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Review Article

Biochar: A sustainable tool for soil health, reducing greenhouse gas emissions and mitigating climate change

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Abstract

The transformation of agricultural waste into biochar that is both eco-friendly and cost-effective is not only a wise recycling strategy but also a solution to environmental pollution management. Due to its low cost, high efficiency, simplicity of use, ecological sustainability, and reliability in terms of public safety, biochar from agricultural residues can be a useful alternative technique for controlling contaminants. Biochars have achieved significant progress in the following areas: reducing greenhouse gas emissions, reducing soil nutrient dispersion, sequestering atmospheric carbon into the soil, increasing agricultural productivity, and reducing the bioavailability of environmental contaminants. A comprehensive scientific assessment of the relationship between the properties of biochars and their impact on soil properties, environmental pollutant remediation, plant growth, yield, and resistance to biotic and abiotic stresses is warranted by recent advancements in the understanding of biochars. The primary factors influencing biochar's properties are the feedstock nature, heat transfer rate, residence duration, and pyrolysis temperature. The efficacy of biochar in the management of pollutants is significantly influenced by its elemental composition, ion-exchange capacity, pore size distribution, and surface area, which are contingent upon the nature of the feedstock, preparation conditions, and procedures. The chapter investigated the potential of biochar derived from agricultural refuse as a viable alternative for the long-term application of biochar in the environment, soil conditioning, and the remediation of environmental pollutants.

Keywords: Biochar, Carbon sequestration, Climate change, Greenhouse gas emissions, Life on land

INTRODUCTION

Approximately 93 million tons of crop residues are burned annually in India, mostly to clear the fields of straw and stubble left over from the previous year's harvest. The issue with irrigated agriculture is serious, especially in the mechanized rice-wheat system in Northern India. This includes a lack of labor, the high expense of removing residues from the rice-wheat cropping system, the usage of combine harvesters, and the short time interval between rice harvest and wheat sowing. In addition to contributing to air pollution, burning leftovers depletes straw of all of its C, 80% of its N, 25% of its P, 50% of its S, and 20% of its K content, all of which have a negative impact on soil fertility (Zhang *et al.,* 2019). Furthermore, burning agricultural waste releases airborne particles and ozone-depleting chemicals such as carbon dioxide, methane, carbon monoxide, nitrogen oxide, and sulfur dioxide that have a negative impact on the composition of the atmosphere. Because it keeps soil moisture and plant nutrients in the soil and promotes the expansion of the soil microbial community, biochar has the special capacity to improve soil fertility indirectly. The current global population growth rate is predicted to reach 9 billion by 2050. Food output in the developing world must double by 2050 to fulfil the increasing demand for food from a growing population. Agricultural productivity needs to be increased by up to 70%. (Das *et al.,*2023). Organic matter in the soil is essential for healthy soil. Organic matter is easily prone to mineralization and decomposition in wet tropical conditions. In a few seasons, mineralization results in low nutrient content and the production of CO_2. When applied as a soil conditioner in conjunction with organic and inorganic fertilizers, biochar greatly enhances soil tilth, productivity, and nutrient retention and availability to plants through both direct and indirect slow-nutrient release fertilizing properties and enhanced water-holding capacity, nutrient-holding ability, and soil aggregate stability (Haider *et al.,*2022) Furthermore, adding more organic carbon to soil, particularly in dry areas and coarse-textured soils, can improve the physical and chemical characteristics of the soil while also helping to absorb carbon and reduce greenhouse gas emissions from the atmosphere (Abdelhafez *et al.,* 2017). In response to these problems, biochar, alsoo referred to as "black gold" in the agricultural industry, has become a promising new resource that can remedy many of the shortcomings of traditional agriculture. Biochar is a carbon-rich substance. Among its many advantages are increased agricultural output, improved soil fertility, and—above all—a reduction in the effects of climate change (Oni *et al.,* 2017).

