3-2023

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Journal of Agriculture and Food Research 11 (2023) 100498

Contents lists available at ScienceDirect

Journal of Agriculture and Food Research

journal homepage: www.sciencedirect.com/journal/journal-of-agriculture-and-food-research

Biochar application: A sustainable approach to improve soil health

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ARTICLE INFO

Keywords:
Biochar
Soil fertility
Biomass
Crop production

ABSTRACT

Soil is a fundamental part of successful agriculture, and its quality has to be improved to maximize crop yield and soil fertility. To increase crop productivity and soil fertility, biochar can be applied to the soil. Biochar is a solid carbon-rich product produced from biomass of agricultural crop residues, wastes, and wood, through pyrolysis in an oxygen-deficient condition. Carbon sequestration through biochar is important because of its potential applications in recycling wastes, retaining nutrients in the soil and lowering greenhouse gas emissions. In this review, we explore the various applications of biochar to ensure the safe and sustainable improvement of soil fertility. This review provides an overview of biochar properties, production technology, and its employment in the agriculture. This review would be a useful resource for researchers, farmers, and academics who are interested in the utilization of biochar.

1. Introduction

Globally, agricultural wastes or plant residues represent a significant issue for the environment due to their role in increasing greenhouse gas emissions. Thus, several researchers exploited these wastes in different forms such as soil mulching [1–4], organic fertilizers [5,6] and biochar. Biochar is a substance extracted from the different components by the thermal conversion process with limited oxygen delivery at temperatures of less than 700 °C [7–9]. It is a versatile renewable energy source with the capacity to produce heat, electricity, and liquid biofuels [10]. Biochar, charcoal produced through pyrolysis [11,12], contains a well-maintained porous structure with enough functional groups, different inorganic nutrients, and well-stable carbon components [7]. Biochar is a stable soil nutrient compared to other types of organic nutrients and plays crucial role in adsorption and mineralization [8,9,11]. It can increase nutrient availability in the soil and enhance the environmental quality [9]. It is a carbon-rich substance that functions as a soil supplement in agricultural territory and further diminishes the probability of environmental pollution and degradation [8,13]. The biochar production is dependent on three factors, i.e., the manufacturing process (methods, temperature), biomass types (rice hulls, food wastes, animal by-products, and other different solid wastes) and manufacturing technology (pyrolysis, thermal carbonization, gasification) [8].

Three categories of biochar are 1) lower carbon ash-containing feedstock (3–5%), e.g., bamboo, nut shells; 2) ash-containing feedstock (3–5 to 10–13%), e.g., agricultural residues, tree bark, green wastes; and 3) ash-containing feedstock (>13%), e.g., waste paper, manures, industrial effluent, municipal solid wastes (Fig. 1) [14]. The conversion of biomass into a carbon compound is increasing daily to reform the degraded soil [15–17]. Recently biochar has taken off as an interdisciplinary topic due to its different characteristics [18]. As a sustainable medium for biochar production, woody feedstock such as oak sawdust is used primarily [13]. Biochar use is increasing rapidly for the sustainable production of agricultural goods and to improve food security [18,19].

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https://doi.org/10.1016/j.jafr.2023.100498
Received 28 October 2022; Received in revised form 28 December 2022; Accepted 5 January 2023

Abbreviations

SSA	Specific Surface Area
TSA	Total Surface Area
HGI	Hardgrove Grindability
H/C-ratio	Hydrogen–Carbon ratio
O/C ratio	Oxygen–Carbon ratio
pH-vale	Potential of Hydrogen value
CEC	Cation Exchange Capacity
HTC	Hydrothermal Carbonization
FW	Food Waste
BY	Biochar Yield
GHGs	Green House Gases
PAHs	Polycyclic Aromatic hydrocarbons

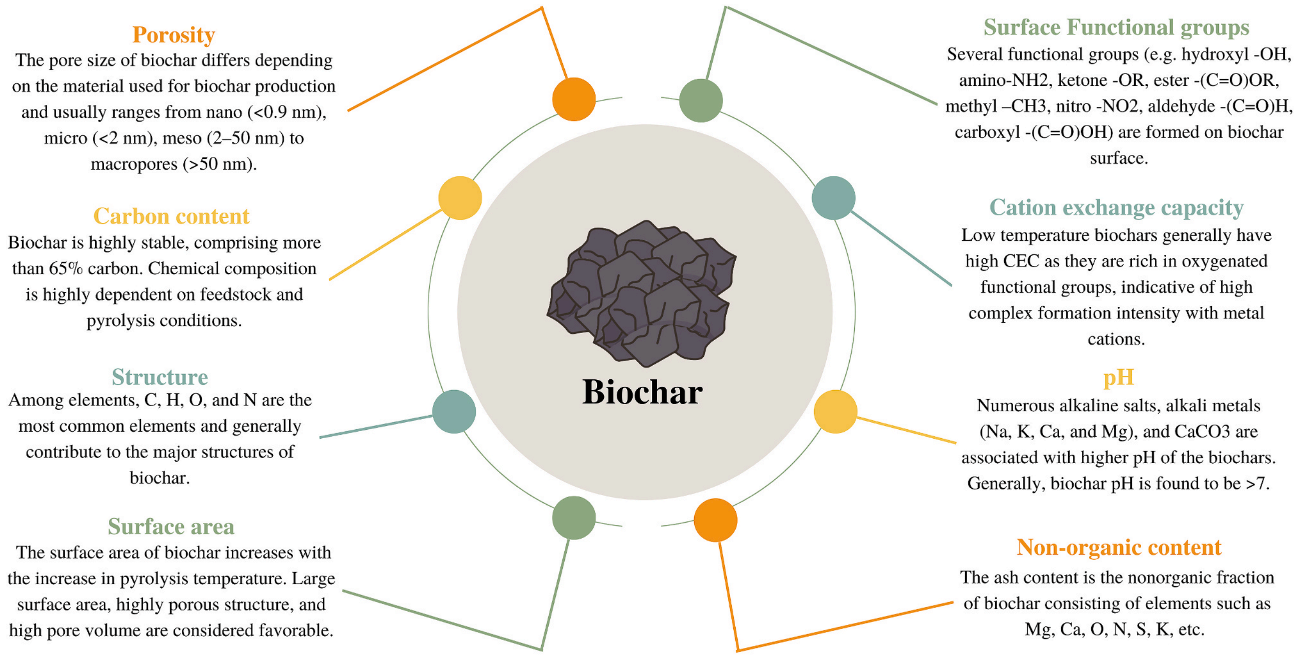
Biochar positively affects soil properties, nutritional qualities, microorganisms, and agri-output [20]. In 2006, China announced a plan to restore the carbonized stew in the field with biochar, which clearly explains biochar as a carbon-rich component derived from agricultural waste [18]. The biochar produced at different temperatures shows different functions and properties. Biochar has a greater concentration of functional groups that are oxygenated at 400–450 °C; compounds dissolve in organic substances and water, which gives better germination and enhances microorganisms' growth, thus leading to a higher water holding capacity than compared to biochars produced at a temperature greater than 450 °C [14]. Biochar's low cost, eco-friendly nature, and multipurpose application have been a better agriculture choice [20,21]. Biochar helps to improve soil quality and reduce pollutants and is crucial for decreasing greenhouse emissions, thus mitigating global climate change [22–24]. Biochar can also substitute for soil's hydraulic properties [25]. Most of the carbon may be extracted via the short-lived carbon cycle once biochar is applied to the soil [26]. Biochar has many physical and chemical characteristics, affecting how well it can transport different types of bacteria into the soil [27].

