygen-depleted atmosphere (Danish *et al.*, 2015). Biochar is not pure carbon, but rather a mixture of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S), and ash in various quantities (Boateng, *et al.*, 2015).

PRODUCTION OF BIOCHAR

Biochar is a material produced by the thermal conversion process with limited oxygen delivery at temperatures less than 700 °C (Wang *et al.,* 2021) (Clough and Condron, 2010). It is a diverse renewable energy source capable of generating heat, electricity, and liquid biofuels (Xie *et al.,* 2015). The methods used to create biochar, such as pyrolysis, hydrothermal carbonization, gasification, and so on, as well as diverse bio-organic materials, pyrolysis temperature, modification methods, and other aspects, will all have an impact on the performance of biochar. Biochar is made from a wide range of biomasses, including crop leftovers thermally decomposed under various working conditions. It has an equally vast variation of composition. In this case, Xie *et al.,* (2015) provided a compilation of different biochar conversion technologies, along with their operating conditions and product yields, and discovered that with a longer residence period (up to 4 h) at moderate temperature (up to 500 °C), the biochar yield ranged from 15 to 35%, while the bio-oil yield ranged from 30 to 50%. However, with a shorter residence period (up to 2 s), more bio-oil (50-70%) was discovered.

Biochar is created by heating biomass at high temperatures (300-600 °C) in a closed reactor with no to minimal air. Under these conditions, biomass thermochemically converts to biochar (Liang *et al.,* 2008). Biochar has received a lot of attention in the political and academic worlds because to its multiple potential applications in agriculture, energy, and the environment. Biochar has a wide range of applications, including energy production, agriculture, carbon sequestration, wastewater treatment, and bio-refinery (Kambo and Dutta 2015). It also serves as an alternate method for handling organic waste. These benefits have rekindled agricultural experts' interest in making biochar from bio-residues and using the product as a soil amendment. Hakala et al. (2009) conducted a study to examine the potential of crop leftovers from 1997 to 2006 and discovered that crop residue availability ranged from 4.8 to 5.1 billion tonnes.

According to Kumar et al. (2015), India has the potential for a considerable amount of biomass feedstock from various sources. Hiloidhari et al. (2014) estimated that around 686 million tonnes of gross leftovers are available in India each year from agricultural crops, with a surplus potential of approximately 234.5 million tonnes.

Impact of Biochar on Soil health

Some research has concentrated on the effect of biochar amendment on physical and chemical qualities of various soils (Table 1). Biochar is a high carbon-content substance (greater than 50%) formed by heating biomass in the absence of oxygen. When biochar is applied to soil, it interacts primarily with the soil matrix, soil microorganisms, and plant roots (Gangothri and Yuvaraj 2017). The types and speeds of interactions vary depending on factors such as biomass and biochar composition, biochar preparation processes, physical properties of biochar, and soil environmental conditions, particularly soil temperature and moisture. Biochar can operate as a soil conditioner by increasing soil physical and biological qualities such as water retention and nutrient retention, as well as enhancing plant development. (Sohi *et al.,* 2010). The extensive spectrum of these atmospheric and soil benefits brought about by the use of biochar is illustrated in figure 1. Biochar is resistant to decomposition. When added to the soil, it sequesters carbon for an extended period, helping to mitigate climate change by reducing greenhouse gas emissions. Carbon sequestration also improves soil structure and promotes long-term soil health.

1. Cation exchange capacity (CEC) and nutrient retention

Biochar has a high surface area and porosity, allowing it to retain nutrients such as nitrogen, phosphorus, and potassium in the soil. It acts as a sponge, preventing leaching of these nutrients, making them more available to plants over time. Many studies suggest that after applying biochar to soil, soil acidity was lowered significantly and critical mineral absorption increased, with long-term impacts (Blackwell *et al.,* 2012). Biochar contains considerable levels of K and modest amounts of Mg, Ca, Cu, Zn, and Fe, which have fertiliser potential (Mwampamba *et al.,* 2013). Stockmann *et al*. reported that soil is the biggest terrestrial pool of organic carbon, containing roughly 2344 Gt of organic carbon globally. Small changes in the organic carbon store of the soil could have a big impact on the carbon concentration in the atmosphere. The physical, chemical, and biological integrity of the soil is critical to the sustainability of agricultural production. Biochar improves soil nutrient retention capacity, which is dependent on biochar porosity and surface charge. Biochar improves soil nitrogen retention by minimising leaching and gaseous loss, and it also improves phosphorus availability by slowing the leaching process. However, in terms of potassium and other nutrients, biochar has variable (both positive and negative) soil effects. Porosity, aggregate stability, and the amount of water contained in the soil after the addition of biochar increase and bulk density decreases. Biochar, in general, raises soil pH and hence alters plant nutrition availability. Biochar also changes the biological features of the soil by boosting microbial populations, enzyme activity, soil respiration, and microbial biomass. Finally, the application of biochar to soil improves fertiliser usage efficiency and nutrient uptake. Thus, biochar can be a possible nutrient reservoir for plants as well as a beneficial soil amendment (Hossain *et al.,* 2020). Biochar is rich in carbon and contains essential plant nutrients. When incorporated into the soil, it acts as a slow-release fertilizer, providing a sustained supply of nutrients to plants. This improves soil fertility and promotes healthier plant growth. Biochar, a carbon-rich product is known to increase soil carbon sequestration, reduce greenhouse gas emissions, and ultimately improve soil physicochemical properties (such as improved water-holding capacity, cation exchange capacity, and overall stability). It is also useful for improving soil fertility (such as nutrients availability and retention) and also participate in soil nitrogen cycling (Oladele *et al.,* 2019).