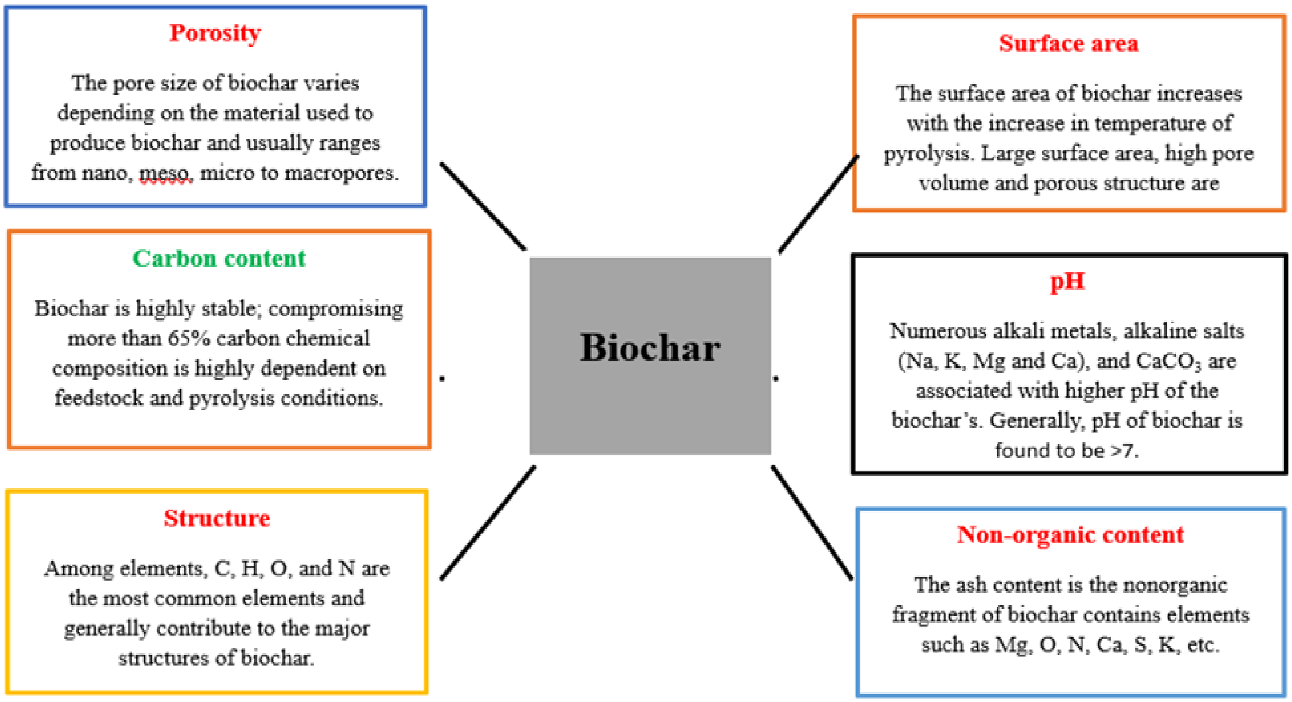
Properties of biochar and different feedstocks

Primary feedstock conditions with different physical and chemical properties, along with the pyrolysis process, affect the properties of the resultant biochar, as mentioned in Fig.1 and Table 1.

Applications of biochar

Utilization of biochar as a soil amendment

In direct contrast to the normally utilized Oxisol soils nearby, the Amazonian people used biochar along with other organic wastes over generations to change the surface soil horizon into a highly productive soil known as Terra Preta (dark earth). Even after decades of leaching from heavy tropical rains, this region is still extremely fruitful because of the significant amounts of biochar absorbed into its soils. A pyrolyzed substance known as biochar is created when organic materials undergo a thermochemical breakdown without oxygen. The type of feedstock and pyrolysis conditions employed during the preparation process will largely determine the characteristic features of the produced biochar (Brassard *et al.,* 2019). In order to address important challenges like climate change, future food security, and the management of agricultural residual waste, biochar can be a huge help to agriculture as a soil supplement. Furthermore, it has been suggested



The pore size of biochar varies depending on the material used to produce biochar and usually ranges from nano, meso, micro to macropores.

Biochar is highly stable; compromising more than 65% carbon chemical composition is highly dependent on feedstock and pyrolysis conditions.

Among elements, C, H, O, and N are the most common elements and generally contribute to the major structures of biochar.

The surface area of biochar increases with the increase in temperature of pyrolysis. Large surface area, high pore volume and porous structure are

Numerous alkali metals, alkaline salts (Na, K, Mg and Ca), and $CaCO_3$ are associated with higher pH of the biochar's. Generally, pH of biochar is found to be >7.

The ash content is the nonorganic fragment of biochar contains elements such as Mg, O, N, Ca, S, K, etc.

Fig. 1. *Properties of biochar and different feedstocks used for the preparation of biochar (Source: Biorender.com)*

Table 1. Feedstocks used in biochar manufacturing using various experimental conditions

S. No.	Feed stock	Pyrolysis/device	Temperature range (°C)	Resident time (min)	References
Waste from Agriculture					
1	Cotton stalk	Fixed bed reactor Muffle oven	450-700 400-700	60 180	Kurt et al., 2021)
2	Rice straw	Slow pyrolysis	400-700	120	Ippolito et al., 2020
3	Wheat straw	Vertical kiln	350-500	60	Greco et al., 2018)
4	Maize stover	Fixed bed reactor	400	30	Li et al., 2019
5	Maize cob, husk	Fixed bed reactor	400	30	Yang et al., 2019
6	Corn straw	Ceramic pots	300-600	250	Vijayaraghavan, K. (2019).
7	Sugarcane bagasse, leaves	Electrical muffle furnace and a pyrolysis canister	450-700	60	Janu et al., 2021
8	Below ground peanut biomass	Slow pyrolysis	600-700	60	Tag et al.,2016
9	Coconut shell, Palmyra nutshell	Slow pyrolysis	400	10	Rodriguez et al.,2020
Municipal waste					
1	Papermill sludge	Slow pyrolysis unit	550	-	Wang et al., 2020
2	Papermill sludge and Poultry litter	With and without steam activation	550-400	40	Huang et al., 2021
3	Sewage sludge	Horizontal quartz reactor, Hot air oven	300-700 650	180 120	Burachevskaya et al., 2023
4	Sewage sludge, wastewater sludge, broiler litter, dewatered pond sludge, dissolved air floatation sludge	Steam gasification with slow pyrolysis	680	8-10	Goldan et al., 2022
Woody biomass					
1	Pine sawdust	Fluidized bed reactor	600-700	60	Ji et al.,2022
2	Hardwood, waste wood chips	Slow pyrolysis	290-700	160	Abukari et al., 2021
3	Pinewood coconut fiber	Fixed- bed quartz reactor	200-300	20	Ji et al., 2022