Biochar has a certain water-holding capability, surface area, and carbon: nitrogen concentration which influences the survival of inoculant microorganisms in soil [27]. All processed and unprocessed biomass can be applied as feedstock in biochar production [28]. Biomass from agriculture and agro-processing industries is the more economically critical waste for biochar production [28,29]. The different studies focus on determining the positive and negative effects of biochar's long-term impact on soil, which enhances the properties of soil biochar applications [30]. Research shows that biochar is a negative-release technology that estimates economic, technological, and sustainable development capability [31]. A recent report suggests efforts to produce and utilize different types of biochar for various purposes [30].

The aim of this review is to provide information on the production technology of biochar, its properties, applications of biochar, and its advantages and disadvantages.

2. Properties of biochar

Biochar gets affected mainly by the primary feedstock conditions and the process of pyrolysis, which differ in physical and chemical properties [32]. Biochar from wood with high lignin content has higher carbon amounts than herbaceous feedstocks; however, it lacks nitrogen (N) content [33]. Carbonization decomposes the parts of the biomass but keeps a massive amount of carbon content. The alteration of properties of biochar leads the product to be more carbonaceous and it becomes convenient to use in the technical process [34]. The composition of charcoal includes the function of the fuel type and burn conditions, which include oxygen supply, temperature, and duration, as it results from the partial combustion of plant material. Oxygenated conditions give complete combustion, which creates a loss of all carbon and remains only white ash. However, under the condition of low oxygen, if plant tissue is burned, carbon is left as charcoal as oxygen, nitrogen, and hydrogen are ejected in the gaseous form [35]. The biochar composition has both unstable and stable components because it is heterogeneous. The surface area, carbon, and mineral matter (ash) are the components that are regarded as biochar's major constituents for characterization. Biochar's two natural properties that make it capable of long-period carbon storage in the soil [32,36]: 1) stability, which includes resistance to living and non-living decay in the soil, and 2) the higher carbon content of biochar compared to biomass [36].



Porosity
The pore size of biochar differs depending on the material used for biochar production and usually ranges from nano (<0.9 nm), micro (<2 nm), meso (2–50 nm) to macropores (>50 nm).

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 contribute 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 biochars 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 of the biochars. Generally, biochar pH is found to be >7.

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

Fig. 1. Physical and chemical properties of biochar.

2.1. *Physical properties*

The crashing of fibrous biomass structures changes biochar's physical properties [34]. The physical properties of biochar are associated with how it affects soil systems directly and indirectly (Fig. 1) [37]. Specific surface area, density, porosity, pore volume and size, thermal conductivity, water holding capacity, heat capacity, hydrophobicity, and grindability come under the physical properties of biochar.

2.1.1. *Specific surface area (SSA)*

Biochar includes a specific surface area as an important property that gives an active area for reacting with the species targeted and influences its catalytic capability and chemical kinetics [24]. During the carbonization process, the change in the porosity and the total surface area of the biomass results from escaping volatile gases. Biochar's cation exchange capacity and water-holding capacity are other qualities related to its surface area (Fig. 2) [34]. Methods involved in improving the SSA of biochar, include metal doping, high-temperature pyrolysis, and CO_2-feeding pyrolysis. Similarly, the radicals from steam vapour partly oxidize the carbon matrix. As a result, it produces new pores on the biochar, which may also be employed for hydrothermal pyrolysis and steam activation to increase the surface area of biochar [24,38].

2.1.2. *Density and porosity*

Biochar's bulk density and compression strength, first drop and subsequently rise when the carbonization temperature is raised (Fig. 2) [39]. During pyrolysis, the devolatilization of gases from the solid biomass structure leaves a char with pores. As the porosity increases, the char per unit volume becomes lighter [34]. The changing porosity does not directly influence the true density as it accounts for neither vacant space in bulk nor pores in the solid and only provides knowledge about the solid part. In contrast, the particle density considers only the solid and closed pores [34,37].

2.1.3. *Hydrophobicity and water-holding capacity (WHC)*

The surface functional groups' outcome is hydrophobicity and water-holding capacity that pivots on the biochar's bulk volume porosity [40]. The hydrophobic qualities of biochar are increased by raising the pyrolysis temperature by removing more polar surface functional groups and increasing the fragrance [34]. The hydrophobic surface in the pores does not let water enter the porous structure of the biochar [38]. Therefore, the changes in the amount of water to be adsorbed are due to increased porosity [34,38,40].

2.1.4. *Pore volume and pore size distribution*

Biochar pores are of two types, i.e., macropores and micropores, where pore volume is determined by N_2 sorption (Fig. 1) [24,34,41]. As a broad surface area consists of multiple small pores, certain gases may not be able to readily reach them, which restricts the capacity of biochar to adsorb a particular gas [41,42]. Many micropores are present in the biochar pore structure, resulting in more than 80% of the pore volume [34].

