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Review article

Sustainable biochar: A review on agronomic applications of biochar produced from plant residues

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ABSTRACT

Disparity in the use of chemical fertilizers affects the quality of soil, which in long term, has severe implications. Biochar mimics the benefit of chemical fertilizers in a sustainable way without harming the surroundings, rather it improves soil quality and helps in climate mitigation. Biochar has emerged as a promising solution for achieving sustainability and has attracted significant interest in recent years owing to its diverse range of agronomic applications. Numerous plant-based materials have been explored for the production of biochar via techniques such as pyrolysis, hydrothermal carbonization and gasification. Biochar can be applied for various agronomic applications such as for suppression of greenhouse gases, stimulating crop growth and microbial population and for the amendment of soil properties. Biochar can combat the detrimental gas emissions, such as carbon dioxide, nitrous oxide, and methane with great efficiency. Biochar has also been known as a highly effective soil amendment that can enhance soil fertility and increase crop yield. The application of biochar has been found to enhance soil quality by increasing its cation exchange capacity, water retention ability, and nutrient absorption. Furthermore, it can also stimulate microorganisms and alter their population dynamics for better outcomes. Extensive studies done on biochar have proved its diverse applicability in the agronomic sector and appraised biochar as a potent tool to emerge as a sustainable and powerful tool to combat the present environmental health conditions. This review article gathers extensive information on the biochar prepared from variety of plant residues only and its overall effect on plant-soil-microbiome system. This review serves as a knowledge repository for the beginners in the field of biochar.

1. Introduction

Biochar is a carbon rich product having fine structure and high porosity produced by thermal decomposition of biomass in limited supply or non- availability of oxygen (Phadtare and

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Kalbande, 2022). Two factors that make plant-based residues such as crop straws, corn stovers an excellent substrate for biochar production is its high percentage of lignin-cellulose content and its availability in abundance (Spokas and Reicosky, 2009, Adekanye et. al., 2022). The characteristics of biochar are primarily influenced by the feedstock biomass and the production parameters, specifically the temperature and residence time. The functional properties of biochar, including surface adsorption characteristics, surface area, porosity, structural groups, and alkalinity, are predominantly influenced by the feedstock materials and pyrolysis conditions (Huang et al., 2023). The half-life of biochar is estimated to range from several hundred to several thousand years, depending on the specific biochar type and production conditions. This is due to the fact that biochar contains a stable form of carbon that is primarily aromatic and resistant to degradation. Consequently, biochar has the potential to be available in the soil for a long time, ranging from several centuries to millennia. Consequently, the utilization of biochar as a soil amendment is expected to confer enduring soil attributes, surpassing those of uncharred organic matter such as compost, manure, or crop wastes (Wu et al., 2013).

Biochar is a promising solution for achieving sustainability and has attracted significant interest in recent years owing to its diverse range of agronomic applications (Choudhary et. al., 2021). Biochar is accountable for the mitigation of detrimental gas emissions, such as carbon dioxide, nitrous oxide, and methane (Phadtare and Kalbande, 2022). Biochar is known as a highly effective soil amendment that can enhance soil fertility, increase crop yield, and facilitate the sequestration of atmospheric carbon into the soil. The application of biochar has been found to enhance soil quality by increasing its cation exchange capacity, water retention ability, and nutrient absorption (El-Hassanin et al., 2020). Biochar is now also being used in wastewater treatments to absorb dyes and heavy metals that are commonly used in industrial effluents (Oliveira et al., 2017). The application dynamicity of biochar in different fields is presented in Figure 1.

The aim of this article is to highlight the agronomical applications of biochar derived out of plant-based biomass only. Potential of different plant-based materials to serve as substrates for the production of biochar will also be explored, alongwith the common production techniques. Some of the agronomical applications of biochar that would be discussed are crop growth, microflora stimulation, modifications in soil properties and suppression of greenhouse gases.