that adding biochar to soil can both improve soil functions and qualities while reducing the effects of climate change by sequestering carbon over an extended period of time (Muñoz *et al.,* 2016; Kamali *et al.,* 2022; Muhammad *et al.,* 2017). Adding biochar to soil can alter its composition on a variety of levels, affecting its physical, chemical, and biological characteristics.

Biochar influenced soil physical properties

The addition of biochar stimulates the physical-chemical interaction and causes the surface of the biochar to come into physical contact with the soil. The characteristics of biochar determine how well it works as an amendment. The wide surface area, high carbon content, and porosity of biochars (Adhikari *et al.,* 2022) enhance their adsorptive qualities and may change soil's water retention, aggregation, bulk density, and penetration resistance. Table 1 summarizes research on biochar's impact on the physical characteristics of soil. The majority of research results indicate that applying biochar improves the bulk density of the soil (Kang *et al.,* 2022, Rombel *et al.,* 2022); it also increases the soil's ability to hold water (Ali *et al.,* 2017). Adding biochar to deteriorated or nutrient-depleted soils can also improve their physicochemical characteristics. Because of its large surface area, biochar can form bonds and complexes with metals, anions, and other constituents of soil, improving the soil's ability to retain nutrients, as mentioned in Table 2. According to Ali *et al.,* 2017, soil treated with biochar showed a markedly increased microporosity relative to control, possibly at the price of macropores. Because macropores influence aeration and hydrology and micropores are involved in molecular adsorption and transport, soil physical quality increases with total porosity (micro- and macropores). After applying biochar to infertile soils, numerous studies have shown that the soil's bulk density decreases, its total pore volume increases, and its water-holding capacity increases (Sun *et al.,* 2021; Zhao *et al.,* 2022; Liew *et al.,* 2022). Goldan *et al.* (2022) also discovered that adding biochar to the non-calcareous loamy sand reduced its bulk density. In a two-year field study, Vijay *et al.,* 2021 also noted a 9.4 ± 2.2 decrease in soil BD from biochar application rate, which may indicate improved soil aeration, aggregation, and structure. Oguntunde *et al*. (2008) reported a 9% decrease in bulk density on soils at the charcoal site compared to nearby field soils. According to Janu

Table 2. Effect of biochar from different feedstock on physical properties of soil

Properties	**Biochar**	**Feedstock**	**Pyrolysis**	**Soil type/texture**	**References**
Bulk density	Reduced	Rice husk		Non-calcareous/ loamy sand	Zhang et al., 2021
Bulk density	Decrease	Municipal green	450 °C	Residue sand	Abukari et al.,
Bulk density	Decreases	Peanut (Archis hypogaea)Pecan (Carya illinoensis) Poultry litter Switchgrass (Panicumvirgatum)	400 °C 350 °C 350 °C 250 °C-500 °C	Norfolk loamy sand	Singh et al., (2022)
Porosity & surface area	Increases	Jarrah woods (Eucalyptus	600 ° C	Sandy soil	Agbede et al., 2020
Porosity & surface area	Increasing	Peanut hulls (Arachis	500°C @1 h	Loamy sand	Zheng et al., 2019
Water stable aggregates	Increased	Corn stover	350 and 550°c	Typic fragiaqualf (alfisol), typic haplud and (andisol)	El-Sharkawy et al., 2022
Water holding Capacity	Increases	Ponderosa pine (pinus ponderosa)	450 °c	Sandy loam	Zhang et al., 2021
Infiltration rate/saturated hydraulic conductivity	Increased	Wood		Haplic acrisol	Somerville et al., 2008
Infiltration rate/saturated hydraulic conductivity	Increased	Rice husk	620°C	Non-calcareous/ loamy sand Sandy clay loam	Zheng et al., 2019
Penetration Resistance	Reduces	Hydrochar	220 °c	Albic luvisol	El-Sharkawy et al., 2022)

et al. (2021), even with a 0.5% (g g^{-1}) biochar application, biochar-amended soils showed improved WHC and water retention. After a significant downpour, biochar helps water seep through the big pores in the soil to the topsoil (He *et al.,* 2021). Terrón-Sánchez *et al*., 2021 showed that the hydrophobic nature of biochar may be the reason for its increased available water content in sandy soil, lack of effect in loamy soil, and decrease in moisture content in clayey soil. Similarly, other groups also showed increased available water capacity by 22% (Kizito *et al.,* 2019) and from 0.12 to $0.13 m^3 m^{-3}$. Addition of biochar with manures decreased soil bulk density (BD) and crack volume and increased infiltration rate (IR) and rice production in sandy clay loam soil (Jakhar *et al.,* 2019).