2.1.5. *Thermal conductivity and heat capacity*

The direction of heat flow changes thermal conductivity, and when heat flow is directed in the grain direction, it gives the highest value [34,42]. The thermal conductivity of biochar decreases due to the formation of the porous structure [43]. With increasing pyrolysis temperature, multi-directionally measured thermal conductivities converge because of biomass fibres' decomposition and structural complexity loss during the carbonization process [24,34]. The conductivity of biochar becomes an effective shield as it increases with carbonization temperature [24].

2.1.6. *Grindability*

Due to mechanical stability throughout the carbonization process, the char is more delicate and has better grindability than the raw material [24]. The grindability of biochar and coal can be compared by determining Hardgrove Grindability Indices (HGI) [24,34,41]. Low HGI means poor grindability; in contrast, high grindability implies the material is easily grindable [34].

2.2. *Chemical properties*

The chemical characteristics of biochar are assessed in terms of its

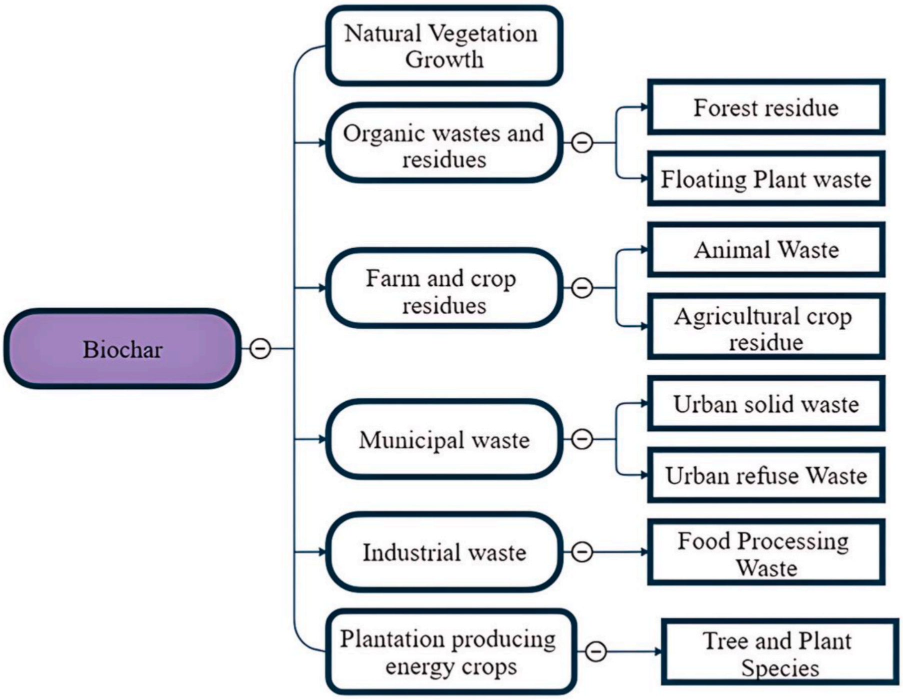


Fig. 2. Classification of various forms of biomass for biochar production (Modified from Refs. [28,51]).

elemental composition, self-ignition, energy content, degradation, pH value, and reactivity that occur during storage based on temperature and residence duration (Fig. 2) [34].

2.2.1. Functionality

The decomposition of biomass structures by heat results in the separation of functional groups, and hydrogen and oxygen liberation are important processes during carbonization [34]. This process, as compared to low-temperature biochars, results in biochars of low H/C–ratio consisting of more fragrant structures and fewer functional groups [38]. Furthermore, due to consistent variations in the pH value of the contents of the surface, the acidic functional group of biochar decreases with increasing temperature [44].

2.2.2. pH-value

pH-value is the property of biochar where chars from pyrolysis are different from those of chars produced through hydrothermal carbonization [34,44]. Increasing alkalinity leads directly to an increasing pH value (Fig. 2) [38]. pH-value as a property of biochar is beneficial for agricultural use, such as soil conditioners [34]. Temperature is the most important factor influencing 'biochars' pH value [44].

2.2.3. Reactivity

The reactivity of biochar impacts biochar applications that involve the thermochemical conversion of material [34,38]. The biochar conversion may be described as the interaction between water vapour and carbon monoxide to produce hydrogen and carbon dioxide [34,35,38].

$$C + CO_2 \rightarrow 2CO$$

$$C + H_2O \rightarrow CO + H_2$$

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

Temperature and gas concentration affect how quickly a reaction occurs [38]. The reactions mentioned above are surface reactions. Additionally, reactant gases need access to the solid's interior surface area [34,35,38]. The linear and non-polar CO_2 might permit various areas more than the non-polar but polar H_2O molecule. The reactivity of the biochar is also promoted by the inorganic components, as those components may act as catalysts [34,38].

2.2.4. Proportions of atoms

The carbonization process alters the chemical composition of the fuel, primarily by separating functional groups [34,45]. The hydrogen and oxygen-containing groups evolve during this process, decreasing corresponding ratios with carbon [38,43]. The natural carbonization process releases oxygen at almost doubles the rate of hydrogen unless hard coal forms [38,44]. Similarly, the ratios of both the H/C and O/C drop as the temperature rises [34]. This drop is sustained for raw biomass at high temperatures in contrast to the natural carbonization process [34,45].

2.2.5. Elemental composition

Compared to raw biomass, biochar has a different chemical composition and typically has greater carbon content because of the separation of functional groups comprising hydrogen and oxygen [43]. Lower levels of hydrogen and oxygen resulting from a rise in carbon content due to an increase in reaction temperature [34]. The carbon content in high-temperature biochars is more than 95% while the oxygen and hydrogen contents are 5% and 5–7%, respectively, but the hydrogen content is reduced to less than 2% during pyrolysis [34,43].

