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BIOCHAR APPLICATION IN IMPROVING SOIL HEALTH AND SUSTAINABILITY

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Abstract *Soil is the most significant component in productive agriculture; hence, improving soil quality is essential for increasing crop yields and overall soil fertility. Biochar is suitable for application in soil to improve productivity and fertility for crops. It is a carbon-rich compound that is produced through burning in circumstances with little oxygen from agricultural crop biomass. The importance of biochar in carbon sequestration lies in its various uses such as waste recycling, soil nutrient retention, and reduction of the global warming effect. This assessment will explore the importance of biochar to improve soil fertility safely and sustainably. This article provides information on biochar properties, manufacturing processes, and uses in farming. This review will be a valuable resource for those concerned with biochar applications.*

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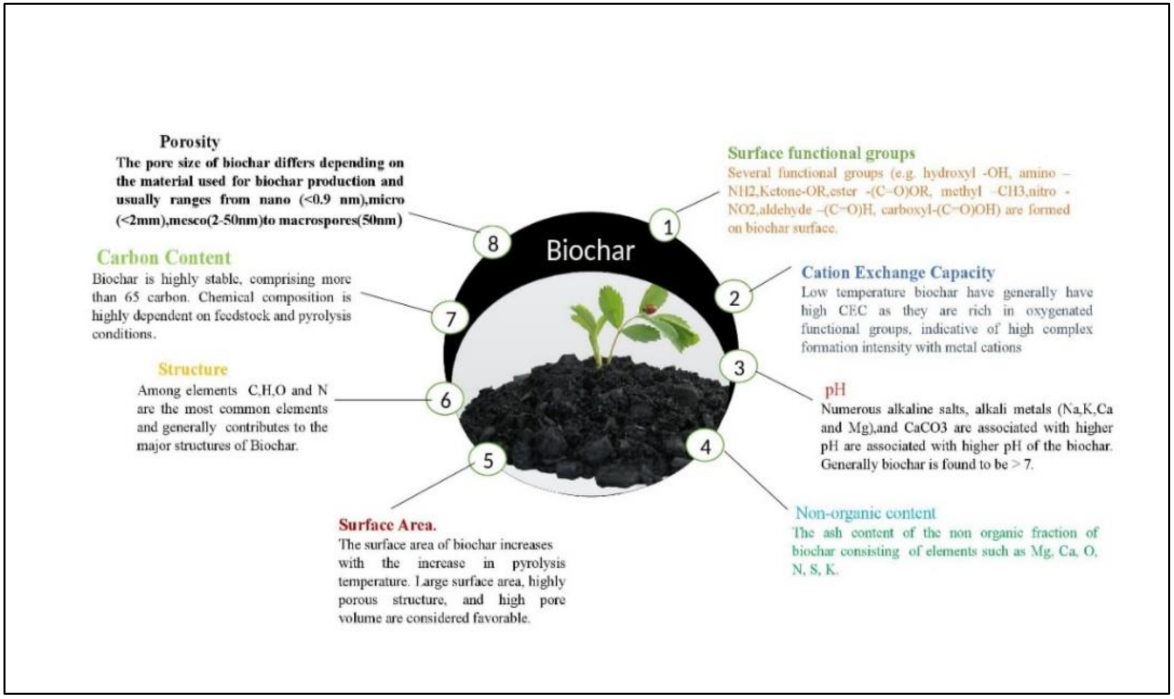
Keywords: *Biochar; Agriculture; Soil Health; Agricultural Sustainability; Pyrolysis; Global Warming*

Introduction

Plant remains and agricultural wastes are major environmental problems worldwide because they contribute to rising greenhouse gas emissions. As a result, different scientists split these materials down into numerous products, such as biochar, biological fertilizers (El-Metwally *et al*., 2022; Salem *et al*., 2021), and soil mulching (Mubarak *et al*., 2021). Biochar is a raw material that breaks up from its parts through a process of thermal conversion and limits the input oxygen that impacts the production at temperatures below 700°C (Clough & Condron, 2010; Wang *et al*., 2022). It is also a source of renewable energy, and heat, electricity, and liquid fuels are by-products (Xie *et al*., 2015). Biochar, formed through the process of pyrolysis (Lehmann & Joseph, 2024; Talberg, 2009), has a durable porous surface with terminal groups, various mineral nutrients, and consistent carbon compounds (Wang *et al*., 2022). In contrast to other organic nutrients, biochar is an essential factor in attachment and mineral formation processes (Clough & Condron, 2010; Kulyk, 2012; Lehmann & Joseph, 2015) and works as an eco-friendly fertilizer. Biochar increases soil nutrient accessibility and helps the environment be healthier (Clough & Condron, 2010). This substance, abundant in carbon, serves as a soil amendment in farming settings, reducing the potential for environmental contamination and degradation (Kulyk, 2012; Ulusal *et al*., 2021). The biochar manufacturing process is dependent on three main factors: the manufacturing method (including techniques and temperature), the kind of biomass used (like rice husks, food particles, animal remains, and other waste materials), and the technologies used such as carbonization, thermal decomposition, and gas conversion. Biochar can be classified into three categories according to the percentage of carbon in the feedstocks: 1) feedstocks containing 3-5% such as bamboo and nut shells, 2) feedstocks containing 3-5% to 10-13% such as leftovers from farming, bark from trees, bio waste, while feedstocks containing over 13% carbon comprise products such as discarded paper, organic fertilizers, industrial wastewater, and solid city garbage (Figure 1) (Joseph & Taylor, 2014). It has been in high use day in and day out to convert biomass into a carbon compound that revives the exhausted soil (Karimi *et al*., 2020; Shakya & Agarwal, 2020). Biochar has recently become increasingly popular as a multidisciplinary field due to its unique properties (Chen *et al*., 2019). Oak sawdust is highly used as a green source of biochar. The use of biochar is increasing swiftly to produce sustainable agricultural products and enhance food security (Hossain *et al*., 2022). Biochar has been shown to improve the structures of soils, enhance nutrient availability, and promote beneficial microorganisms' activities, thereby stimulating crop yields (Khan *et al*., 2024; Yadav & Ramakrishna, 2023). In 2006, China started a project on biochar-based carbon-rich soil reclamation. The outcomes have shown it can be used for quality improvement of soils and growing crops (Chen *et al*., 2019). Features and functions greatly depend on the production temperature. The higher oxygenated functional group is recorded from the biochar prepared at 400–450°C which enhances the dissolution of compounds in organic matter and water, hence seed germination, microbial growth, and water retention are highly boosted as compared to higher temperature preparation than 450°C (Joseph & Taylor, 2014). The most prominent advantages of the usage of biochar for agricultural purposes are low costs, eco-safety, and elasticity (Akhil *et al*., 2021; Mian & Liu, 2018). The effectiveness of biochar in recovering soil health and reducing pollution and emissions of greenhouse gas is critical to mitigating climate change issues globally (Das & Ghosh, 2020). Biochar can often replace some of the hydraulic properties of soils (Rabbi *et al*., 2021). The survival rate of inoculated micro-organisms in soils may further depend on the surface area of biochar, the ratio of carbon to nitrogen as well as their water-retention capacity. Biochar can be produced either from processed or unprocessed biomass as a fuel. The most valuable biomass for making biochar is produced by the agricultural and agro-processing sectors (Kamali *et al*., 2022; Parmar *et al*., 2014). Research on the long-term effects of biochar on the soil is currently underway, comprising the advantages and disadvantages in terms of the improvement of the quality of the soil through this method (Kamali *et al*., 2022; Kuppusamy *et al*., 2016). This study concludes that its possible benefits in terms of economic sustainability, technical efficacy, and ecological sustainability are significantly outweighed by its adverse environmental impacts. The review aims to present all the information regarding the production process of biochar, along with its characteristics, uses, as well as pros and cons.