Biochar-influenced soil chemical properties

The soil's inorganic and organic matter composition, the colloidal characteristics of the soil particles, soil reactions, and the buffering effect of the soil in both basic and acidic soils are some of its chemical properties. The soil collisions have a major impact on the chemical characteristics of soils. For this reason, understanding the nature of soil colloids is crucial in order to understand how they affect the different chemical properties of soils. In addition, pH is a crucial parameter for identifying the kinds and rates of soil reactions (Bilias *et al.,*2021). All of the factors mentioned above will interact when any foreign material is added to soil, influencing the chemical reactions that occur there based on the characteristics of the material. Therefore, to understand any potential effects on soil quality, soil amendment material must be thoroughly examined before being administered (Chen *et al.,* 2020).

Although using biochar as a soil amendment is not new, research into its potential effects on the three main environmental concerns of climate change, food security, and residue management is still in its early stages. According to Masek (2009), the chemical makeup of biochar is a mixture of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), and ash in varying amounts rather than pure carbon. Furthermore, the kind of biomass utilized to prepare the biochar has a considerable impact on its chemical composition. For example, phosphorous (P), potassium (K), sodium (Na), calcium (Ca), and magnesium (Mg) were present in biochar made from *Lantana camara* at a pyrolysis temperature of 300 °C in available concentrations of 0.64 mg kg^{-1}, 711 mg kg^{-1}, 1145 mg kg^{-1}, 5880 mg kg^{-1}, and 1010 mg kg^{-1}, respectively (Jing *et al*., 2020). The potential for fresh biochar to release significant amounts of nitrogen (N) and phosphorous (P) within the concentration range of 23–635 mg kg^{-1} and 46–1664 mg kg^{-1}, respectively, was also documented by two other groups (Li *et al.,* 2021).

The addition of bagasse biochar greatly increased the soils' ability to store nutrients and exchange cations and anions. According to Singh *et al. (*2022) research, various reactive functional groups, some of which are pH-dependent, are present on the surfaces of the biochar particles, contributing to their high reactivity. As biochar ages, it produces more hydroxyl and carboxyl groups (Velli *et al.,*2021); nevertheless, as biochar ages in soil, quinine functional groups form (Parker *et al.,* 2021). As a result, oxygen-containing functional groups are produced on the surface of aged biochar. Aromaticity due to the H:C ratio and oxidation state due to the O:C ratios are thought to be crucial factors in characterizing these attributes. One of the key physical characteristics of biochar that influences its sorption capacity, ability to store water, and microbial habitat is its specific surface area (Murad *et al.,* 2022). Apart from its direct impacts, biochar can also increase the effectiveness of nitrogen fertilizer (Mosharrof *et al.,* 2021) by reducing leaching-related losses of nitrogen and potassium (GAo *et al.,* 2008). It follows that adding biochar to soil causes positive chemical changes reinforced by the soil's unique physical properties and biochar, as mentioned in Table 3.

Biochar influenced soil biological properties

Numerous studies (Zheng *et al.,* 2019; Zaheer *et al.,* 2021; Karimi *et al.,* 2020) have shown that adding biochar increases plant growth and carbon sequestration. These findings may be related to changed abiotic characteristics, such as elevated pH, CEC, and improved soil water content (Egamberdieva *et al.,* 2022; Ma *et al.,* 2022; El-Sharkawy *et al.,* 2022). According to Table 4, the physicochemical changes in the soil brought about by adding biochar may also be very important in determining the biodiversity of soil bacteria. Differentiations in microbial signaling through sorption of the molecules themselves (Zhang *et al.,* 2021), increased electron transfer leading to an increase in biological processes (Hale *et al.,* 2021), changes in microbial N cycling (Somerville *et al.,* 2020), and a decrease in the abundance of fungi in comparison to bacteria (which could use biochar substrates for growth; are just a few examples of the diverse interactions that biochar-mediated microbial communities may experience. Brady rhizobia and Hypho microbiocidal populations increased in a short-term pot experiment on ryegrass, and soil amended with biochar showed an increase in the abundance of bacteria and archaea reducing ammonia to nitrates and nitrites (Zaheer *et al.,* 2021). Adding biochar increased the number of mycorrhiza colonies because the material's large surface area and porous nature create an ideal environment for bacteria (Karimi *et al.,* 2020). According to Ginebra *et al.* (2021), there were less culturable filamentous fungi, such as Pseudomonas spp. and Actinomycetes spp., but more culturable colonies of general bacteria, Bacillus spp., yeasts, and Trichoderma spp. In phosphate-rich soils,