2.2.6. Cation exchange capacity (CEC)

Cation exchange capacity refers to the number of exchangeable cations (Mg^{2+}, Na^{+}, Ca^{2+}, and K^{+}) in the soil as well as the capacity for nutritional cation exchange at plant roots caused by negative charges on clay in the soil (Fig. 1) [34,38,43]. In addition to relying on the surface area that makes the surface charges accessible, CEC also depends on the surface structure since it includes functional groups that give surface charges [34,44].

Biochars produced at lower temperatures have high cation exchange capacity as surfaces are increased, and functional groups remain in the structure to provide negative charges during low temperatures [44,45].

3. Biochar production technique

The various forms of biomass for biochar production are given in Fig. 2. Biochar can be produced by utilizing agricultural and agro-industry residues, which is the most economical method of waste management [28] and it can be obtained when agro-wastes are heated in an air-tight container with proper restriction of oxygen flow [46]. Woody and dry matter, such as straw, husks, and nut shells, are ideal for biochar extraction [28,47]. Biochar can be made from agricultural waste and used to improve soil quality. Biochar's properties, such as negative charge density, high surface area, and negative surface area, improve nutrient holding capacity and make it more stable than other bio-fertilizers. More than 50% of the carbon in agricultural products can be lost by burning [38]. Biochar has products in solid, liquid, and gas forms. Solid and liquid products of biochar can be maximized by using slow and fast pyrolysis [46,47]. The outcome of biochar obtained by various production techniques is considerably less than theoretical expectations and can be computed by formula (BY) [11,46]. Superior quality charcoal is made from feedstuffs and has a caloric value of 30–33 MJ kg^{-1}, a volatile matter (VM) content of 21–23%, a fixed carbon content of 70%, and an ash content of 1–3% [47]. Because of their nutritional properties, algae are considered sustainable for biochar production; additionally, all three solids, liquids, and gases can be extracted [48]. During biochar production, cyclones can be used to distinguish the solid product from liquids and gases [49]. Biofuel is classified into four generations depending on lignin and cellulose content. Oil seed crops and food crops such as sugarcane, maize, and rapeseed are used to produce the first generation of fuels. The 2nd generation biofuel is obtained from non-food plants having high lignin content, like forest wood, alfalfa, etc. And the 3rd generation biomass is generally produced from algae, whereas the 4th generation biomass is obtained from energy drought-tolerant crops [50].

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

3.1. Torrefaction

Torrefaction is the thermal conversion of feedstuffs into solid components at 200–300 °C and atmospheric pressure in anaerobic conditions (Fig. 3) [48,52]. After the attainment, the required time removes the reacting agent from the oven and is left to cool at room temperature [56]. In this thermal process, pre-treatment (dry or wet) is given to eliminate various volatile substances (moisture, carbon dioxide, and oxygen) through decomposition to increase the quality of the final product [52]. Isothermal properties of torrefaction of food waste (FW) were examined between 200 and 300 °C for 60 and 180 min, where the constant increase in temperature of 15 °C/min increases the amount of carbon, energy density, and caloric content of FW [56]. The dry method can provide dense energy products quickly as the transfer rate is high, and the wet method is high caloric with low ash content products quickly [48,52]. Because FW contains a high percentage of moisture, it is oven dried for 24 h at 105 C before being pulverized by a cutting mill to 9 mm. Untreated pulverized is stored in air-tight polythene bags in a desiccator until torrefaction. Before conducting torrefaction, the reacting agent was flushed with nitrogen gas in a small stream for 10 min to remove any remaining oxygen (Fig. 4) [56].

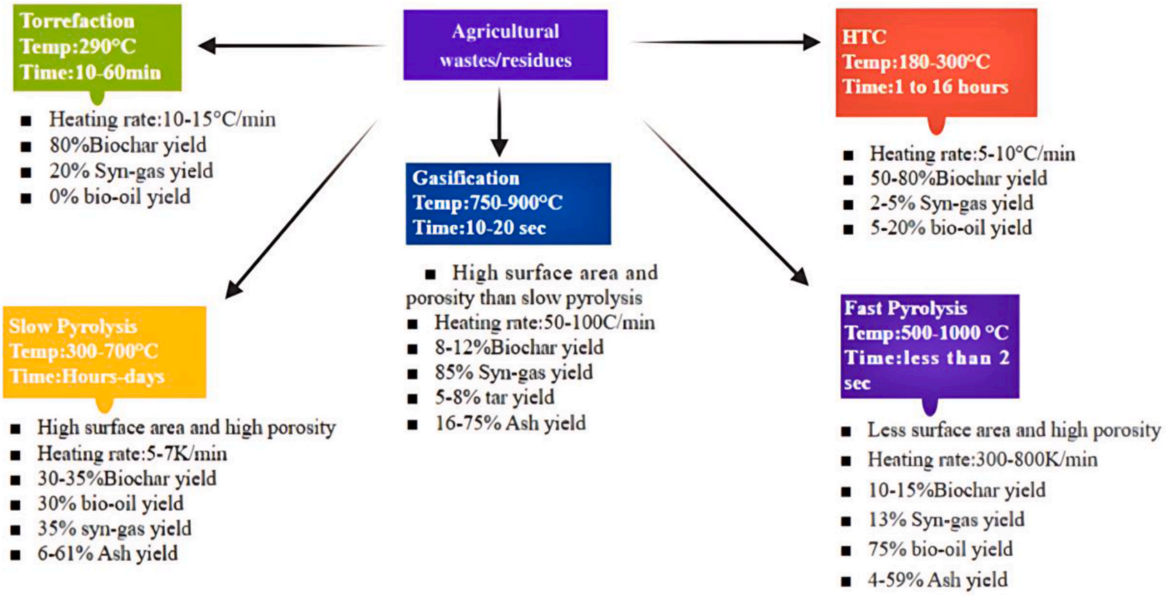


Fig. 3. Yields and properties of biochar produced using various biochar production methods: Fast pyrolysis; Slow pyrolysis; Torrefaction; Hydrothermal Carbonization (HTC); and Gasification (Modified from Refs. [38,52–55]).