Properties of Biochar

The physical and chemical properties of biochar include the feedstock and the method of pyrolysis, with carbon content in wood biochar being higher than that of plant material that contains more nitrogen, such as herbs (Usevičiūtė & Baltrėnaitė-Gedienė, 2021). Carbonization deteriorates the elements of biomass but preserves a lot of carbon. This modification results in more carbon in biochar, making it even more useful for technical applications (Pituello *et al*., 2015; Weber & Quicker, 2018). Charcoal varies in composition depending on the feedstock and the combustion process depending on several conditions like the availability of oxygen, temperature, and time, which mold it as partly during this process, plant material is partially burnt (Saidur *et al*., 2011). In the presence of oxygen, complete combustion occurs in which all carbon is burnt and white ash is formed (Senneca, 2008). In the case of inadequate oxygen, plants produce charcoal when they burn. The gases emitted during combustion include oxygen, nitrogen, and hydrogen.



Porosity
The pore size of biochar differs depending on the material used for biochar production and usually ranges from nano (<0.9 nm),micro (<2mm),mesco(2-50nm)to macrospores(50nm)

Carbon Content
Biochar is highly stable, comprising more than 65 carbon. Chemical composition is highly dependent on feedstock and pyrolysis conditions.

Structure
Among elements C,H,O and N are the most common elements and generally contributes to the major structures of Biochar.

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

Surface functional groups
Several functional groups (e.g. hydroxyl -OH, amino –NH2,Ketone-OR,ester -(C=O)OR, methyl -CH3,nitro -NO2,aldehyde –(C=O)H, carboxyl-(C=O)OH) are formed on biochar surface.

Cation Exchange Capacity
Low temperature biochar have generally have high CEC as they are rich in oxygenated functional groups, indicative of high complex formation intensity with metal cations

pH
Numerous alkaline salts, alkali metals (Na,K,Ca and Mg),and CaCO3 are associated with higher pH are associated with higher pH of the biochar. Generally biochar is found to be > 7.

Non-organic content
The ash content of the non organic fraction of biochar consisting of elements such as Mg, Ca, O, N, S, K.

Figure 1. Chemical and Physical features of Biochar

Physical Features

Degradation of lignocellulosic biomass alters some physical properties in the resulting biochar, including surface area and density, porosity, heat conductivity, and water-holding capacity, thereby changing its interaction with the soil systems. (Figure 1)(Downie, 2011).

Specific surface area (SSA)

The specific surface area represents a critical characteristic determining its catalytic properties and rates of chemical reactions because of interaction sites with specific species (Wang *et al*., 2019). Volatile gases emission from carbonization impacts soil permeability and biomass surface area (Kwon *et al*., 2020). Apart from this, surface area is directly proportional to the cation exchange capacity, as well as the water-holding capacity of biochar (Weber & Quicker, 2018). CO_2-feeding pyrolysis, doping with metal, and high-temperature pyrolysis are some techniques using which the specific surface area of biochar can be enhanced. In addition to that, steam vapor radicals may oxidize the carbon matrix partially. Hence, there is a chance of getting some new pores inside the biochar. Furthermore, the surface area of biochar can be increased through steam activation and hydrothermal pyrolysis (Ghodake *et al*., 2021).

Density and porosity

An elevation in the carbonization temperature initially increases the bulk density and compressive strength of biochar, followed by a rise in pyrolysis (Figure 2) (Z. Cao *et al*., 2019). During pyrolysis, solid biomass releases gases that form pores in the resulting char. The density of the char per specified volume decreases as the space within the material increases (Weber & Quicker, 2018). Changes in porosity do not impact the true density, which solely considers the density of the solid portion without factoring in any empty spaces or pores within the material (Downie, 2011). However, particle density solely includes solid and closed pores.

Water-repellent properties and water-holding capacity (WHC)

The surface functional groups, which rely on the bulk volume porosity, have an impact on the hydrophilic property and water-holding ability of biochar (Antonangelo *et al*., 2019). Water cannot enter the porous system due to the hydrophobic surfaces of the pores (Gray *et al*., 2014). Consequently, the increase in the porosity of biochar affects variations in the amount of water that can be absorbed (Liu *et al*., 2017).

Pore volume and size distribution

The number of pores in biochar is regulated by nitrogen dioxide absorption (Figure 1) (Li *et al*., 2020; Zdravkov *et al*., 2007). Adsorption of a specific gas by biochar is limited since a wide surface area has so many small holes and the gases may find it difficult to travel through such small pores (Wen *et al*., 2023). Biochar has a lot of micropores of the order over 80% pore volume, according to Leng *et al*. (2021).

Thermal conductivity and heat capacity

The highest change in thermal conductivity occurs when the heat transfer is within the direction of the grain (Klemens, 1985). This has reduced the biochar's heat conductivity due to its porosity (Atinafu *et al*., 2021; Rawal *et al*., 2016). As the structure of the fibers of biomass cracks into parts and disappears with the process of carbonization, the values of thermal conductivity measured in different directions converge with an increase in temperature during pyrolysis (Fu & Yao, 2022). A perfect barrier is when the conductivity of biochar increases with an increase in the temperature of carbonization.

Grindability

The char can be ground more easily than the raw material because of the mechanical stability it maintains during carbonization (Assis *et al*., 2016). Hardgrove Grindability Indices (HGI) are utilized to compare the grindability of coal and biochar (X. Huang *et al*., 2022). A low grindability index indicates the opposite of a high grindability index, meaning the material is difficult to grind (Jewiarz *et al*., 2020).

Chemical Features

Biochar's chemical properties, which include high pH, cation exchange capacity, and pH, are the key attributes that allow it to be an effective material for agricultural purposes. This withholds all the basic nutrients like nitrogen, phosphorus, and potassium, under the surface, due to which, the plant can grow larger harvests as the soil becomes better fed with biochar. The elemental makeup, pH level, and reactivity of biochar are assessed to determine its characteristics. Functional groups enhance interactions with soil components, leading to long-term benefits like carbon sequestration and improved soil health as described in Figure 2.