Table 3. Biochar impact on soil chemical properties

Properties	**Biochar**	**Feedstock**	**Pyrolysis Temperature**	**Soil type/ Texture**	**References**
pH	Increased	Red gram, cotton, maize stalk	250 @ 450°C;	Acidic/red soil	Zhang et al.,2021
pH	Increased	Rice husk	900 & 1100 °C	Acidic/sandy loam	Sun et al.,2022
Soil organic carbon	Increased	Rice husk	500 °C for 6 h	Acid purple soil	Bilas et al.,2021
Total carbon	Increased	Poultry litter	450°c & 550°c	Alfisol	Abukari et al., 2022
Total phosphorus, availablephosphorus, Available potassium	Increased	Rice husk	500 & 700°c	Acid purple soil	Li et al., 2020
Total phosphorus, availablephosphorus, Available potassium	Increased	Hardwood	500°C @ 12 hours.	A sandy loam Alfisol	Adekiya et al.,2020
Carbon/nitrogen ratio	Increased	Wheat straw	450°c	Black chernozem	Singh et al., 2022
Soil microbial biomass carbon	Increased	Liter from coppice woodland	550°c	-silty loam	Parker et al.,2021

wood biochar and phosphorous solubilizing microorganisms (PSM) increase PSM activity for P mobilization; yet P-deficient soils greatly increase crop output (Ma *et al.,* 2022). Biochar increases the activity of soil microorganisms, which has a good effect on soil biological fertility (Zhang *et al.,* 2021). Rondon *et al*. (2007) noted in a different study that legumes' nitrogen fixation is enhanced by biochar. Furthermore, soil microbes may be physically protected by the pores of biochar. pH has a significant impact on microbial diversity, abundance, and activity. Maintaining proper pH conditions and minimizing pH variation in the microhabitats within biochar particles may also be aided by the soil solution's buffering capacity or its capacity to withstand pH shifts given by biochar CEC (Song *et al.,* 2020). In soils impacted by leaching, microbial immobilization is a crucial strategy for retaining N. A higher N demand due to increased microbial activity brought on by increased C availability encourages nitrate immobilization and recycling. Crop yield, soil microbial biomass, plant tissue K concentration, total soil C and N, soil P and K, nodulation and BNF by common beans (Zheng *et al.,* 2019), red clover (Zaheer *et al.,* 2021), soybean and *faba* bean have all increased with the addition of biochar.

Biochar role in carbon sequestration, pollution management and greenhouse gas mitigation

Earth's soils hold 4.5 times more carbon than plant and animal life and 3.3 times more than the atmosphere. Because of this, soils are both a significant source of greenhouse gasses and a significant sink that aids in increasing carbon sequestration. Approximately 25% of global greenhouse gas emissions are produced by agriculture (Gupta *et al.,* 2020). It is imperative to use climate-smart methods to mitigate the worst impacts of climate change while maintaining agricultural output and incomes. Compared to the small amounts retained after burning (3%) and biological decomposition (< 10–20% after 5–10 years), conversion of biomass C to biochar results in the sequestration of approximately 50% of the initial C. This produces more stable soil C than burning or direct land application of biomass (Elkhlifi *et al.,* 2023). Additionally, biochar reduces water pollution by improving soil nutrient retention and sequesters CO_2 into the soil (Sarfraz *et al.,* 2019). Applying wheat straw biochar to Anthro sol paddy soil showed that, at application rates of 10 and 40 Mg ha^{-1}, respectively, CH_4 emission increased by 31 and 49% and N_2O emission decreased by 50 and 70%. These results were attributed to increased soil aeration, sorption of NH_4^+ or NO_3^-, or the presence of microbial inhibitor compounds like ethylene. When compared to an unamended control, Nan *et al.,* 2022 found that silt loam soil treated with wood chip biochar released less CO_2 at a rate of more than 20% (w/w). On the other hand, some research has shown negligible effects or no discernible variations in the net greenhouse gas fluxes during field testing or incubation experiments in the lab. Significant suppression of greenhouse gas emissions from soils was observed for gases like CO_2 and N_2O, which have a potency over 300 times that of CO_2 (Majumder *et al.,* 2019). According to Woolf *et al*. (2016), biochar may be crucial in removing carbon from the atmosphere. In addition to lowering the requirement for fertilizers that

Table 4. Effect of biochar on soil biological properties

Biochar	Feedstock	Pyrolysis Temperature	Soil type/ Texture	References
Increase bacteria and archaea oxidizing ammonia to Nitrates & nitrites	Hardwood	500°C @ 2 hours	-	Zheng et al., 2019
Increase Brady rhizobia and Hypho microbicide populations	Pinus radiata	-	Silt-loam soil	Zaheer et al., 2021
Increase nitrification, nitrogen fixing, nitritereduction	Switchgrass (Panicumvirgatum)	350°C	Aridic subsoil	Karimi et al., 2013)
Increase Rhizobacteria (S and P mobilizing bacteria)	Miscanthus Giganthus	600 °C @ 15 min;	Poorly drained clay/loamy	Ma et al., 2022
Increase Bacteria: Bacillus spp. yeasts and Trichoderma spp, decrease inculturable filamentous fungi Pseudomonas spp, Actinomycetes spp	Citrus wood	-	-	El-Sharkawy et al., 2022
Enhance PSM activity, significantly improvedthe crop	Lignin-rich wood	350–500° C	Fine textured/silt loam	Zhang et al., 2021
Increase in nitrogen fixation in legumes.	Eucalyptus Deglupta	350°C @ 1 h	Typic Haplustox (oxisol)/ clay–loam	Hale et al., 2021

are the source of excess nitrogen, biochar helps lessen the amount of nitrogen that leaches into groundwater (Layek *et al.,* 2022).