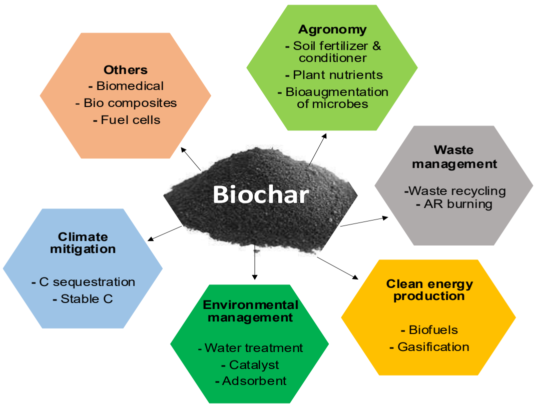

Fig 1 Multidimensional applications of biochar

2. Plant residues as feedstock for biochar production and Characterization

Researchers all around the world have performed numerous studies and have tested enormous varieties of plant-based materials for the production of biochar via pyrolysis. Biomass can be categorized as woody and non-woody. The composition of woody biomass is predominantly composed of residual content from trees and forestry operations. Wood biomass exhibits low moisture content, low particulate matter, minimal voids, high mass per unit volume, and elevated thermal efficiency. Non-woody biomass is composed of organic matter derived from animal excreta, as well as solid waste generated by industrial and agricultural activities. Non-woody biomass exhibits characteristics such as elevated debris content, high moisture content, increased porosity, reduced density, and a lower calorific value. Moisture content is a crucial factor affecting biomass formation among the diverse characteristics of biomass feedstock. Biomass with low moisture content is more desirable for the creation of biochar because it requires less amount of energy for the pyrolysis process. This makes the formation of biochar economically viable in comparison to biomass with high moisture content (Armah et al., 2022, Ronsse et al., 2013). According to Akhtar et al. (2012) the process of pyrolysis involving cellulose and hemicellulose results in a higher quantity of liquid yield, commonly referred to as bio-oil. On the other hand, lignin produces a stable yield, known as biochar. Therefore, biomass possessing a higher proportion of lignin is suitable to produce biochar. Numerous scientific investigations have discovered that the properties of biochar are affected by the type of feedstock utilized, and that varying feedstocks may be suitable for distinct applications.

Plant based materials include shells, straw, peels, husks, bagasse, cobs, hull, barks, fibres, chip, leaves, stem and many more. They may be categorized into three classes, agro-residues like straw, husk, hull and others are produced as waste at the farmer's field, agro-processed wastes like palm shell, coconut shell, peanut shell, almond shell, nut shell, orange peel, sugarcane bagasse etc and thirdly, parts of biomass like bamboo stem, spruce wood, pine chip, pine bark etc. Agro-residue wastes remain at the discretion of farmers to be properly discarded or recycle, but they are usually Shells, peels, cobs, stems, bagasse etc are the wastes produced during the processing of certain biomass.

Some of the studies that well demonstrated the potential of certain substrates for the production of biochar have been presented in **Table 1**.

Table 1 Globally studied agricultural residues (biomass) for biochar production

Biomass for biochar	**Pyrolysis temperature (°C)**	**Characteristics of biochar**					**Reference**
		Total carbon (%)	**Fixed carbon (%)**	**Volatile matter (%)**	**Ash content (%)**	**Moisture (%)**	
Palm shell	400	61.0	41.8	49.7	8.5	3.7	Abdullahi et al, (2017) Wang et al, (2017)
	600	90.6	88.5	11.5	6.7	2.2	
Coconut shell (green)	350	-	34.41±8.39	29.53±8.77	33.56±0.41	2.5±0.03	Devens et al, (2018)
	600	93.9	91.9	8.1	4.1	7.1	Wang et al, (2017)
Orange peel	350	-	59.26±2.98	30±2.26	9.26±0.7	1.48	Devens et al, (2018)
Rice husk	450	63.90	54.59	22.06	22.81	0.54	Herrera et al, (2022)
	500	64.20	52.45	24.09	23.14	0.32	
	550	65.60	51.57	24.84	23.35	0.24	
	600	69.3	48.65	27.00	24.12	0.23	
	500	-	38.66	22.03	34.40	4.91	Nguyen et al, (2018)
	700	-	43.1	15.08	38.22	3.6	
	900	-	44.67	12.95	39.22	3.16	
	600	54.5	86.1	13.9	47.0	5.7	Wang et al, (2017)
	450	-	58.42	19.42	11.16	11.00	Billa et al, (2019)
Bamboo	500	82.1±0.6	81.5±0.4	8.10±1.7	3.9±0.4	6.5±1.0	Hernandez-Mena, (2014)
	500						
	700	-	51.56	31.45	11.1	5.89	Nguyen et al, (2018)
	900	-	55.06	25.87	13.56	5.51	
		-	58.88	22.37	13.56	5.19	

Sugarcane bagasse	400	66.38	63.12	26.51	7.13	3.24	Sekar et al, (2014)
	600	-	69.10	20.35	7.58	2.97	
	800	-	73.80	15.26	8.13	2.81	
	600	88.6	69.9	30.1	13.0	3.7	Wang et al, (2017)
Corncob	300	67.21	49.1	43.6	4.9	2.4	Liu et al, (2014)
	400	79.65	71.7	20.8	5.4	2.1	
	500	83.27	81.6	8.6	8.2	1.6	
	600	84.31	82.4	7.2	8.7	1.7	
	600	79.5±0.38	69.6±0.33	18.3±0.18	12.4±0.05	-	Thies et al, (2012)
	650	-	65.73	4.34	23.41	6.52	Billa et al, (2019)
Sawdust	500	87.61	80.6	13.1	5.1	1.2	Liu et al, (2014)
	520	-	68.91	6.19	13.28	11.62	Billa et al, (2019)
Cornstalk	500	77.34	76.6	8.9	12.7	1.8	Liu et al, (2014)
	600	73.4±0.46	75.0±0.22	15.4±0.31	9.6±0.02	-	Thies et al, (2012)
Melaleuca	500	-	64.18	27.59	2.83	5.4	Nguyen et al, (2018)
	700		72.88	18.94	3.20	4.98	
	900		74.82	17.20	3.30	4.68	
Water hyacinth	500	-	14.66	34.45	44.38	6.51	Nguyen et al, (2018)
	700		18.95	25.58	50.98	4.49	
	900		26.14	18.82	51.32	3.72	
Spruce wood	600	86.7±0.29	88.1±0.23	10.5±0.21	1.5±0.09	-	Nguyen et al, (2018)
Wheat straw	600	75.3	78.8	21.2	23.4	8.1	Wang et al, (2017)
Cotton stalk	600	83.2	71.2	28.8	9.5	8.5	Wang et al, (2017)
Olive	600	71.8	79.1	20.9	18.1	10.0	Wang et al,