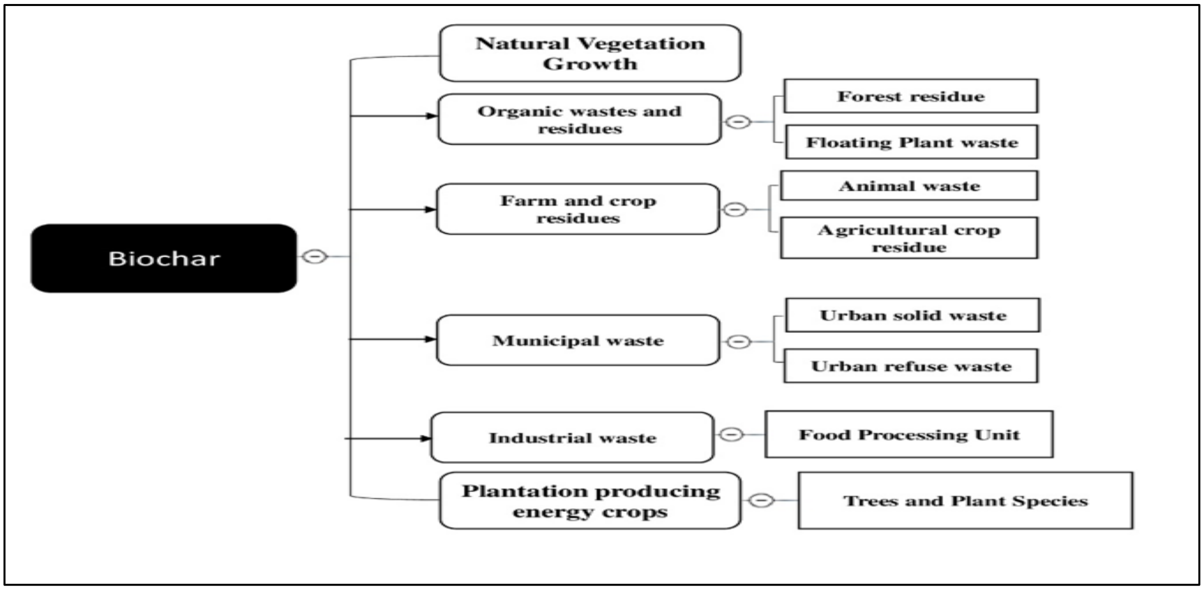


Figure 2. Categorization of different types of biomass to produce biochar (Modified from Refs (Panwar *et al*., 2019; Parmar *et al*., 2014)

Functionality

Biomass disintegration during the carbonization process leads to the release of hydrogen and oxygen, thus producing biochar with a low H/C ratio (Qin *et al*., 2022; Ronsse *et al*., 2015). However, due to pH fluctuations, the acidic functional groups of biochar decrease with an increase in temperature while the number of aromatic structures increases with an increase in temperatures for the production of biochar (Al-Wabel *et al*., 2013; Cao *et al*., 2022).

pH-value

The pH value of biochar is the characteristic that allows chars produced by pyrolysis to be distinguished from those made via hydrothermal carbonation (Krysanova *et al*., 2019; Schimmelpfennig & Glaser, 2012). Higher alkalinity favors a higher pH value (Cornwall *et al*., 2017). Because of its pH, biochar can be applied as a soil amendment in agriculture. Temperature is the most significant influence on the pH value of biochar (Ippolito *et al*., 2015).

Reactivity

The reactivity of biochar determines the applications of the material due to conversion. Biochar has been characterized by hydrogen and carbon dioxide from water vapour and carbon monoxide (Farid *et al*., 2020).

$C + CO_2 \rightarrow 2CO$

$C + H_2O \rightarrow CO + H_2$

$4C + 3O_2 \rightarrow 2CO + 2CO_2$

The reaction rate depends on temperature, gas concentration, and also on surface availability (Beckingham *et al*., 2017). Various gases show different interactions with the surfaces. Inorganic constituents in biochar increase the reactivity as catalysts (Ghodake *et al*., 2021), and non-polar regions favored the O molecules over polar hydrogen. The solid's inner surface must be available for the gas reactions.

Atomic Proportions

Carbonization alters the chemical makeup of the fuel by removing functional groups (Kidena *et al*., 1996; this leads to the release of hydrogen and oxygen-containing groups, and an associated reduction of carbon ratios (Burg & Cagniant, 2007). Oxygen is released more rapidly through natural carbonization, but at high temperatures, this reduction is preserved in raw biomass (Amer & Elwardany, 2020).

Elemental Composition

The chemistry of biochar differs from that of raw biomass as it contains a high content of carbon because some of the functional groups it originally contained, which carried hydrogen and oxygen, had been eliminated (Saletnik *et al*., 2019). This is for the reason that the presence of hydrogen and oxygen lowers because the temperature of the reaction elevates (Lu *et al*., 2018). The high-temperature biochar contains more than 95% carbon, but oxygen and hydrogen are just at 5% and 7%, respectively. However, the content of hydrogen decreases to less than 2% during pyrolysis (Jindo *et al*., 2014).

Cation exchange capacity (CEC)

Cation Exchange Capacity refers to the total number of exchangeable cations in the soil as well as the capability of soil clay to facilitate nutrient exchange near plant roots (Ćirić *et al*., 2023; Ghodake *et al*., 2021; Khaledian *et al*., 2017). The surface structure is relevant to CEC, owing to the functional groups, which produce surface charges, as well as the surface area by which those charges may be accessed. Generally, low-temperature biochars have had high CEC because they retain expanded surface areas and functional groups that supply negative charges (Tomczyk *et al*., 2020).

Biochar production technique

The various sources of biomass used for biochar manufacture are presented in Figure 2. The cheapest form of waste management is through the usage of residues from agro-products and agro-industries for biochar manufacture, whereby agro-wastes are heated in sealed containment with minimal oxygen inflow (Varghese *et al*., 2023; Yadav *et al*., 2023). Biochar may be accessed easily from materials that are woody and contain less moisture, such as husks, stalks, and shells (Noor *et al*., 2012; Ok *et al*., 2015). Agricultural waste can be employed for the production of biochar. It can be utilized to increase soil fertility after its application in agricultural fields (Diatta *et al*., 2020). While other bio-fertilizers possess these qualities in part, the large surface area, negative charge density, and negative surface area of biochar make it better at capturing nutrients and enhancing stability (Haider *et al*., 2022; Wang *et al*., 2022). Agricultural product losses may exceed half of their carbon content when burned. Biochar products can be available in solid, liquid, or gaseous forms. Processes for both fast and slow pyrolysis are utilized to maximize the production of solid as well as liquid biochar. However, the real production volume in many cases is less by several orders of magnitude compared to the theoretical value calculation which may be done with the formula (BY). High-grade charcoal is produced from feedstocks and will contain 21–23% volatile matter, and 70% fixed carbon, with an ash content of 1–3%, and a calorific value of 30–33 MJ/kg. Algae have been considered suitable for the production of biochar through their nutritional aspects; further, each of the solids, liquids, and gases can be removed as well (Fernández *et al*., 2023). Cyclones are applied in the production of biochar for the separation of solids from liquid and gas. There are four types of biofuels differentiated based on the amount of lignin and cellulose present (Kikas *et al*., 2016). The first type of fuel is crop-based from crops like sugarcane, maize, and rapeseed; and food and oilseed sources (Koçar & Civaş, 2013; Rasool & Hemalatha, 2016). The second-generation biofuel is derived from non-food crops containing a high amount of lignin, such as alfalfa and forest wood. Energy-efficient crops are the source for the fourth generation, but the source of third-generation biomass is usually algae (Joyia *et al*., 2024). The yield for biochar can be calculated using this formula.