Anthropogenic pollution activities have increased with the world population's steady rise. Numerous issues have resulted from this condition, such as increases in global air temperatures, acid rain, droughts, floods, and the spread of disease. We haven't yet found workable and economical answers to these issues. It has been discovered that biochar can both directly and indirectly lessen the incidence and consequences of these issues. Among its many applications is the elimination of contaminants from wastewater, both organic and inorganic (Li and Tasnady, 2023). Antibiotics have been extracted from wastewater using biochar. Biochar has also been used to extract nutrients (nitrogen and phosphorus) and heavy metals (Cu, Pb, Ni, and Cd) from wastewater. Because biochar can remove contaminants including pathogens and particulate matter, it can be used in wastewater treatment either in place of or in addition to sand filters (Khadem *et al.,* 2021).

Additionally, it has been employed in a treatment procedure where a chemical oxygen demand (COD) elimination effectiveness of 74 ± 18% was noted. The release of toxins from residential, commercial, and industrial sources frequently results in the degradation of the environment or adjacent systems (Luo *et al.,* 2023). Both organic and inorganic pollutants have a greater impact on soil and water media within an ecosystem, primarily due to human activity. The soil and water remediation field has seen a sharp rise in technological improvement. Reducing bioavailable pollutants is one of the most important technologies since it will significantly lessen the buildup of hazardous substances in plants and animals. For a very long time, carbonaceous materials have been used as sorbents for both organic and inorganic pollutants in soil and water (Purakayastha *et al.,* 2021). Because of its many uses, biochar has the potential to be used as a sorbent for both organic and inorganic pollutants in soil and water. Because of their toxicity and accumulation capacity, organic pollutants such as pesticides, herbicides, dyes, polycyclic aromatic hydrocarbons, and antibiotics have raised the most concerns (He *et al.,* 2022). Biochar has been utilized to sequester heavy metals in the soil medium. Heavy metals are not eliminated during this process; they are immobilized and may be transformed into phosphate, carbonate, and hydroxide precipitates. Biochar amendments to soils have also been shown to sequester carbon, a mitigation step against climate change, and remove chemicals from contaminated soils. Due to its growing ability to act as a carbon sink, lower greenhouse gas emissions, lessen demand for burning coal, and eventually clean up contaminated soil, biochar has drawn the attention of most soil environment researchers in recent years. The capacity of biochar to adsorb organic contaminants is significantly influenced by its properties, which include carbonaceous components, degree of aromatization, elemental makeup, pH, pore structure, surface chemistry, etc. (Gwenzi *et al.,* 2022). Therefore, CO_2 emissions into the atmosphere are decreased with biochar. The unrestrained utilization of natural resources and the swift escalation of environmental degradation due to human activities have already placed a strain on endeavors to preserve the natural environment. Biochar can also neutralise acidic soils because of its capacity to raise pH and the calcium and magnesium carbonate. However, reducing acidity may have a negative impact on fungi and worms that like acid in the soil environment. Furthermore, because biochar has appropriate surfaces for microbial attachments and adds nutrients like N, P, and K, it can be utilized to accelerate the biodegradation of organic contaminants (Bao *et al.,* 2022). Biochar has been utilized in anaerobic digesters to reduce the impact of NH_4^+ and might also be used as a buffering agent. Biochar has also been discovered to have numerous applications in enhancing air quality (Dai *et al.,* 2021).

It has been applied to regulate the emission of air pollutants such as NO_2 and NO, which cause localized ozone formations and greenhouse impacts, respectively. For example, using biochar, 67% of the NO in soils has been removed. This is made possible by biochar's capacity to lower the amount of nitrogen soil microorganisms can make available for their metabolic processes (Zhang *et al.,* 2024). Moreover, biochar has been used to remove gaseous mercury. Numerous studies demonstrate that biochar surfaces are typically negatively charged, strongly attracting positively charged metal ions like Hg^{2+}. The surface and elemental qualities of the biochar, the feedstock, and the pyrolysis conditions used to create the biochar all influence removal efficiency. Although biochar has a low affinity for CO_2, it must be modified to absorb CO_2 effectively, even if it can be used to reduce CO_2 emissions (Terrón-Sánchez *et al.,* 2023). Nitrogen impregnation is one modification technique that enhances biochar's CO_2 removal capabilities by up to 55%. Biochar has been utilized to remove H_2S gas from biogas production processes with up to 95% removal efficiency. It has been demonstrated that the elimination of H_2S is enhanced when carboxylic and hydroxide functional groups are present. Biochar has also been used to eliminate other gasses, such as methyl tert-butyl ether, ozone, benzene, ammonia, and toluene (Das *et al.,* 2023). Even though a lot of agricultural waste is available for manufacturing biochar, it is still important to use it sustainably. This is especially important as the process of making biochar uses energy and could release pollutants (particulate matter and gaseous emissions). Reusing biochar, producing biochar from feedstock less