pomace							(2017)
Coconut fiber	600	82.6	74.9	25.1	13.5	10.4	Wang et al, (2017)
Peanut hull	400	72.9	59.8	25.2	6.9	8.1	Yang et al, (2020)
Pine chip	400	78.5	63.0	27.8	1.8	7.4	Yang et al, (2020)
Almond shell	400 500 600	82.07±1.23 82.85±1.34 85.50±0.98	46.79±1.34 52.93±1.54 59.20±1.98	37.35±5.30 36.07±0.28 31.94±1.27	15.86±1.05 11.00±0.59 8.86±0.50	-	Cui et al, (2013)
Nut shell	400 500 600	78.15±0.09 79.09±0.02 81.13±0.07	37.45±2.30 40.63±2.00 47.85±1.89	59.19±0.96 57.43±0.85 50.03±1.22	3.36±0.11 1.94±0.07 2.12±0.30	-	Cui et al, (2013)
Chamaecyparisobtusa (Hinoki cypress)	350 400 500 600	75.74 77.85 85.79 91.56	58.52 66.10 78.06 86.73	41.17 33.45 21.26 12.45	0.32 0.45 0.69 0.83	-	Yang et al, (2020)
Cassava	600	-	70.36	5.32	17.12	7.20	Billa et al, (2019)
Coffee	490	-	65.09	12.50	12.79	9.62	Billa et al, (2019)
Ground nut	580	-	67.37	6.82	16.40	9.41	Billa et al, (2019)
Wood	300 450 600 750	71.3 86.3 92.3 92.5	57.4 83.2 93.6 97.4	42.6 16.8 6.4 2.6	0.5 1.2 1.3 1.1	-	Rogovska et al, (2014)
Straw	300 450 600 750	76.2 86.4 90.3 93.7	66.5 84.1 92.6 95.9	33.5 15.9 7.4 4.1	19.1 22.9 24.5 25.8	-	Rogovska et al, (2014)
Oat hull	300 500	70.13 76.97	18.37 15.64	73.93 74.93	7.70 9.43	2.20 1.64	Gonzalez et al, (2013)

Pine bark	300 500	57.92 72.39	8.65 19.85	77.59 59.76	13.76 20.39	2.06 1.98	Gonzalez et al, (2013)

3. Conversion of biomass into biochar, Thermochemical processes

The process of thermochemical conversion is a widely utilized method for the production of biochar as depicted in Fig. 2. The various techniques employed for thermochemical conversion include pyrolysis, hydrothermal carbonization (HTC) and gasification.