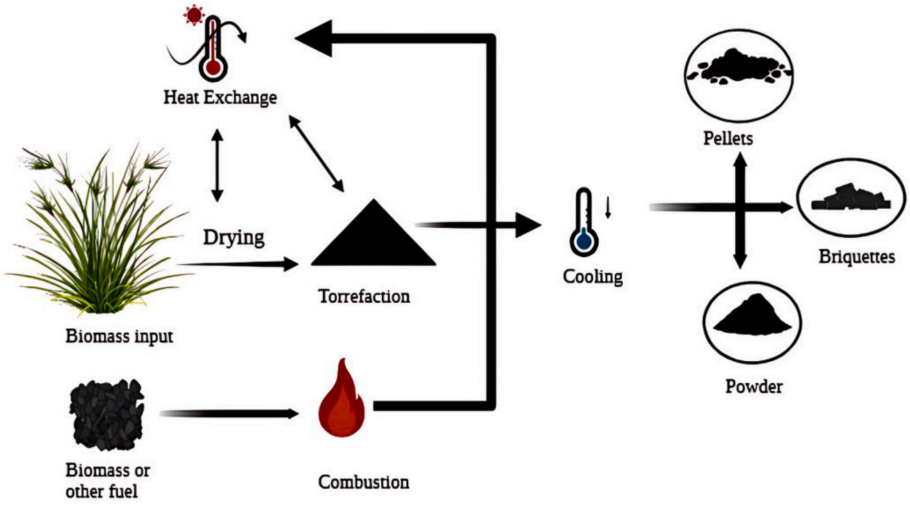


Fig. 4. Biochar manufacturing scheme using the torrefaction method (Modified from Ref. [52]).

3.2. *Pyrolysis*

Pyrolysis is the process of thermal decomposition applied to obtain high carbon-containing elements like biochar; if such decomposition is held on a subcritical aqueous substrate, it is known as hydrothermal carbonization (HTC) [28,48]. The temperature and rate of heating applied to the stuff, among other pyrolysis parameters, affect the yield and composition of the pyrolyzed product. The temperature ranges from 400 to 600 °C, and the heating rate ranges from 5 to 25 °C per minute (Table 1) [46,47]. An increase in temperature and heating rate decreased the final yield and vice versa [48]. The final product is carried out in this method through an exit pipe connected to various cooling condensers [46]. Multiple reactors are involved in this process, such as wagon reactors, agitated drums, kilns for sand rotating, and paddle pyrolysis kilns. It reduces the liquid production as the cracking reaction improves in this process [52]. Pyrolysis can be performed in continuous and batch modes depending upon the final yield and can be improved through the continuous mode as compared to the batch mode, as continuous input can be given [57]. Batch mode includes earthen and mound kilns or brick, concrete, and metal kilns that can operate at temperatures ranging from 300 to 500° Celsius and are less expensive, simpler to design, and operate [51,57]. Pyrolysis is divided into two types depending on the given heat rate, pressure, temperature, and residence time [52]. In hemicelluloses, lignin is converted to non-condensable gas and then to condensable organic vapours and aerosols, bio-oil, and biochar with the proper required temperature for decomposition [11,58]. The use of C4 plants for the production of biochar is prevalent in Europe as the dry weight content of C4 plants is generally higher than that of other plants [59].

3.2.1. *Dry pyrolysis*

Thermal decomposition of the dry chemical-free substrate under an anaerobic condition at a high temperature is called dry pyrolysis. Different variables involved in this process are high temperature, heating rate, the interaction between vapour and solid, heat transfer rate, pressure, etc. [28]. Various feedstock characteristics, like the size of

Table 1
Feedstock from different sectors and their technique of synthesizing biochar.

S. N.	Feedstock	Process	Temp (^{0}C)	Time (min)	Heating rate (^{0}C/min)	Biochar yield (%)	References
1.	Sugarcane bagasse	Slow pyrolysis (Fixed bed reactor)	530	–	–	26	[49]
2.	Cotton stalks	–	450	–	–	–	[55]
3.	White pine	Slow pyrolysis	500	30	15	30	[53]
4.	Tamarind seed	Pyrolysis	–	–	–	–	[28]
5.	Birch	HTC	175	30	12	70	[53]
6.	Chicken manure & green waste	–	550	–	–	–	[55]
7.	Safflower seeds	Slow pyrolysis	400	30	30–50	30–34	[53]
8.	Pinyon-juniper wood, Aspen, Fir pallets, Lemna, USU algae, Pine brake, Fir fines, Pine shredded	Slow pyrolysis (Rotary drum reactor)	500	–	–	19–51	[28,49]
9.	Barley straw	Slow pyrolysis	400	120.	3	31	[53]
10.	Orchard prune residue	–	500	–	–	–	[55]
11.	Coconut fibre	HTC	220	30	5	76.6	[53]
12.	Walnut seed	Pyrolysis	–	–	–	–	[28]
13.	Fruit cuttings	Slow pyrolysis	600	60	10	37.5	[53]
14.	Wastewater sludge	–	500	–	–	45.9	[38]
15.	Turkey litter	Slow pyrolysis (Rotary drum)	500	–	–	19–51	[28]
16.	Quail litter	–	500	–	–	–	[55]
17.	Spruce	HTC	175	30	12	88	[53]
18.	Palm oil press waste	HTC	–	–	–	–	[28]
19.	Eucalyptus	HTC	250	120	4	40	[55]
20.	Pinewood chips	Slow pyrolysis (Auger reactor)	500	–	–	30	[38]
21.	Corn Stover, Rice husk, Cassava stalk, switchgrass	Slow pyrolysis (Auger reactor)	300–450	2.5–5	5	15–28	[28,49,53]
22.	Waterweeds	–	500	–	–	58.4	[38]
23.	Peanut shell & wheat straw	Slow pyrolysis	350–500	–	–	15–28	[55]
24.	Cornstalk	HTC	250	240	4	35.48	[53]
25.	Swine solids	Pyrolysis	–	–	–		[28]
26.	Cow manure	–	500	–	–	57.2	[38]
27.	Hardwood	HTC	250	240	4	38.1	[53]
28.	Oil stones	Slow pyrolysis (Rotary drum)	500	–	–	26	[49]
29.	Cassava waste	Slow pyrolysis (Auger reactor)	450	–	–	15–28	[28]
30.	Pig manure	–	500	–	–	38.5	[38]

matter, structure, physical character, ash content, and combination of lignin, cellulose, and hemicellulose affect the overall production [28, 47].