$$\text{Biochar yield (BY)} = \frac{\text{Weight of biochar}}{\text{Weight of moisture-free product}} \times 100$$

Torrefaction

Torrefaction is one of the conversion processes that involves transforming material into solid forms under temperatures ranging from 200-300 C and under air pressure, excluding oxygen (Kambo & Dutta, 2015; Yu *et al*., 2017) (Figure 3). It involves removing volatile compounds such as moisture, carbon dioxide, and oxygen through pre-treatment methods that break down the same (Alvarez-Chavez *et al*., 2019; Devi *et al*., 2021). Elkhalifa *et al*. (2022) recently examined the effect of torrefaction on food waste (FW) as it is exposed to isothermal conditions, heated from 200 to 300 ◦ with a steady temperature rise of 15 C for either 60 or 180 minutes. The rate of ◦C/min proved to influence the carbon content, energy density, and caloric value of FW (Pahla *et al*., 2018). The unprocessed ground MSW is kept in sealed plastic bags in the desiccator till the torrefaction process. The reacting agent is charged with nitrogen gas for 10 minutes to displace all oxygen (Figure 4).

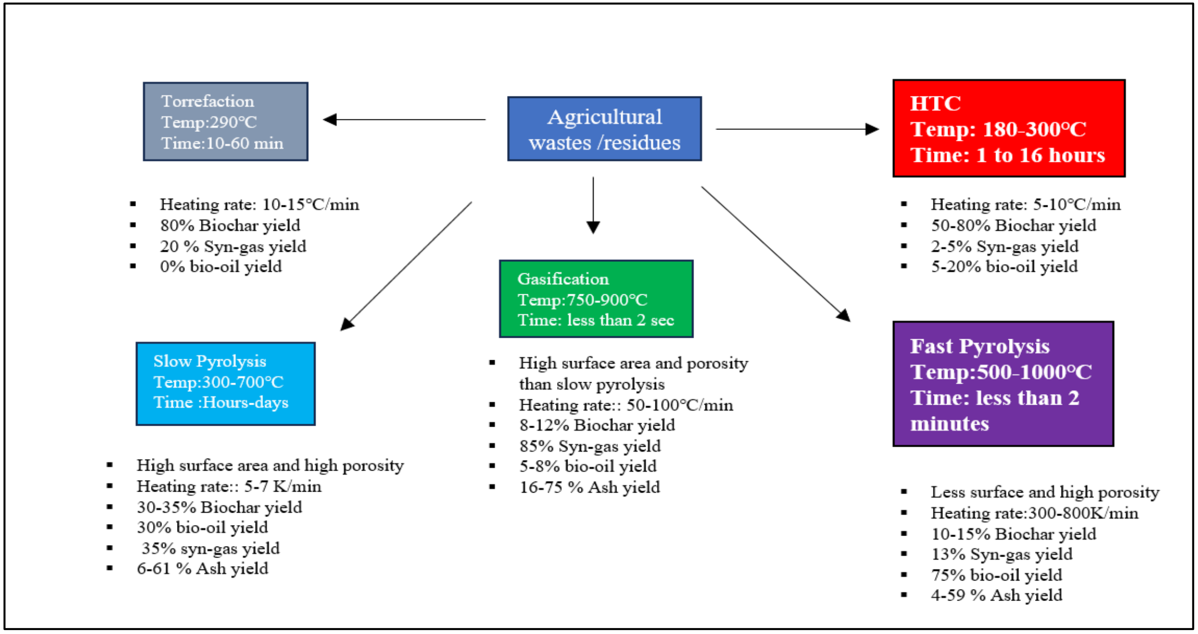


Figure 3. Biochar yields and qualities are compared among different biochar production techniques (Zhang *et al*., 2019)

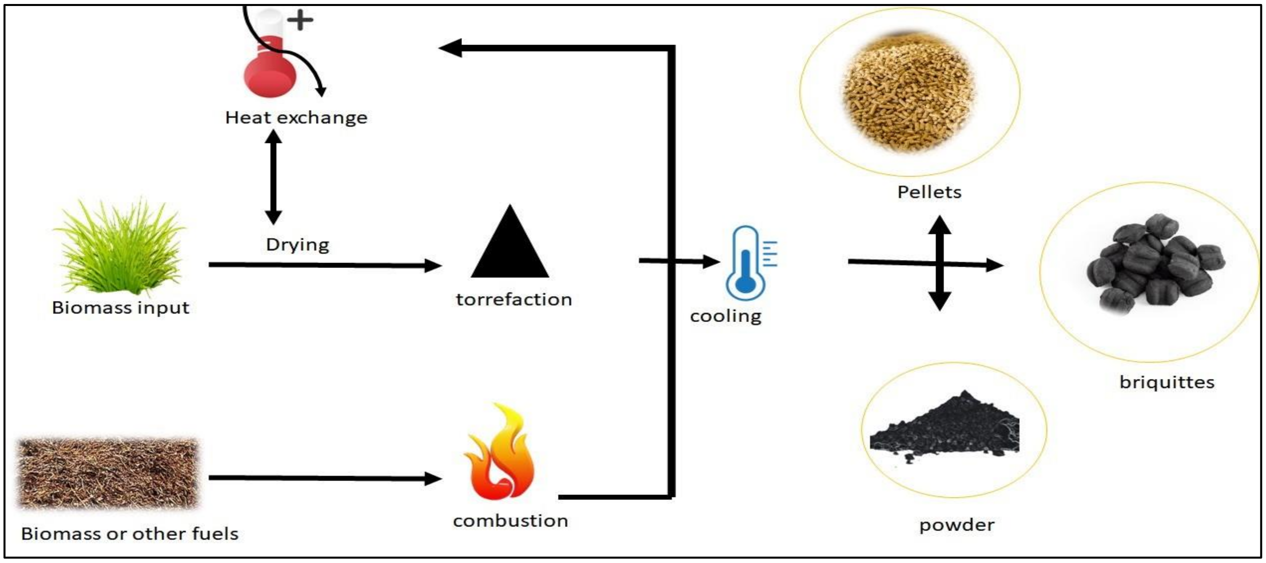


Figure 4. Torrefaction method utilized in biochar production process (Zhang *et al*., 2019)

Pyrolysis

Pyrolysis is one of the available thermal decomposition methods for producing biochar, while HTC is a decomposition done in a subcritical liquid medium. Temperature and heating rate affect the production level and composition of the pyrolyzed product (Safdari *et al*., 2019). Generally, the temperature ranges from 400 to 600 degrees Celsius with a heating rate ranging from 5 to 25 degrees Celsius per minute, as shown in Table 1. Higher temperatures and heating rates result in a lower final yield of the product (Noor *et al*., 2012; Yu *et al*., 2017). The product is obtained by using an exit tube attached to chilling condensers. This process employs different reactors such as wagon reactors and kilns to reduce liquid production. Pyrolysis can be either continuous or batch modes, but kilns belonging to batch mode are more straightforward and inexpensive (López Ordovás, 2020). Multiple factors like heat rate, residence time, temperature, feedstock type, reactor design, pressure conditions, and desired end products influence the efficacy of the pyrolysis product (Kan *et al*., 2016). Hemicelluloses and lignin are produced in the gaseous form, organic vapors, bio-oil, and biochar at the corresponding decomposition temperatures (Elkhalifa *et al*., 2022). Furthermore, the increased dry-weight content has made C_4 plants significantly utilized in Europe (Wiedner *et al*., 2013).