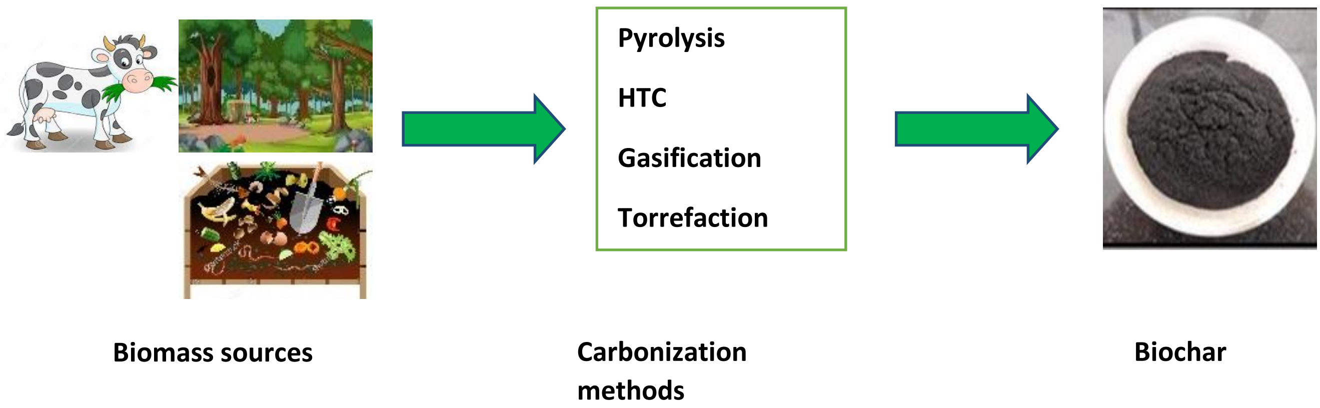

Fig. 2 Different methods of thermochemical conversion from biomass to biochar

Pyrolysis is a chemical process that involves the decomposition of organic substances in the absence of oxygen, typically at temperatures that fall within the range of 250 to 900 degrees Celsius (Yashika et al., 2020). In the absence of oxygen, biomass can undergo heating above its thermal stability limit, leading to the formation of more robust by-products, such as solid residues. an anaerobic environment prevents combustion of biomass during the heating of process (Armah et al., 2022). The yield of a process is primarily determined by the operating temperature. As the temperature of the pyrolysis is elevated, there is a decrease in the production of biochar and an increase in the generation of syngas (Wu et al., 2013, Armah et al.,2022). Pyrolysis can be classified into three primary categories, namely slow, flash, and fast pyrolysis (Figure 3). In slow or conventional pyrolysis, the feedstock is slowly heated over an extended period at a low heating rate to low- moderate temperatures. During the process of slow pyrolysis, the biomass undergoes gradual devolatilization. Biochar is the predominant by-product, accounting for 35-45% of the total yield, while bio-oil and syngas constitute 25-35% and 20-30% of the yield, respectively (Phadtare and Kalbande, 2022, Armah et al., 2022). In flash pyrolysis the process of carbonization takes place at higher heating rates and temperatures over a short period of time. Flash carbonization involves temperatures of up to 1000°C for a few seconds (Phadtare and Kalbande, 2022). Fast pyrolysis is a direct thermochemical process that has a significant potential for use in the production of liquid bio-oil from solid biomass. The process of fast pyrolysis takes place in the absence of oxygen, at temperatures above 500°C and with a heating rate above 300°C per minute. The process of fast pyrolysis yields a bio-oil as a major product (60%), while the remaining 40% is divided equally between biochar and syngas, with each constituting 20% of the total yield (Wu et al., 2013, Armah et al., 2022). The process of hydrothermal carbonization is considered to be an economically appealing technique for the production of biochar due to its ability to be carried out at a relatively low temperature range of 180-250°C. The product produced through the hydrothermal method is referred to as hydro char. In this process the biomass is homogenized with water and subsequently introduced into an enclosed reactor (Wu et al., 2013). Gasification is a thermochemical process that occurs at higher temperatures ranging from 700 to 900°C. The primary product of this method is syngas, which predominantly comprises hydrogen. Char is regarded as a secondary product with a comparatively lower production rate, which also includes ash, tar, and a relatively small amount of oil (Wu et al., 2013, Armah et al., 2022). The impact of reaction temperature on biochar production and characteristics is crucial. The rise in pyrolysis temperature leads to thermal cracking of heavy hydrocarbons. This, in turn, causes a reduction in solid product and an increase in liquid and gas output. At high temperatures, the transformation of energy into biomass may exceed the bond dissociation energy, thereby promoting the release of a volatile element from the biomass (Wu et al., 2013; Ronsse et al., 2013). In the majority of the experimental studies, it was found that the pyrolysis process resulted in an increase in ash content, fixed carbon, while volatile matter, showed a decrease with increasing pyrolysis temperatures. Therefore, it can be inferred that lower temperatures are more optimal to produce biochar (Adekanye et al., 2022; Phuong et al., 2015).

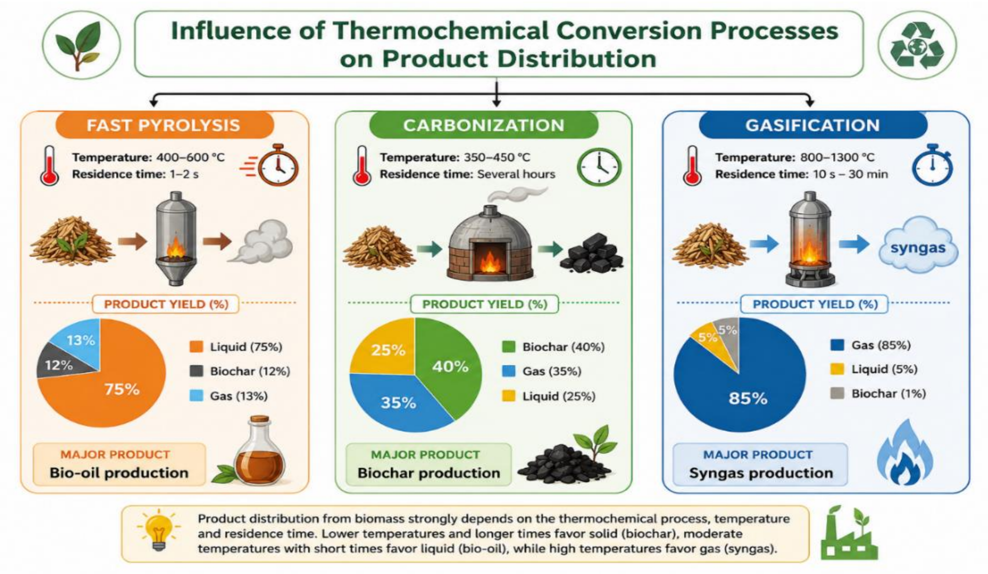

Fig. 3 Classification of pyrolysis and product yield profile

4. Sustainability of biochar

4.1. Enhanced soil properties

The two qualities that set biochar amendment apart from other organic materials are its high stability against decomposition, which enables it to stay in the soil for longer periods of time and provide long-term benefits to the soil, and its higher capacity to retain nutrients. Biochar improves the soil quality by enhancing soil properties such as bulk density, porosity, Water holding capacity, pH and Cation exchange capacity etc., which are crucial properties in determining soil fertility and crop growth (Prayogo et a., 2014). **Table 2** summarizes the results of different studies conducted to evaluate the role of biochar in altering different soil properties.