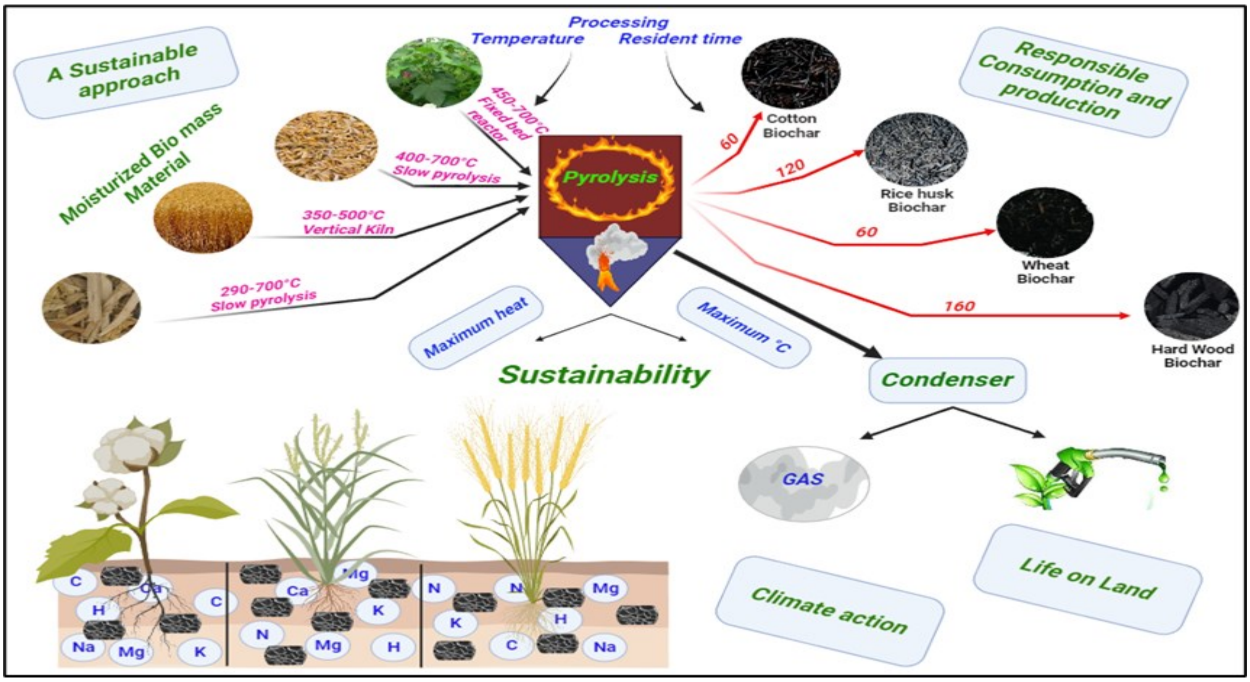


Fig. 2. *Application of biochar in agriculture and climate resilience (Source: Biorender.com)*

likely to include pollutants, and using calculated or optimized amounts in field applications are all examples of sustainable biochar use (Duan *et al.,* 2021).

Application of biochar in environmental safety and sustainable agriculture

Agricultural areas are currently eroding because of ongoing farming, which results in nutrient mining and a decline in soil organic matter. The main problem for growing crops in agricultural fields is decreased soil fertility. Until better management procedures are implemented, agricultural lands will continue to have declining soil quality (Semida *et al.,* 2019) The foundation of a sustainable and functional food system is healthy soil. Since agricultural land is continuously farmed, nutrient cycle, release, and uptake are typically disrupted. This lowers the natural supplies of essential nutrients for plant development and slows the rate at which crops grow in farm soils (Das *et al.,* 2020). Depending on the application rates, feedstock type, and temperature, biochar enhances crop yields, improves soil health, and sequesters carbon (Ayaz *et al.,* 2021). There are four primary methods by which the addition of biochar to the soil enhances agricultural productivity and plant health as indicated in Fig. 2. The first mechanism has to do with the biochar's capacity to encourage helpful bacteria in the rhizosphere. Microbes that support plant growth and microbial populations can benefit from biochar's lower carbon compound content and increased micronutrient availability (Asadi *et al.,* 2021). However, it has been reported that the effects of nutrient and water retention, the creation of active surfaces that provided the ideal habitat for microorganisms, weak alkalinity, and partial inhibition of destructive and simultaneous support for beneficial microorganisms were the causes of the increase in microbial biomass that resulted from microbial growth following biochar application. Second, biochar improves the soil's water regime because of its high capacity to retain water (Abukari *et al.,* 2022). This is especially beneficial for sandy soil areas, as biochar lessens moisture leaching and decreases water loss, while encouraging water drainage in clay soil lowers water-logging risk. The third mechanism has to do with biochar's ability to absorb and neutralize organic molecules that are phytotoxic, like xenobiotics, anthropogenic substances, and naturally occurring allelopathic compounds (Chukwuka *et al.,* 2020). The pyrolysis-induced increases in specific surface area are directly linked to this detoxifying capacity. The fourth method, which is very helpful for acidic soils, is an increase in soil pH.