3.2.2. *Slow pyrolysis*

Making biochar from various bio-stuffs through slow pyrolysis is a promising carbon-negative procedure as it reduces the composition of CO_2 in the atmosphere and recalcitrant carbon into various products [46]. Slow pyrolysis is conducted at temperatures ranging from 350 °C−400 °C to 600 °C−700 °C with a heating rate of 5 °C per minute (Figs. 3 and 5) [11,46,47]. Heat is supplied for the decomposition of cellulose and hemicelluloses [11]. Agricultural leftovers can be used for

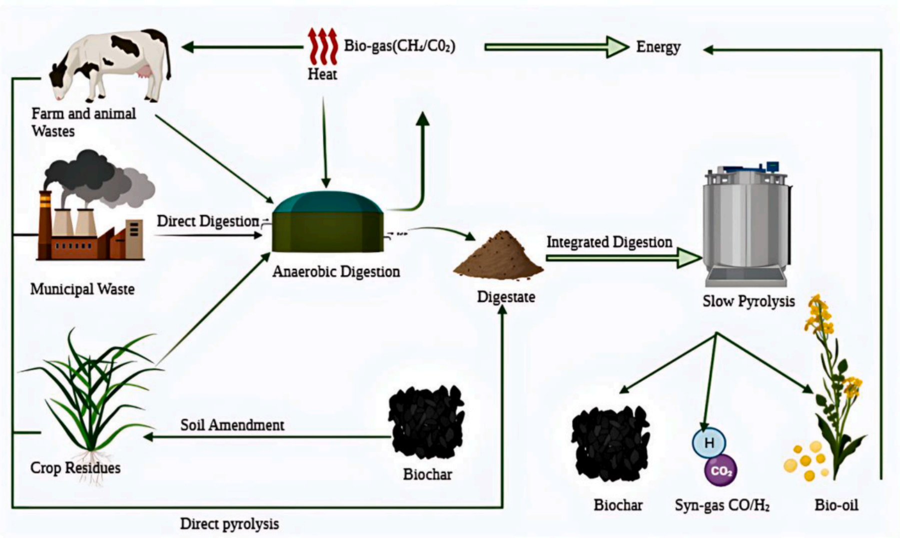


Fig. 5. Overview of the slow pyrolysis technique proposed herein for the production of biochar (Modified from Refs. [46,61]).

slow pyrolysis [46]. Slow pyrolysis is used to maximize the solid product of biochar [46,48] which can be carried out on a lab scale using a slow pyrolysis system. The entire grounded product is elevated to provide pre-drying treatment after grounding to get a moisture-free product. The presence of moisture in the product decreases the heating efficiency during pyrolysis. The moisture of grounded materials is eliminated by placing them into the conventional oven at 105 °C until the weight of the sample remains constant [46]. Slow pyrolysis provides a char yield, whereas hydrothermal provides a high hydrochar yield, Torrefaction is a process where pre-treatment is applied to the stuff to obtain carbon-rich products. During slow pyrolysis, pre-pyrolysis occurs before solid decomposition to obtain a product [48]. Conventional biochar extraction processes include steel kilns, earthen, and bricks, which release various types of volatiles into the atmosphere, which cause air pollution. When 1 kg of the log is subjected to slow pyrolysis, it provides 30–35% biochar, 40–45% liquid product, and 20–25% gaseous product. Reactors involved in slow pyrolysis are retorts, converters, and kilns [49]. Different researchers have adopted slow pyrolysis techniques to generate biochar from agricultural wastes like corn stover [15], rice waste and wood sawdust [60].

3.2.3. *Fast pyrolysis*

Fast pyrolysis is performed at 800 °C to 1300 °C with a heat rate of 200 °C/min for no more than 10 s to improve bio-oil production by up to 75% [52,58]. Reactors involved in this process are bubbling fluidized beds, circulating beds, rotating-cone and ablative reactors [52]. Fast pyrolysis is used to maximize the liquid product [46,48]. Using softwood results in the highest production of the liquid product, plus hardwood, grass, and other farm residues. During fast pyrolysis, biomass degradation occurs in anaerobic conditions at 10 °C to 100 °C within 0.5–2 s [49]. Various reactors involved in fast pyrolysis are vacuum, ablative reactors, rotating cones, entrained flow, and fluidized beds [58]. The final product contains 60–75% liquid, 10–20% gaseous, and 10–20% solid products [49,58].

3.2.4. *Microwave assists pyrolysis*

Microwave-assisted pyrolysis is one of the most efficient thermochemical processes [48,62]. The conventional type of pyrolysis is conducted as a typical heating process, while the microwave goes through pre-treatment before heating. The by-product of conventional is pyrolyzed gas, whereas the liquid product, warm water, is a non-compressible gas [48]. It overcomes the disadvantages of conventional biochar production and improves the quality of the product by preventing the formation of secondary reactors. It is also known as an electric volumetric heating method, conducted at 915 MHz frequency and 2.45 GHz as specified by international agreement. It saves energy, is pollution-free, and has high efficiency [62].

3.3. *Hydrothermal carbonization (HTC)/wet pyrolysis*

Hydrothermal Carbonization (hereafter HTC) is the thermal decomposition of an organic substrate in the subcritical aqueous substrate for obtaining a high carbon-containing product [28,52]. Temperatures ranging from 180 to 250 °C, including 2–10 Mpa of pressure and water are the specific conditions for biochar. Friedrich Bergius invented it, and the technique was refined by Antonietti [28,53]. The aqueous substrate involved in HTC is the main component in the carbonization and decomposition of lignin, cellulose, and hemicelluloses at low temperatures compared to dry pyrolysis [28,52]. As a result, HTC is particularly ideal for processing feedstocks or waste residues with high moisture values, like algae and aquatic plants [63]. A hydrocarbon is divided into smaller portions through dehydration, polymerization, hydrolysis, aromatization, and decarboxylation, which again remains a substrate similar to lignite, the final substrate. Chemicals found in this method are glucose, levulinic acid, organic acid, hydro methyl furfural, and various organic acids. Intermediate products can be used in industry for different purposes. It reduces the hazardous properties of various substances by eliminating organic pollination and microorganisms [28,52,53]. HTC is conducted in water under pressure below 10 bars, from which biochar, liquid products, and gaseous products can be obtained. It can provide more significant output quality quickly at a lower energy level and temperature [48]. It is highly applicable for farm-based biochar production and small scales and is the most cost-effective process at 180 °C−250 °C underwater. Several parameters are involved in this process, which affects its final production, and the final yield is about 40–70% of biomass (Fig. 3) [52].