4.1.1. Bulk density and porosity

Biochar application in soil led to significant increase in Porosity while decreasing the bulk density as reported by (Kang et al., 2018; Adekiya et al., 2020; Sekar et al., 2014; Nyambo et al.,2018; Tanure et al., 2019). Increase in the porosity of soil can be attributed to formation of macropores and aggregation of soil particles due to high pore volume and exceptionally porous structure and high pore volume of the Biochar. While the low temperature can be correlated with relative low bulk density of Biochar (Sakhiya et al., 2020), biochar produced at higher pyrolysis temperature are characterized by high porosity and relatively larger surface area which gives an edge over biochar produced at lower temperatures in improving the bulk density, porosity and adsorption ability of soil (Alotaibi and Schoenau, 2019).

4.1.2. The pH

Biochar is known for its liming potential due to its alkaline pH. Several studies have reported a significant increase in the soil pH at higher application rate (Alotaibi and Schoenau, 2019; Chan et al., 2007; El-Hassanin et al., 2020; Rogovska et al., 2014, Mohan et al., 2018). The negatively charged phenolic, carboxyl, and hydroxyl groups that are bound to H^+ ions on the surface of biochar reduce its activity in the soil and raise the pH of the soil. Additionally, biochar has relatively higher ash content and the ash contains alkali metal oxides and hydroxides that readily dissolve in and react with soil, elevating soil's pH levels (Tanure et al., 2019).

4.1.3. Cation exchange capacity (CEC)

Biochar has a large surface area per mass and a high surface charge density, adding it to soil can boost the soil CEC, because of increase in the soil colloids' exchange points which can result in the adsorption of a variety of ions by the soil as reported in several studies (Mohan et al.,2018;Adekiya et al., 2020; Kang et al., 2018; Alotaibi and Schoenau, 2019; Kamara et al., 2015). The cation exchange capacity of biochar depends on the availability of functional groups such carboxylic and phenolic OH groups on the biochar's surface, but the CEC varies with the feedstock and pyrolysis conditions (Mahmoud et al., 2019). Other characteristics such as higher porosity and surface area of biochar also play an important role in increasing the CEC of the soil (Nyambo et al., 2018).

4.1.4. Water holding capacity (WHC)

A number of studies have been conducted by researchers to evaluate the effect of biochar on the water holding capacity of soil (Karhu et al., 2011; Mangrich et al., 2015; Alotaibi and Schoenau, 2019; Mohan et al.,2018; Tanure et al., 2019). Physical properties of biochar such as particle size, porosity, surface area and distribution of pore affect the ability of Biochar to alter water holding capacity of soil. Biochar with higher surface area significantly increases water retention property of soil. Size and shape of biochar particles plays a significant role in governing the efficiency of biochar in improving WHC of soil because the interaction between the biochar and soil particles can either lead to increase or decrease of inter pore volume that directly influences the WHC of soil (Ndede et al., 2022). Biochar produced at low temperatures generally possess high degree of hydrophobicity due to presence of a number of aliphatic groups, these aliphatic groups when subjected to high pyrolysis temperatures gets volatilize hence biochar produced at higher pyrolysis temperatures exhibit better water retention capacity than those produced at lower temperatures (Alotaibi and Schoenau, 2019).

Table 2 Effect of biochar amendment on soil properties

Parameter	Feedstock	Application Rate	Impact	References
pH	Date Palm	8 t/ha	Significant decrease with the treatment of BC300	Alotaibi and Schoenau (2019)
	Green Waste	10, 50 and 100 t/ha	Increase with increase in application rate	Chan et al. (2007)
	Rice Straw	1.25, 2.5,5 and 10% (w/w)	Significant increase with highest biochar dosage (10%)	El-Hassanin et al. (2020)
	Mixed Hardwood	0, 19.2, 38.3, 57.5, 76.6, and 95.8 Mg/h	Increase by 1 -1.4 units. High application rate led to more significant increase	Rogovska et al. (2014)
	Corn Stover and Rice husk	0.5, 1.5 and 3 (wt.%)	Increase by 0.3 - 0.8 units.	Mohan et al. (2018)
Bulk Density	Barley Straw	10 t/ha	5.95% lower than control	Kang et al. (2018)
	Hard Wood	10, 20 and 30 t/ha	Reduced by 46.3% and 74.7% in first and second year of treatment (30 t/ha) respectively	Adekiya et al. (2020)
	Subabul	30 Mg/ha	Decreased by 7.3%	Sekar et al. (2014)
	Maize crop residue	0, 2.5, 5, 7.5 and 10%	Gradual Decrease with increase in application rate from 2.5 to 10%	Nyambo et al. (2018)
	Eucalyptus spp. bark	0, 5, 10, 20, 40 and 60 g/kg	Significant decrease at higher application rates	Tanure et al. (2019)
Water Holding Capacity	-	9 t/ ha	Increased by 11%	Karhu et al. (2011)
	Palm oil, sugar bagasse and Water Hyacinth	5% (m/m)	Increased by 5.5, 6.5 and 8% respectively	Mangrich et al. (2015)
	Date Palm residues	8 t/ha	Low temperature BC increased Water retention by 46% Water retention increased with increased incubation time.	Alotaibi and Schoenau (2019)
	Corn Stover and Rice husk	0.5, 1.5 and 3 (wt.%)	21.8 wt.% and 29.7 wt.% with treatment (3%) RHBC and CSBC.	Mohan et al. (2018)