2. pH modification and liming effect

Depending on the feedstock used in its production, biochar can have varying pH levels. It acts as a buffer, helping to regulate soil pH and reducing the effects of soil acidification or alkalization. This is particularly beneficial in areas where soil pH is imbalanced, as biochar can help bring it closer to the optimal range for plant growth. The ash percentage (e.g. alkaline oxides, carbonates) in biochar can give significant alkalinity (Vassilev et al. 2013a) depending on the feedstock and technique (Xie et al. 2015). This gives biochars liming capabilities and permits them to be used as liming agents in acidic soils (Chintala et al. 2014). Prior to application, it is necessary to understand the liming potential of the biochar as well as the pH-buffering capacity (pH-BC) of the soil in order to make a lime recommendation. Biochar has the ability to raise soil moisture and pH. Biochar can produce liming by elevating pH. They can boost soil fertility by enhancing microbial activity, improving nutrient availability, and decreasing aluminium (Al3+) toxicity. While biochar is not a fertiliser, studies show that it can help retain nutrients in the soil due to its charged surface and large surface area, which allow it to absorb nutrients such as nitrogen, phosphorus, and carbon (Githinji, L. 2014).

3. Water holding capacity and soil moisture regulation

The porous structure of biochar enables it to absorb and retain water. It helps prevent waterlogging in clay soils by improving drainage, while in sandy soils, it increases water-holding capacity. This property aids in maintaining soil moisture levels, reducing drought stress on plants, and improving overall water management. Straw or grass-derived biochar (at 500-600 °C) enhances soil WHC when applied at 1 to 3%. In comparison to using biochar immediately after production, the review suggests that ageing biochar for at least a year with improved oxidation is advised for enhancing WHC and reducing hydrophobicity (Adhikari *et al.*, 2022). Biochar amendment increased water retention capacity, micropore volume, and accessible water content while decreasing soil bulk density. Higher soil water retention in treated soil is linked to biochar's inherent properties (e.g., internal porosity) and potential changes in soil structure. Microporosity and water retention were improved by using an intermediate biochar rate (12.5 Mg ha1) rather than the maximum rate (25 Mg ha1) studied by

(Lustosa *et al.,* 2020). The addition of biochar to the soil can have both direct and indirect impacts on water retention in the soil, which can last for a short or long time. The direct effect is due to its enormous internal surface area and high number of residual holes, which hold water by capillary action. This increases overall soil porosity and soil water content, minimising water mobility and reducing water stress in plants. An indirect consequence is improved soil aggregation and structure, which affects the soil's water retention capacity (Karhu *et al.,* 2011).

4. Microbial activity and soil biodiversity

Biochar provides a habitat and food source for beneficial soil microorganisms, such as bacteria and fungi. These microorganisms play a crucial role in nutrient cycling, decomposition of organic matter, and enhancing soil structure. By fostering microbial activity, biochar contributes to the overall health and resilience of the soil ecosystem. Biochar boosts soil microbial activity by providing labile C, mineral nutrients, and habitat for bacteria that colonise the biochar surface. Biochar modifies soil biological activities by causing a shift in the microbial community structure and composition. Biochar also shields soil bacteria from the harmful impacts of organic and inorganic contaminants. Biochar increases the efficacy of numerous microorganisms such as plant growth-promoting rhizobacteria and phosphorus-solubilizing bacteria as a result of favourable biochar-microbe interactions, which promotes agricultural yield through a variety of features (Saleem *et al.,* 2022). Biochar influences soil microbial activity and biomass, alters soil bacteria-fungi ratios and enzyme activity, and reshapes the microbial community structure. It should be noted that biochar application can drastically affect microbial community structure even if it has little effect on overall microbial activity or biomass (Zhu *et al.*, 2017). The addition of biochar to drip-irrigated arid soil could improve soil microbial biomass and activity, as well as enzyme activity related to C transformation (-glucosidase and cellobihydrolase) and enzyme activity linked to N transformation (arylamidase and L-glutaminase, but not -glucosaminidase). The 4.5 t ha1 application rate changed the microbial community composition and raised the total bacteria to fungus ratio. (Liao *et al.,* 2016).