3.4. *Gasification*

Gasification is a process of conversion in which a carbon source is converted into a gaseous product (syngas) at a temperature less than 70 °C under the use of a control oxidizing agent (air, oxygen, and steam) (Fig. 3) [52,58]. The final yield is about 10% of the biomass, which is less than that of pyrolysis. Agents involved in this process are reactant/biomass ratio, reaction temperature, residence duration, particle size, and pressure. Among them, the temperature is the agent which affects the overall yield [52]. A gasification process can be used to obtain a higher amount of producer gas, also known as syngas ($CO + H_2$) [47]. In the past, producer gases from pyrolysis were used for domestic cooking, heating, lighting, etc. [49]. During gasification, plants are exposed to two sections. In the first section, gasification occurs, whereas in the second section, syngas is cleaned and cooled [59]. The continuous generation of biochar utilizes the auger type of reactor [49].

4. Application of biochar

Biochar contains a higher percentage of oxygen-containing carbon groups, inert carbon components, and a high surface area. In addition, it has a pore structure that leads to increased potential in carbon sequestration, greenhouse gas reduction, increased soil fertility, improved structure, and increased crop production [64–68]. The structure and properties of biochar influence its application [65]. Biochar can also be used for the production of biofuels [63].

The primary biochar application methods in the soil are topsoil incorporation, depth application, and top dressing [69]. Biochar positively impacts soil properties increasing water retention, permeability, and soil fertility. In addition, its high charge density transported large quantities of nutrients, altering the soil properties and thus enhancing crop output [70].

4.1. *Enhance the soil's properties*

The application of biochar in agricultural soil enhances the soil structure [36,69,71,72]. As a result, the soil's physiological, chemical, and biological properties are improved [73–75], which aids the agricultural soil in increasing its absorption capacity of nutrients [20,28,69]. Furthermore, although several other methods have evolved, biochar easily removes all the heavy metals through adsorption (Fig. 6) [21,64]. In addition, adsorption eliminates toxic elements and organic contaminants in soil and plants [10,66]. According to Refs. [76–81], the application of biochar had been observed to decompose or remove the organic pollutants including polychlorinated biphenyls, halo hydrocarbon, chlorobenzene, *p*-Nitrophenol, polycyclic aromatic hydrocarbons (PAHs), diethyl phthalate and 2-chlorobiphenyl. Recently, the application of biochar in the soil is an advanced method to increase water holding ability, water filtration, availability of soil moisture, nutrient retention [54,82].

4.2. *Improvement in fertility status by increasing nutrient availability*

The restoring of soil fertility and enhancing the physical, chemical, and biological characteristics of the soil may both be accomplished by

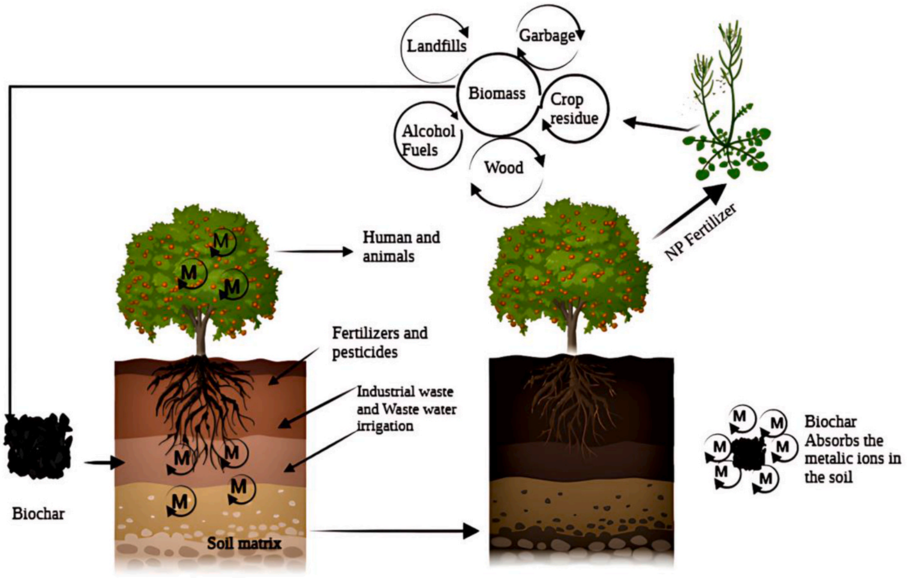


Fig. 6. Metal contamination remediation with biochar implication is depicted schematically by adsorbing the metallic impurities (Modified from Refs. [16,17,54]).

applying biochar to the soil [54]. Soil salinity can affect crop reduction by retarding the absorption of soil nutrients and water by roots from the soil [20]. Biochar reduces the soil salinity, improving ion exchange capacity and increasing the significant and minor soil nutrients in the soil (Fig. 7) [15,20,54]. All the sodium in the soil is adsorbed, which increases the exchangeable magnesium and calcium, which replace the sodium in the soil and makes it less alkaline [54]. Biochar can impact the nutrient interaction in the soil by behaving as a nutrient source by making nutrients available, diminishing nutrient mobility and availability, and changing the nutrient cycle and nutrient reaction in the soil. Biochar is multiple sources of nutrients as it contains most of the essential plant nutrients [22]. It also reduces the soil's leaching loss of