			WHC more significantly increased by CSBC treatment than RHBC	
	Eucalyptus spp. bark	0, 5, 10, 20, 40 and 60 g/kg	Significant increase at high biochar dosage	Tanure et al. (2019)
Porosity	Hard Wood	10, 20 and 30 t/ha	Substantial increase by 46.5% and 65.0% in first and second year of treatment (at 30 t/ha)	Adekiya et al. (2020)
	Wood residues	0, 10, 20 and 40 Mg/ha	Slight increase with increase in application rates. Maximum increase from 0.71 (control) to 0.77 (40 Mg/ha)	Koga et al. (2017)
	Subabul	30 Mg/ha	9.3% higher than control	Sekar et al. (2014)
	Maize crop residue	0, 2.5, 5, 7.5 and 10 %	Increased with increase in application rate. Highest (0.79 kg/m^3) at 10 % after 40 days of treatment.	Nyambo et al. (2018)
	Eucalyptus spp.	0, 5, 10, 20, 40 and 60 g/ kg	Microporosity increased with increase in biochar dosage	Tanure et al. (2019)
CEC	Rice Straw	15 g/kg	Increased [Control -7.4] [amended soil 10.2]	Alie et al. (2015)
	Corn Stover and Rice husk	0.5, 1.5 and 3% (w/w)	Maximum increase observed at 3% (w/w) – 362% and 719% by CSBC and RHBS. Soil treated with RHBC showed greater increase in CEC at all application rates.	Mohan et al. (2018)
	Hard wood	10, 20 and 30 t/ha	Significant increase with increase in application rate	Adekiya et al. (2020)
	Barley Straw	10 t/ha	34.1% higher than the control	Kang et al. (2018)
	Date palm residues	8 t/ha	BC300 treated soil showed significantly higher CEC.	Alotaibi and Schoenau (2019)

4.2. Positive effects on crop growth and yield

Biochar is a promising soil amendment known to increase crop yield, improve germination rate and fruit quality because of its good liming and nutrition retention potential. **Table 3** summarizes the effect of biochar on crop growth and yield in a number of pot and field trials. It has substantial influence on crop growth and yield either by direct or indirect mechanisms. The direct mechanism depends on biochar's exceptional ability to retain and supply nutrients such as K, P, S, Ca and Mg etc which are essential for plant growth, it also acts as a slow-release fertilizer. The indirect mechanism involves its ability to alter physical and chemical properties of soil such as water holding capacity, CEC, porosity, and bulk density etc which enhances the soil quality and fertility hence plays an important role in crop growth and development (Mahmoud et al., 2019; Suthar et al., 2018; Chan et al., 2007). Several studies including both pot and field trials have been conducted to investigate the effect of biochar on crop growth have found that the pyrolysis temperature used for biochar production play the most significant role in influencing the biochar's ability to have a positive effect on crop yield and growth. A number of studies have found that low temperature biochar is mostly suitable for application in improving crop growth (Suthar et al., 2018, Alotaibi and Schoenau, 2019). Another major factor that plays a role in biochar application in crop growth is the application rate, a number of studies have reported that higher application rates lead to higher yield in crops such as wheat, cocoyam, radish (Chan et al., 2007; Adekiya et al., 2020; Esawy et al., 2019). A number of studies have also reported that biochar is not the most efficient tool for crop growth when applied alone, but when applied in combination with mineral fertilizers it has yielded more prominent results (Chan et al., 2007; Alotaibi and Schoenau, 2019).

Table 3 Effect of biochar application on the overall growth and yield of different crops and plants

Crop	Experimental Type	Soil	Region	Biochar	Rate	Effect	Reference
Wheat crop	Pot	Sandy desert	Saudi Arabia	Date palm residues	8 t/ha	Low Temperature BC had significant effect on growth when applied in combination with nitrogen fertilizer	Alotaibi and Schoenau (2019)
Radish plant	Pot	Hard setting Alfisol	Australia	Green waste	10, 50 and 100 t/ha	Substantial increase in yield with higher application rates. when biochar was used in conjunction with nitrogen fertilizer	Chan et al. (2007)
Tomato	Pot	Coarse Sand	USA	Bamboo	1% and 3%	Low temperature BC had a positive effect on plant growth. Led to production of dark red firm tomatoes with higher sugar, amino acid and nutritional content.	Suthar et al. (2018)
Wheat	Field	Silt loam	Pakistan	Cotton Stalk	-	BC in combination with nitrogen fertilizer led to substantial increase in crop growth and yield	Zarmeena et al. (2021)
Cocoyam	Field	Sandy Loam Alfisol	Nigeria	Hard Wood	0, 10, 20 and 30 t/ha	Significant increase in crop yield as application rate increased from 0-30 t/ha	Adekiya et al. (2020)
Rice (ROK3 and NERICA L19)	Pot	Fine Sandy Loam	Sierra Leone	Rice Straw	15 g/kg	Plant height increased significantly by 18.1 and 22.8% for ROK 3 and NERICA L19. Notable differences were also found in tiller number and biomass yield.	Alie et al. (2015)
Wheat, Soyabean	Field	Loamy Sand	China	Maize Stalk	-	Significant increase in grain mass per plant and biomass by 24, and 11% for soyabean and 28 and 32% for wheat.	Lin et al. (2015)
Maize	Field	Saline Sodic soil	Egypt	Wood Saw Dust	5, 10 and 19 t/ha	Positive correlation between maize yield and higher application. Grain yield increased by 20, 25 and 32% with 5, 10 and 19 t/ha respectively	Esawy et al. (2019)
Okra	Field	sandy loam	Ghana	Corn Cob	10 t/ha	Increased yield by 11.4%	Frimpong et al. (2021)
Maize	Field	Sandy	China	Rice Straw	20 and 40 t/ha	Increase in grain yield by 23.9% and 25.3%	Liu et al. (2021)