5. Adsorption of pollutants and soil detoxification

Biochar has a high adsorption capacity for typical livestock effluent contaminants such as organic pollutants, heavy metals, nitrogen, and phosphorus. In comparison to commercial activated carbon products, biochar with good magnetic properties can be easily separated from liquid after magnetization (Han *et al.,* 2016). At the same time, because biochar has a high capacity for nitrogen and phosphorus adsorption, it can be employed as a slow-release fertiliser and has the characteristics of agricultural environment-friendly (Yao *et al.,* 2011). Biochar has been used successfully in the remediation of contaminated soils. It can adsorb heavy metals, pesticides, and other pollutants, reducing their mobility and bioavailability in the soil. This property makes biochar an effective tool in soil remediation efforts. Simultaneously, because biochar has a high capacity for nitrogen and phosphorus adsorption, it can be employed as a slow-release fertiliser. Biochar's sorption qualities vary substantially depending on the biomass source and temperature at which it is produced. Recently, it has been used as a possible adsorbent and an effective method of sequestering pesticide residues in soil. Aside from the sorption or sequestration of these hydrophobic chemicals, it also improves soil fertility and microbial activity, changes in soil physiochemical characteristics, reduced greenhouse gas emissions, and leaching of such contaminants into water sources (Bokade *et al.,* 2023).

CONCLUSION

Crop debris has traditionally been utilised as animal feed in impoverished nations. When it is not used for animal feed, it produces a massive surplus biomass, and farmers who burn it create a foggy and smoky environment. Converting such waste biomass into biochar avoids this problem while also creating job and economic opportunities. The use of biochar in agricultural systems is one possible alternative for increasing natural rates of carbon sequestration in soil, reducing farm waste, and improving soil quality. However, in order to promote the use of biochar as a soil amendment as well as a climate change mitigation option, research, development, and demonstration of biochar production and application are critical. To make the technique economical, low-cost biochar kilns must be developed for small and marginal farmers. The addition of biochar to soil is one of the best practises for overcoming any biotic/abiotic stress, such as heavy metal toxicity, soil acidity, nutrient unavailability, and so on, and increasing crop productivity. As a result, it is advised that biochar be used as a soil supplement to improve soil health and environmental conditions, as well as for long-term carbon sequestration. Biochar should be used as part of a holistic soil management approach, considering other soil health practices such as organic matter addition, crop rotation, and erosion control, to achieve the best results.

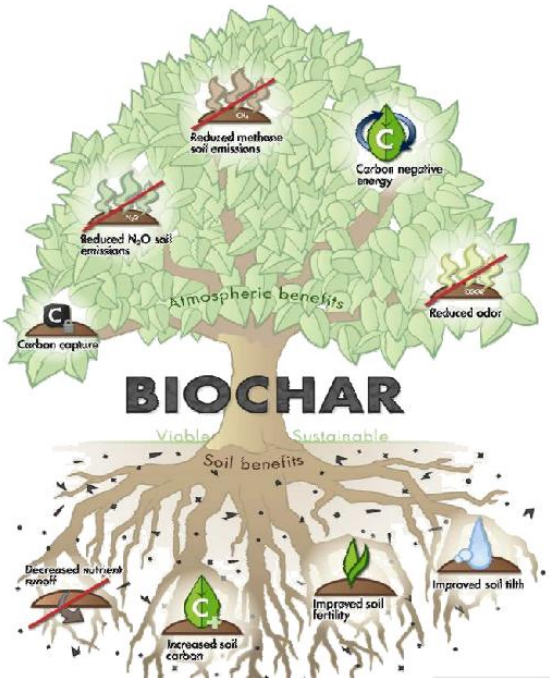

Figure 1: Source: Multiple benefits of biochar (Adapted from Kavin D. Brown)

Table 1 Influence of biochar on soil properties

Biochar rate	Soil type	Incubation	Bulk density (g cm^{-1})	pH	Cation exchange capacity (cmol kg^{-1})	Available P (mg kg^{-1})
Wood- 450,0 t ha^{-1}	Sandy clay loam	Year 2	-	6.86	-	-
Wood- 450,0 t ha^{-1}		Year3	1.04	6.44	-	16
Wood- 450,50 t ha^{-1}		Year 2	-	7.18		-
Wood- 450,50 t ha^{-1}		Year 3	1.08	6.6		16
Control	Sandy soil	Day 0	1.37	5.6	2.2	28
Control		Day 120	1.62	5.2	1.8	29
Peanut hull- 400, 2%		Day 0	1.49	7.3	2.7	47
Peanut hull- 400, 2%		Day 120	1.57	7.1	2.4	39
Peanut hull- 500, 2%		Day 0	1.57	7.4	2.4	38
Peanut hull- 500, 2%		Day 120	1.59	7.4	2.1	33
White lead tree – 700, 0%	Acidic soil	Day 105	1.42	3.95	7.41	-
White lead tree – 700, 2.5%		Day 105	1.15	4.65	9.26	-
White lead tree – 700, 5%		Day 105	1.08	5.07	10.8	-

Source: Ding, Y., Liu, Y., Liu, S., Li, Z., Tan, X., Huang, X., ... & Zheng, B. (2016). Biochar to improve soil fertility. A review. Agronomy for sustainable development, 36, 1-18.

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