Dry pyrolysis

Dry pyrolysis is a process of the decomposition of materials at a high temperature, without using chemicals or oxygen. Many factors have been reported, that impact the final product in the process, which includes pressure, temperature, heating rate, vapor-solid interactions, temperature, and heat transfer rates (Ábrego *et al*., 2019). Structural characteristics affecting the process also include ash concentration, lignin, cellulose, and hemicellulose compositions (Yu *et al*., 2014).

Table 1. Biochar production from different crop residues

Source	Process	Heating Temp.	Temp.	Time	Biochar production rate (%)	References
Sugarcane waste	Slow pyrolysis	–	530	–	26	(Sakhiya *et al*., 2021)
Cotton residue	–	–	450	–	–	(Kannan *et al*., 2020)
Weymouth pine	Slow pyrolysis	15	500	30	30	(Kambo & Dutta, 2015)
Tamarind kernel	–	12	–	–	–	(Parmar *et al*., 2014)
Birch tree	HTC	–	175	30	70	(Kambo & Dutta, 2015)
Poultry manure and plant residues	Slow pyrolysis	30-50	550	–	–	(Kambo & Dutta, 2015)
Carthamus seeds	Slow pyrolysis	–	400	30	30–34	(Kambo & Dutta, 2015)

Pinyon pine wood	Slow pyrolysis (Rotary drum reactor)	3	500	–	19–51	(Parmar *et al.*, 2014; Sakhiya *et al.*, 2020)
Barley residues	Slow pyrolysis	–	400	120	31	(Kambo & Dutta, 2015)
Prune by-products	–	5	500	–	–	(Kambo & Dutta, 2015)
Coconut fibre	HTC	–	220	30	76.6	(Kannan *et al.*, 2020)
Edible walnut	Pyrolysis	10	–	–	–	(Shagali *et al.*, 2021)
Fruit pruning's	Slow pyrolysis	–	600	60	37.5	(Kordoghli *et al.*, 2023)
Biosolids	–	–	500	–	45.9	(Biney & Gusiatin, 2024)
Turkey droppings	Slow pyrolysis	–	500	–	19–51	(Uchimiya, 2014)
Quail manure	–	12	500	30	–	(L. Zhang *et al.*, 2023)
White spruce	HTC	–	175	–	88	(Sreekumar *et al.*, 2023)
Palm oil extraction residue	HTC	4	–		–	(Parmar *et al.*, 2014)
Pine sawdust	HTC	–	250	120	40	(Emenike *et al.*, 2024)
Corn residue, Rice hull, Cassava residue, Native grass	Slow pyrolysis	5	500	–	30	(Hoang *et al.*, 2021)

Slow pyrolysis

Biochar production or slow pyrolysis of biological feedstocks can reduce the release of various gases in the atmosphere and convert carbon into various other products (Kumar & Bhattacharya, 2021; Shalini *et al*., 2021). It occurs between 350°C to 700°C in Fig. 5, leading to higher biochar yields impacting its physical and chemical nature, comprising surface area, porosity, and nutrient content as well (Parmar *et al*., 2014). Heating is required for the decomposition of cellulose and hemicelluloses. Slow pyrolysis can be used for farming residues (Lee *et al*., 2013). Slow pyrolysis, achievable on a small scale using specialized equipment, enhances the final yield of biochar (Brown *et al*., 2011). To create a dry product, all the ground product is raised for pre-drying. Moisture lowers the efficiency of the product during pyrolysis. Once the weight of the sample stabilizes, i.e., once the moisture has been evaporated, the ground materials are placed in a controlled oven at 105°C. Conventional methods to produce biochar utilize metal kilns, earthen kilns, and bricks that have volatile compounds that get released into the atmosphere, causing pollution (Gwenzi *et al*., 2021; Sparrevik *et al*., 2015). Slow pyrolysis generates biochar from agricultural byproducts such as corn stalks, rice straw wastes, and sawdust through 20–25% gaseous product, 40–45% liquid content, and 30–35% biochar content in converters, retorts, and kilns, respectively (Sakhiya *et al*., 2020).

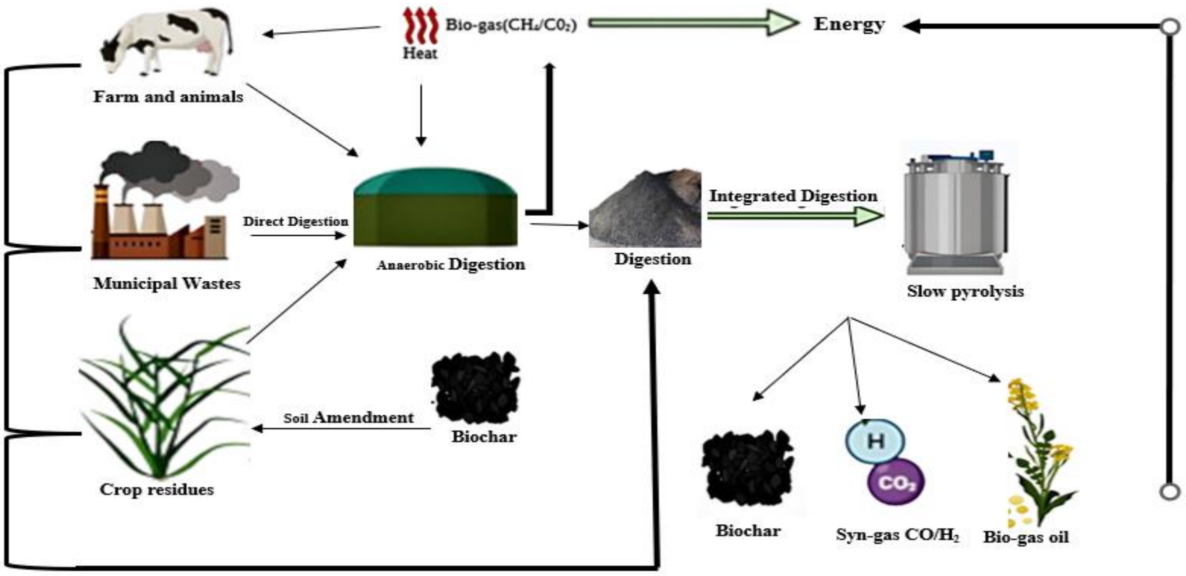


Figure 5. A summary of the slow pyrolysis method presented for making biochar (Ghysels *et al*., 2020)

Fast pyrolysis

Fast pyrolysis is a method that boosts bio-oil output by 75% at temperatures between 800 and 1300 degrees Celsius (Garba & Abdullahi, 2020). It uses reactors like bubbling particle reactors, high-velocity fluidized systems, and spinning cone pyrolysis systems to maximize liquid production (Bamido, 2018; Khan *et al*., 2022). Softwood produces the most liquid product. Fast pyrolysis occurs in oxygen-free environments between 10°C and 100°C, lasting 0.5-2 seconds (Ronsse *et al*., 2021). Different reactor types include low-pressure reactors, thermal scraping reactors, ablative reactors, rotating cones, entrained flow, and fluidized beds used in fast pyrolysis (Zhang *et al*., 2023).