4.3. Soil microflora stimulation

Several studies have found out the favorable effects of biochar on the microorganisms thriving in the soil. Some of the experimental studies proving the purpose are summarized in **Table 4**.Positive results were mentioned by many studies that revealed significant effects of application of biochar on the microbial community in the soil (Gomez et al., 2014; Cui et al., 2013; Pan et al.,2016, Bamminger et al., 2014, Mackie et al., 2015, Fang et al.,2020,Prayogo et al., 2014, Lu et al., 2014, Anderson et al., 2011, Liu et al., 2018). On the other hand, a study observed no effect on the microbial population (Elzobair et al., 2016).

The biochar provides an appropriate condition for the microbial community to thrive. The properties of biochar such as its porous nature and larger surface area offer an optimal environment for the microorganisms like fungi and bacteria to flourish.

Some studies state that the pores present in the biochar may allow the recessive microbes to mask themselves. The porous nature of the biochar can also trap gases such as oxygen and favor the colonization of aerobes in the microenvironment. In the scarcity or absence of oxygen, anaerobic processes may take place. In some situations, the biochar may itself be metabolized by certain microorganisms or the captured matter in the biochar voids can be fed upon by these microbes for consumption (Tanure et al., 2019).

The presence of certain volatile compounds the biochar produced from distinct substrates may pose significant effects on the microorganisms. Ajeng et al., 2020, summarized the effect of phenolic compounds in the biochar produced from corn stems at 450 degrees Celsius to oppose the growth of the *Bacillus mucilaginosus* species. Pine wood biochar produced at 300- 500 degrees celsius has also shown to adversely affect the *Synechococcus* species due to toxic phenolic compounds synthesis. Similarly, polyaromatic hydrocarbons have also shown to adversely affect the microbial population. Supplementation of biochar significantly affects the physical as well as chemical composition of the soil such as density, pH, bulk density, water holding capacity, enzyme activity and nutrients which directly affects the microbial community living in it (Huang et al., 2023). The modification of the parameters of the soil presents remarkable effects on the microbial faction.

Table 4 Effect of biochar application on the soil microflora

Biomass for Biochar	Biochar application rate	Effect on microorganisms	Reference
Oak pellet	0- 20% (w/w)	Overall increase in biomass with higher gram negative bacterial species in comparison to gram positive and fungal species	Gomez et al. (2014)
Wheat straw	0- 40 t/ha	Expanded the amount of both *Actinomycetes* and fungal species	Cui et al. (2013)
Rice straw	3.652 g C/kg	Improved the concentration of gram-negative bacterial species	Pan et al. (2016)
Miscanthus giganteus	2% (w/w)	Elevated the fungi,bacteria ratio, along with increase in biomass	Bamminger et al. (2014)
Hardwood and coniferous wood chip	8 t DM/ha	Increased the titre of *Actinobacteria*, *Acidobacteria* and *Gemmatinonadetes*	Mackie et al. (2015)
Eupatorium adenophorum	0- 5 (w/w)	Deflated the negative impact of chloropicrin fumigant on the beneficial soil species and their activity	Fang et al. (2020)
Willow	2% (w/w)	Elevated the number of gram-negative bacteria, *Actinobacteria* and overall biomass of bacteria	Prayogo et al. (2014)
Corn straw	0.5% (w/w)	Inflated biomass of microbes	Lu et al. (2014)
Pinus radiata	0- 30 t/ha	Increased the concentration of microbes	Anderson et al. (2011)
Rice husk (raw)	2% (w/w)	Deflated the amounts of native microbes, while new strains dominated	Liu et al. (2018)

4.4. Role of biochar in mitigating climate change, Suppression of greenhouse gas emission

Several experimental studies have been conducted on the applications of agriculture-based biochar on the suppression of greenhouse gas emission from the soil into the environment. Some of the studies that have shown positive results on mitigating the greenhouse gases such as nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) are summarized in **Table 5**.

Some of the experimental studies that gave positive results in the remission of greenhouse gas such as nitrous oxide has been done by many scholars (Spokas and Reicosky, 2009, Spokas et al.,2009, Case et al., 2012, Zhang et al., 2012, Wang et al., 2012, Song et al., 2016, Spokas et al., 2009,Wu et al., 2013, Fidel et al., 2019, Yang et al., 2020).