Role of biochar in mitigating climate change

The following goals can be fulfilled by biochar: preventing land degradation, minimizing climate change through the reduction of greenhouse gas emissions, improving soil health and quality, adsorbing hazardous elements onto its surface, and achieving food security through increased crop productivity (Lehmann *et al.,* 2021).The use of biochar transformed terra preta soil into extremely productive soil, which is a great illustration of biochar's benefits to the environment and soil sustainability. The burning of numerous crop wastes is the main source of the agriculture sector's large emissions of greenhouse gases (Yadav *et al.,* 2017). The fields generate a significant amount of CO_2, which degrades the surrounding ecosystem. Because of its complex aromatic structure and recalcitrant nature, biochar is a revolutionary approach used with thoughtfulness to slow and continuously eliminate CO_2 from the terrestrial environment (Woolf *et al.,* 2018). It is thought that turning leftovers into biochar is preferable to burning it. Compared to conventional conservation agriculture and microbial degradation, over 50% of the carbon is retained in the soil during biomass conversion to biochar, making this a more stable soil carbon sink than burning or applying biomass directly. Because biochar has a residence length of up to millennial time scales, adding it to soils can thus play a critical role in C sequestration to prevent climate change. In terms of reducing atmospheric carbon emissions globally, biochar-bioenergy has the potential to mitigate unpredictable climate change significantly (Arif *et al.,* 2020). At lower prices, it aids in absorbing and storing carbon from the atmosphere, and the use of biochar greatly increases crop output. Biochar can potentially absorb between 62 and 66% of CO_2 emissions. Therefore, using biochar to absorb more CO_2 from the soil's atmosphere can be a beneficial way to slow down global warming. In addition to CO_2, releasing other greenhouse gases like methane (CH_4) and nitrous oxide (N_2O) has become a serious environmental hazard. Depending on the kind of soil, the characteristics of the biochar, and the surrounding conditions, adding biochar to the soil reduces the emission of CH_4 by inhibiting the oxidation of ambient CH_4. However, it is currently unclear how biochar affects the nitrogen transformation process. Unlike other fresh organic materials, applying biochar decreases N_2O emissions and NH_4^+ leaching from the soil (Gupta *et al.,* 2020). Since biochar surfaces undergo oxidative reactions with age, it lowers N_2O emissions at reduced paddy fields. The total amount of N_2O released decreased by 10.7% to 41.8%, respectively, with biochar at 20 and 40 Mg ha^{-1}. Moreover, soil N_2O fluxes have dropped to 79% in soil treated with biochar.

Biochar and crop productivity

Applying biochar reduces the environmental impact on soil and water resources while increasing soil productivity by bettering the soil's physical, chemical, and biological characteristics (Agegnehu *et al.,* 2017; Diatta *et al.,* 2020). A study on Australian soil by Jiang *et al.* (2020) revealed improvement in soil structure, increased soil water retention, and decreased soil strength. Kapoor *et al.,* 2022 examined the nutrient leaching losses and soil fertility of a neighbouring unamended Ferralsol and Anthrosol. Compared to the Ferralsol, the Anthrasol exhibited noticeably higher P, Ca, Mn, and Zn availability. It also enhanced the biomass of rice and cowpea by 38–45% in the absence of fertilization. When biochar from paper mill waste was applied in addition to inorganic fertilizer, soybean and radish biomass increased compared to inorganic fertiliser alone (Murtaza *et al.,* 2021). Corn biomass was raised by applying chicken manure and municipal waste biochar (Yu *et al.,* 2019). The increased pH and CEC of the soil caused by biochar is the reason for the increased biomass production. Biochar, sometimes known as "black gold" for agriculture, can increase crop yield, soil fertility, microbial abundance, and carbon sequestration (Kapoor *et al.,* 2022). Increasing soil fertility or nutrient status results in higher agricultural yields and contributes to soil health maintenance. Using biomass efficiently by turning it into a valuable source of soil amendment is one method to enhance crop productivity and soil health.

Conclusion

The review illustrates the viability of utilizing agricultural waste-derived biochar as a viable substitute for soil conditioning, long-term biochar use, and environmental pollution remediation. Crop residues in fields can lead to significant issues with crop management. Each year, 435.98 million tons of agro-residues are produced in India, of which 313.62 million tons are surplus. One strategy for maintaining soil fertility and health is effectively using biomass as a valuable source of soil amendment. Biochar made from agricultural wastes can guarantee sustainability and environmental safety. Because minerals have a major impact on the characteristics of biochar, it is important to optimize the kind and quantity of minerals in biomass for the desired environmental application. Biochars have made significant strides in lowering greenhouse gas emissions, decreasing soil nutrient leaching, storing atmospheric carbon in the soil, raising agricultural production, and lowering the bioavailability of environmental pollutants. Biochar is well known for its capacity to act as a pollutant remediator, and it is essential for producing bioenergy and mitigating climate change. The production of crops and plant health are enhanced by adding biochar to soil.

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Conflict of interest

The authors declare that they have no conflict of interest.

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