Microwave assists pyrolysis

Microwaving assisted is an encouraging pyrolysis technique and a substitute for the process of decomposing before pyrolysis with pre-treatment. This technique is highly efficient for producing biochar yield which is obtained by removing the need for secondary reactors. It allows for efficient thermal decomposition that produces high-quality biochar with better physical characteristics such as higher surface area and nutrient retention (Cao *et al*., 2024). Besides this, it offers a higher biochar yield compared to traditional techniques. However, it can operate at relatively low temperatures and for shorter periods than typical methods for such operations, thus saving energy (Aziz *et al*., 2024). Another reason why microwave pyrolysis helps to support sustainable methods is its action of sequestering carbon while affording a good option for waste management (Dalbanjan *et al*., 2024). In conclusion, microwave-assisted pyrolysis is an efficient way of producing biochar and renewable energy (Balasubramanian, 2023). It serves as an inexpensive alternative process replacement for the traditional pyrolysis method since high proficiency with negligible emissions and energy savings are performed by it (Mishra *et al*., 2023).

Hydrothermal carbonization (HTC)/wet pyrolysis

Hydrothermal carbonization is a process wherein organic substrates experience breakdown in an aqueous medium at high temperatures, and products like biochar with high carbon content are produced. Friedrich Bergius discovered it, but improvement was found by Antonietti, which is very effective in processing materials rich in moisture content, such as algae and aquatic plants. It carbonizes lignin, cellulose, and hemicelluloses at 180-250°C and 5-10 bar pressure through dehydration, polymerization, and decarboxylation (Saleh, 2024). The three major products obtained through HTC are solid biochar, a liquid phase full of organic compounds, and gaseous by-products mainly carbon dioxide (Sivaranjanee *et al*., 2023). The HTC biochar can be utilized in wastewater treatments and also enhances soil health by sequestrating carbon (Cavali *et al*., 2023). Another benefit is that the liquid product may be further purified into biofuels or chemicals (Pfleger & Takors, 2023). This will put HTC in green alternatives for biomass conversion technologies and also waste minimization and a reduction level of greenhouse gases (Kataya *et al*., 2023).

Gasification

Gasification is the process of converting a carbon-based material into a gaseous form product, called syngas, that utilizes air, oxygen, and steam at temperatures less than 70 degrees Celsius. Its product yields about 10% of the biomass produced in the gasification process, which is smaller compared to pyrolysis (Nguyen-Thi *et al*., 2024). Among other parameters, variables that influence the gasification process include heat, pressure, reactor time, particle size, and the reactant-to-biomass ratio. Temperature has the highest effect on the overall yield of products in the gasification process (Portofino *et al*., 2013), and Producer gas, or syngas ($CO + H_2$), can be produced in larger quantities (Chiesa *et al*., 2005). Earlier, pyrolysis gases were used for cooking, heating, lighting, and other household purposes (Dirisu *et al*., 2024).

Applications of Biochar

Biochar is rich in stable and oxygenated carbon compounds; it can enhance soil permeability, reduce greenhouse gas emissions, improve soil structure, and enhance crop yields (Abhishek *et al*., 2022; Y. Wang *et al*., 2023). The performance of biochar in agriculture is closely associated with its properties and structure (Chen *et al*., 2017; Yavari *et al*., 2015). The primary application of biochar in biofuel production. However, there are three major pathways for biochar application into soils: mixing with topsoil, deep incorporation into the soil, and top dressing on the surface (Shackley *et al*., 2010). Biochar increases the porosity, fertility, and water-holding capacity of soils because of its high charge density contributing to favourable alteration in the soils and enhanced crop production (Diatta *et al*., 2020; Yu *et al*., 2019).

Enhance the soil's properties

The application of biochar to agricultural soils enhances their structure, thus, leading to improved chemical, physical, and biological qualities. It also improves the ability of the body or the crops to absorb nutrients-thus improving the quality of not only the soil but also the crops. Biochar also has high adsorption capacity which can lead to the removal of toxic metals from soils and plants as well as harmful substances and organic pollutants (Gholizadeh & Hu, 2021) (Figure 6).

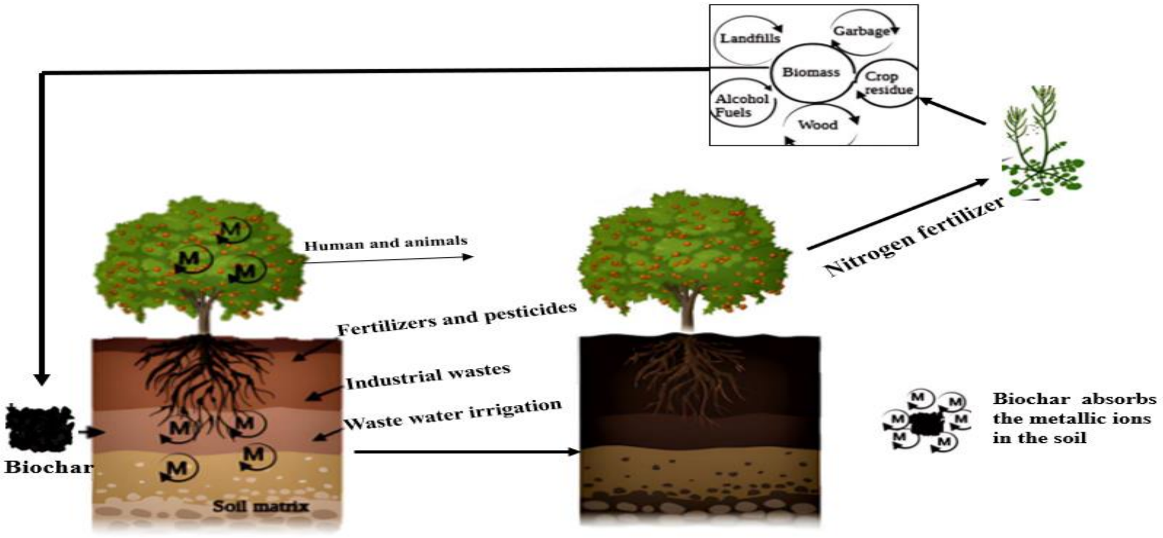


Figure 6. Biochar used for schematic metal contamination remediation process

Soil structure Properties

Biochar has been used for the improvement of soil structure in crop fields, leading to enhanced physiochemical and biological characteristics; consequently, resulting in improved nutrient absorption by plants (Rajani-Brown *et al*., 2012; Murtaza *et al*., 2021; Abukari *et al*., 2022). For instance, biochar exhibits great absorption capabilities and is now recognized as an effective approach for eliminating heavy metals from soil and plants, as well as harmful substances and organic pollutants (Gholizadeh & Hu, 2021). Furthermore, it can break down PCBs, halogenated hydrocarbons, PAHs, phthalates, and chlorobenzene while also improving soil moisture (Osman & Osman, 2018).