Table 5 Effect of biochar application on the greenhouse gas emission from the amended soil

Biomass for Biochar	Biochar application rate	Nitrous Oxide	Carbon Dioxide	Methane	Reference
16 different biochars	10% (w/w)	Reduced by almost all biochars	Reduced by 3 biochars for agricultural soil, Reduced by 13 biochars for forest nursery soil and Reduced by 14 biochars for landfill cover soil	Reduced by almost all biochars	Spokas. and Reicosky (2009)
Mixed sawdust	>20% (w/w)	Significant reduction	-	-	Spokas et al. (2009)
Hardwood	22 t/ha	Reduction by 49%	-	-	Case et al. (2012)
Wheat straw	40 t/ha	Reduction by 41.8%	-	-	Zhang et al. (2012)
Rice husk	0, 25, 50 t/ha	Reduction by 54% during rice cultivation and by 53% during wheat cultivation	-	-	Wang et al. (2012)
Hardwood	50 t/ha	-	Reduction by 37% in field and Reduction by 55% in laboratory	-	Case et al. (2014)
Husk	20- 30 t/ha	Reduction by 16% in general, Reduction by 20% in paddy field and Reduction by 18% in upland	Reduction by 5% in paddy field	-	Song et al. (2016)
Hardwood and Softwood mixture	0.5% (w/w)	Significant reduction	-	-	Fidel et al. (2019)
Wheat straw	0, 10, 25	Significant	-	-	Wu, et al. (2013)

	t/ha	reduction			
Corn residue	0, 15, 30, 45 t/ha	Reduction by 39- 110%	Reduction by 18 - 41%	Reduction by 124 - 132%	Yang et al. (2020)

The studies that proved right for combating the carbon dioxide emissions into the environment were also performed (Spokas et al., 2009, Case et al., 2014, Song et al., 2016, Yang et al., 2020). Studies that involved the declination of methane were also done (Spokas et al., 2009, Yang et al., 2020).
The depreciation in the release of the greenhouse gases by the addition of biochar in the soil may be associated with many mechanisms based on the physical, biotic as well as abiotic factors. Nitrous oxide suppression in the soils correlates to the elevation in the rate of aeration in the soil and adsorption of ammonia or nitrate in the soil. Biotic factors such as inhibitory compounds like ethylene that hinder the growth of microorganisms may also play a role in mitigating the release of nitrous oxide from the soil. Methane emission reduction relates to the increased oxidation activity in the methanotrophic microorganisms in the soil that oxidize methane or production of lower amounts of methane due to elevated porosity and aeration in the soil as a result of addition of biochar to the soil (Mukherjee et al., 2013). Carbon dioxide sorbs between the pore spaces of the biochar and acts as the major mechanism for the capture of the greenhouse gases. It influences and modifies the action of some microorganisms which are linked to the carbon cycle. Furthermore, the biochar affects the plants and their capacity to utilize the carbon, thereby leading to the lower amounts of carbon dioxide emissions and carbon sequestration (Wang et al., 2023).

However, many studies revealed that addition of biochar to the soil increased the amounts of greenhouse gases released into the environment. In some experimental studies, carbon dioxide emissions increased on application of biochar to the soils (Spokas et al., 2009, Zhang et al., 2012, Wang et al., 2012, Case et al., 2014, Song et al., 2016, He et al., 2017). Increased emissions of methane were also seen in studies done by many scholars (Wang et al., 2012, Song et al., 2016).

The inflated levels of carbon dioxide on supplementation of soil with biochar may be linked to escalated levels of decomposition of the organic matter in the soil by incrementing microbial activity or by biochar carbon mineralization. The microorganisms may also initially act upon the compounds present in liable state in the biochar and add up to the released carbon dioxide (Mukherjee et al., 2013). The higher emission of methane on addition of biochar to the soil may be due to increased amounts of organic carbon dissolved in the soil, acting as the source of energy for the methanogens (Wang et al., 2017).

5. Conclusion

Biochar is a promising solution for achieving sustainability and has attracted significant interest in recent years owing to its diverse range of agronomic applications. This paper summarizes that biochar has the potential to be applied for agronomic uses. Its application in soil has the potential to improve soil porosity, aeration, water holding capacity, nutrient availability, decrease soil acidity, stimulate the microbial population in the soil and boost crop yields, while it can also act as potent suppressor for greenhouse gasses. The wide variety of feedstocks available for the production of biochar make it more economical and applicable. Production temperatures, feedstock type and application rate plays a major role in determining the applicability of biochar. Despite the benefits offered by biochar applications, lack of long-term field research raises concerns about the global impact, capability, and sustainability of biochar in the long run. The implementation of biochar use is still not well feasible at commercial scales due to financial matters (Maroušek et al., 2023*)*. The outcomes of shorter trials are inadequate to provide a precise cost-benefit evaluation for determining the quantity and frequency of application of biochar amendments. Future research should prioritize conducting long-term field trials to assess the effects of biochar on soil health and plant growth across diverse climatic and soil conditions. The other application areas such as suppression of greenhouse gasses and stimulation of microbial community must also be further assessed to enable biochar to emerge as a sustainable and powerful tool to combat the present environmental health conditions.

Declarations

Ethics approval and consent to participate, Approval was obtained from the CSIR-NEERI ethics committee. Informed consent was obtained from all individual participants included in the study.

Competing interests,

The authors have no competing interests to declare that are relevant to the content of this article.

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