Enhancement of fertility through increased availability of nutrients

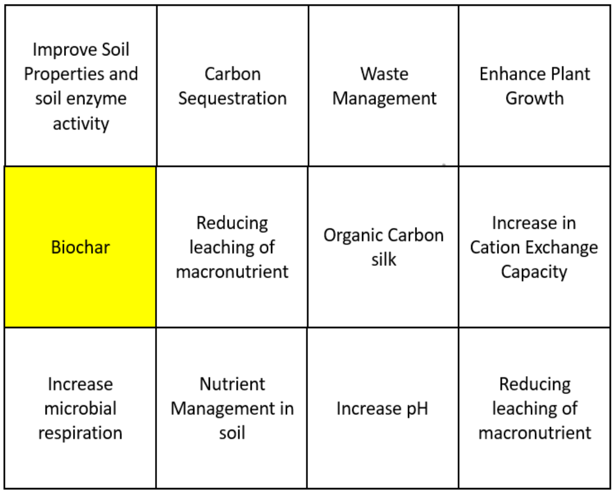
Soil biochar application enhances the fertility status of soil and boosts its physiochemical properties. Aluminum toxicity and soil salinity reduce agricultural yield by slowing down the rate at which the soil nutrients accumulate in the soil (Alkharabsheh *et al*., 2021). Field application of biochar increases the salinity of the soil by enhancing the ion exchange capacity as well as primary and secondary nutrients of the soil (Mahmoud *et al*., 2019; Xiao *et al*., 2022). It permits the removal of sodium from the soil, thereby increasing the levels of exchangeable magnesium and calcium, which decreases the acidity of the soil (Javeed *et al*., 2023) (Fig. 7). Besides increasing nutrient intake by plants, reducing nutrient runoff, and changing mechanisms of nutrient recycling, biochar provides an alternative source of nutrients in soils (Liu *et al*., 2018; Zdravkov *et al*., 2007). It provides necessary nutrients that improve the quality of the soil, promoting plant growth. Biochar may absorb all the potassium, organic material, nitrogen, and phosphorus in the soil, which can then increase the contents of inorganic nitrogen and nutrients.

Soil restoration

A major problem in the current world is soil pollution from industrial and household waste that may leach into ponds, lakes, and other water bodies and influence the behaviour of microorganisms (Wato *et al*., 2020). Remediation of contaminated soils using biochar has been documented for the past three years (Gao *et al*., 2022; Yuan *et al*., 2019). Biochar of *Carya spp* is cost-effective and environmentally friendly technology for soil remediation in reducing contaminants and enhancing immobilization strategies, especially for heavy metals and metalloids contaminated soils (Hasnain *et al*., 2023; Sharma & Chhabra, 2024).

Stimulates microbial growth in the soil.

The application of biochar alters the physiochemical characteristics of the soil, which influences its potential as a source of media that provides microorganisms to the soil (Gul *et al*., 2015). Microorganisms in soil influence the decomposition of organic matter, nutrient cycling, and crop productivity. Biochar enhances the performance of such microorganisms by offering niches for microbial growth (Palansooriya *et al*., 2019). Biochar alters mycorrhizal fungi and other microorganisms in the soil, influencing soil quality and health (Gujre *et al*., 2021). In this regard, it is documented that fresh biogas-derived biochar favors the microbiota by controlling the inhibition caused by arsenic and ferric ions. It enhances the productivity of soils due to increased structure and better retention of nutrients while at the same time facilitating carbon sequestration and enhancing agriculture.



Improve Soil Properties and soil enzyme activity	Carbon Sequestration	Waste Management	Enhance Plant Growth
Biochar	Reducing leaching of macronutrient	Organic Carbon silk	Increase in Cation Exchange Capacity
Increase microbial respiration	Nutrient Management in soil	Increase pH	Reducing leaching of macronutrient

Figure 7. Use of biochar in the Agriculture

Agricultural significance (enhancement of crop yields)

Biochar enhances crop yield and productivity through enhanced availability and efficiency of nutrients (Alkharabsheh *et al*., 2021). It has been reported to enhance crop yields by up to 10%. Additionally, biochar reduces the salinity of soils and enables crops to utilize nutrients more efficiently, thus enhancing crop yields (Khan *et al*., 2024; Yu *et al*., 2019). Biochar also aids in disease and pest management in agriculture. The application of 3-5% biochar slows down fungal diseases and harmful insects. It also proves to be beneficial for weed control in faba beans and crop yield enhancement in *Phaseolus vulgaris, Cucumis sativus, and nigrum* (Razzak, 2024; Sharma & Chhabra, 2024). Rice husk biochar in wheat fields is observed to enhance yield and water retention capabilities (Barus *et al*., 2023).

Climate change mitigation

Global warming is among the major issues in this century, mainly because of the increase in greenhouse gases, and carbon is needed both in its formation and for mitigation purposes (Kabir *et al*., 2023). Biochar has outstanding physical and chemical properties that can improve the quality of the environment when applied in different applications (Mariappan *et al*., 2023). Biochar catalytically degrades phosphates and nitrates within soils and potentially decreases the release of nutrients from agricultural watersheds if incorporated with manures (Feng *et al*., 2023) (Figure 7). The position of watching biochar management as a complete approach, rather than just a single component, is highlighted in the effort to decrease greenhouse gas emissions (Gaunt & Cowie, 2012; Verde & Chiaramonti, 2021). Biochar management is crucial in reducing greenhouse gas emissions. It is an important component of the fight against climate change. It emits less CO_2 than its raw materials. It strongly binds to soil particles which makes it effective (Mandal *et al*., 2016; Shalini *et al*., 2021). The different types of biochar and their effectiveness. Are presented in Table 2.

Table 2. Different types of biochar and their efficiency in the removal of contaminants affected by Proposed Sorption Mechanism

Type of Biochar	**Impurities**	**Proposed Sorption Mechanism**	**Removal efficiency (%)**
Rice straws and cereals	Aluminium	Surface Adsorption	–
Hardwood and Sewage sludge	Copper		~75
Waste water sludge	Quinolone derivatives	Adsorption	~80
Poultry litter.	Metabolite of atrazine	The presence of aroma leads to adsorption	~27
Sewage sludge	Zinc	Negatively charged inorganic species and chemical adsorption.	~15
Peanut straw	Methyl violet	Presence of phenolic compounds	~27

Peanut shells	Trichloroethylene	hydroxyl and carboxyl groups	~27
Pine leaves and Prairie grass	Uranium	Ph dependent	~27
9) Hardwood biochar,	Arsenic	–	–
10) Algal biomass, Eucalyptus,	Methylene blue	single-layer adsorption."	~27

Bio sequestration

Carbon sequestration is a process by which plants take in CO_2 through photosynthesis that gets sequestered in biomass and soil, thereby helping build up organic carbon. (Baig *et al*., 2023.; Lorenz & Lal, 2018). Carbon storage, such as biochar, facilitates this by maintaining relatively consistent carbon contents. These promote the storage of carbon, provide an avenue for environmentally friendly alternatives, and enhance the aging of organic carbon (Kumar *et al*., 2020; Gupta *et al*., 2022; Mandal *et al*., 2016; Wu *et al*., 2019). The incorporation of materials impregnated by biochar promotes climate and ecological sustainability.

Global Warming gases

Some estimates suggest that the global application of biochar could lower the release of greenhouse gas emissions by 12% (He *et al*., 2017; Zhang *et al*., 2020). Blending biochar with compost could enhance decomposition by increasing carbon content and creating a positive biochar-compost blend, potentially addressing potential drawbacks of pyrolysis biochar technology (Agegnehu *et al*., 2017; Qian *et al*., 2023). Biochar has been associated with higher levels of soil organic matter and decreased emissions of highly potent greenhouse gases like CH_4 and N_2O (Elbasiouny *et al*., 2021; Subedi *et al*., 2016). The biochar system may demand higher plant growth or lower soil greenhouse gas emissions to have a better emission balance than using biochar as charcoal fuel in practice (Kammann *et al*., 2017; Thakkar *et al*., 2016).

Benefits of Biochar Application

The practicality and cost-effectiveness of biochar engineering techniques are superior to those of traditional carbon activation techniques (Tan *et al*., 2017). It is used in fuel cells, supercapacitors, and as a catalyst support to create composites such as metallic nanoparticles (Akhil *et al*., 2021; Foong *et al*., 2020). Biochar from agricultural and forestry wastes is one of the most available cost-effective solutions for the handling of environmental pollutants, including heavy metals, organic contaminants, and nutrients (Tareq *et al*., 2019). Biochar, a carbonaceous material from agricultural industrial wastes, has the potential used for improving soil fertility and crop yield and thus contributes to sustainability in the energy, environmental, and agricultural sectors (Dwibedi *et al*., 2022). Its production boosts national food security, aids ZVI particles, and captures carbon to counter climate change (Kafeel *et al*., 2022; Qiao *et al*., 2019). Table 3 shows an account of the effects of the application of biochar on crop yield in correspondence with its application rate.

Table 3 Effects of applying biochar on crops yields, corresponding to its application rate

Type of Crop	Biomass feedstock	Soil	Application rate	Yield Response	Other effects	References
Maize	Corn cub	partially leached soils	2% w/w	Improve yield.	–	(Alkharabsheh *et al*., 2021)
Ground nut	Hard wood	smooth, reddish, kaolinite-rich, and temperate soil.	0.89 Mg/ha.	No change	Significant decrease in arsenic (As) contamination levels in the leaves.	(Van Cuong & Van Chuong, 2022)
Soya bean	Acacia Wood	Clay	50+50 Mg/ha	Increase seasonal yield	–	(Kätterer *et al*., 2019)
Mustard	Chicken manure and green waste	Loamy	–	Increase in crop yield	Levels of Cd, Cu, and Pb are decreased.	(Zhao *et al*., 2016)

Cotton	Rice straw	Sandy	–	–	Reduction in free Cu, Pb, and Cd levels; identification of functional groups with strong Cu adsorption affinity.	(Saleh *et al.*, 2020)
Paddy	Wheat straw	Loamy	–	Boost crop yield	CH4 emissions Increase	(Wang *et al.*, 2019)
Corn	Pine chips	Loamy sand	30000 kg /ha	No change	–	(Novak *et al.*, 2019)
Amaranthus	Household organic waste	Alluvial soils.	10t/ha	17/64 percent rise in crop yield	–	(Makinde *et al.*, 2011)
Wheat	Betula	Loamy	–	–	Reduce N_2O and CO_2 emission	(Lebender *et al.*, 2014)
Maize	wattle	Clay	50 +50 Mg / ha	Increase in the seasonal yield	–	(Kimaro *et al.*, 2008)

Drawback of Biochar Application

This biochar application in the soil results in the uptake and neutralization of agrochemicals, including herbicides and fertilizers (Perra *et al*., 2022). Certain types of biochar evaluated in the research study reduced carbon and hydrogen oxidation rates from the soil, which resulted in a reduction in soil and N_2O content (Cayuela *et al*., 2014; Lyu *et al*., 2022). Some chemicals present in biochar can reduce plant growth at the germination stage (L. Huang & Gu, 2019; Joseph *et al*., 2021). Biochar changes the physical and chemical properties of the soil, as it increases porosity and bulk density but decreases the porous structure (Ahmad Bhat *et al*., 2022; Singh *et al*., 2022). Due to the EC and pH levels, the added surplus biochar in the soil impacts the soil seed germination and biological processes (Yuan *et al*., 2019). A series of challenges are also incurred in farmland use especially when the structure of the biochar is fragile coupled with powdery composition, meaning prone to massive loss as experienced through either wind or by rain when applied on soil (Gryta *et al*., 2023; Nogués *et al*., 2023). Biochar cannot be reused once it has been deposited in the soil due to its integration with it. Due to its complexity, it is not possible to apply this in co-generation plants since it will be hard to distribute the amount needed in heating systems (Liu *et al*., 2014). Biochar continues to release harmful substances, including heavy metals and PAHs (Anae *et al*., 2021). All organic wastes are not appropriate to be converted into biochar for agricultural applications (Guo *et al*., 2020). Some specific production methods and feedstock selection may result in biochar that is ineffectual at retaining nutrients and susceptible to microbial breakdown (Dai *et al*., 2020; Lehmann *et al*., 2011).

Conclusion

Biomass, depending on the kind of pyrolysis used in its manufacturing process, has different chemical and physical properties. Biochar enhances agricultural yield by improving soil productivity, nutrient retention, texture, and appearance. Its use can be utilized for cleaning polluted soils, enhancing photosynthesis in plants, increasing carbon sequestration, reducing greenhouse gas emissions, and mitigating the urban heat island effect. Biochar can easily be transported, and it is cheaper compared to chemical fertilizers. Therefore, there ought to be increased cooperation between farmers, soil scientists, researchers, and relevant authorities toward the effective and rapid harnessing of biochar in key areas.

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Declarations

Declaration of Interest Statement

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work.

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Author's contributions

MF and MFI conducted the analysis and planned the data. MF and MFI assisted with data collection. All authors proofread the manuscript. All authors have read and approved the final manuscript.

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Consent for Publication

Not applicable