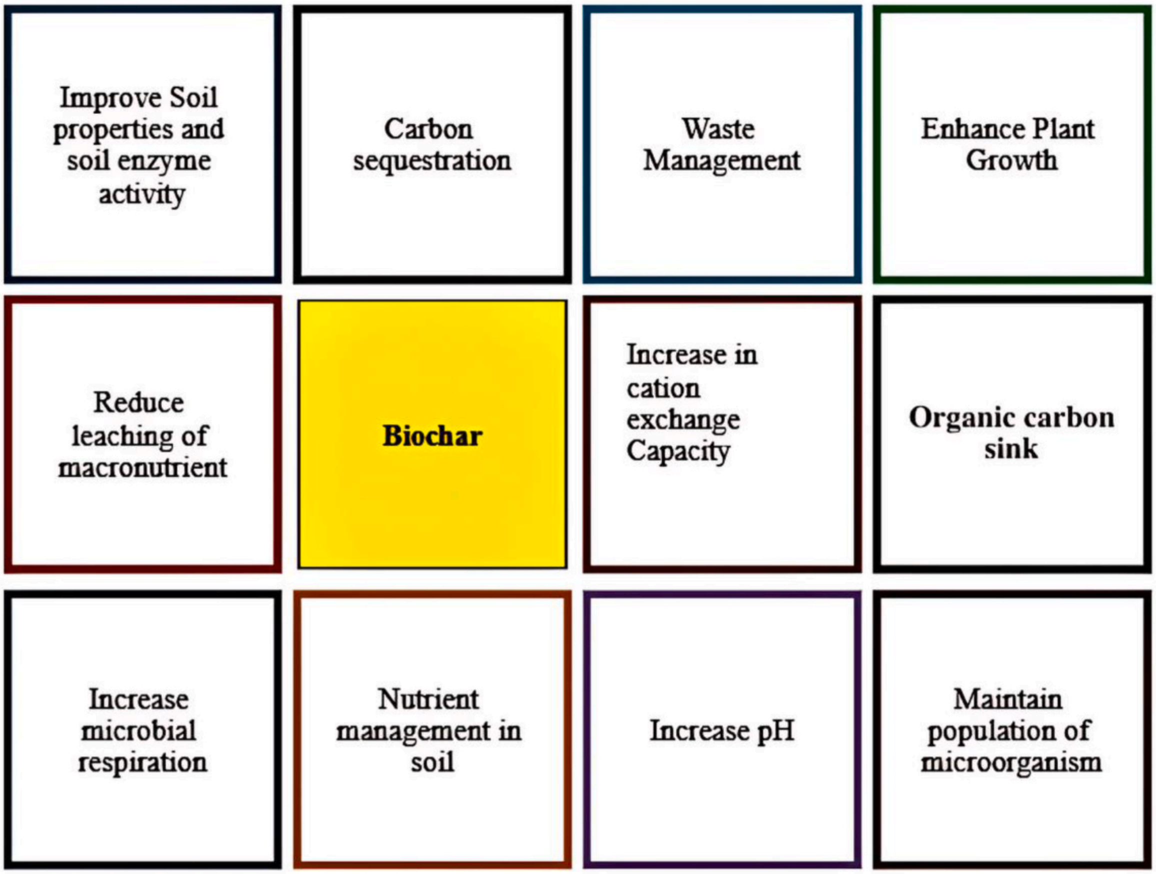


Fig. 7. Benefits of incorporating biochar into the soil with low physicochemical properties (Modified from Refs. [51,91]).

nitrogen fertilizer [54]. It also has a high adsorption capacity that permits the adsorption of potassium, nitrogen, organic matter, and phosphorous in the soil [20]. [15] demonstrated that the use of biochar (BC200) stimulates the soil's inorganic nitrogen and increases the amount of accessible Fe, Cu, and Zn when applied to calcareous soil.

4.3. Soil remediation

A significant issue recently in the world is soil contamination through industrial and domestic activity and various chemicals, compounds, or substances that directly or indirectly affect the activities of non-targeted microorganisms [20,54]. One technique to remove contaminated soil is to utilize biochar, to clean up contaminated soils (Table 2) [27]. It is an affordable, ecologically sustainable solution made from waste to repair the soil [20]. In addition, due to its large surface area, higher water-holding ability, and highly porous nature, it reduces the pollutants in the soil [54]. In support of this, several studies have documented remediating soils for heavy metals and metalloids by immobilization strategies, i.e., the usage of biochar for positive outcomes [16,17,78]. [66] suggested that biochar from *Carya* spp. can significantly adsorb and reduce the leaching of sodium bispyribac and clomazone in the soil.

4.4. Induces microbial activity in the soil

Applying biochar alters soil's physical and chemical properties, affecting the ability to work as a carrier to establish microorganisms in the soil [27]. Soil microorganism activity affects organic substances' decomposition, nutrient cycling, and the nutrient status and production capacity of crops (Table 2) [84]. The microbe's activity in the soil can be increased through biochar [15]. The microbial growth in the soil increases with biochar as it provides a medium for the microbes [28]. According to Ref. [55], the application of biochar influences the functioning and habitat of mycorrhizal fungi and other soil organisms which leads to direct stimulation of the soil quality and soil health. Further [79], documented that the biochar formed from fresh biogas exposes a favourable influence on microbiota by modulating the suppression of arsenic and ferric ions.

4.5. Agronomical importance (crop improvement)

The yield of crops and crop productivity have positive impacts from biochar. It increases nutrient availability and nutrient use efficiency by the crops. A 10% increment in crop yield with biochar application has been reported in the literature (Fig. 7) (Table 3) [28,85]. Biochar acts to remove soil salinity, hence aiding in nutrient availability and leading to higher yields [20]. Biochar can also potentially eliminate or manage diseases and pests from the crop field. A 3–5% biochar application can retard the growth of fungal pathogens and pests [28]. Furthermore, biochar showed a promising role in controlling weeds in faba beans and enhanced crop productivity [86,87]. Moreover, Numerous field tests and pot experiments have shown that applying various types of biochar to the soil increased the production and growth of a variety of crops such as *Phaseolus vulgaris, Cucumis sativus, Fragaria* × *ananassa, Solanum lycopersicum, Zea mays, Citrullus lanatus,* and *Piper nigrum* [88]. Likewise [89], reported that the application of rice husk biochar in wheat crops improves the yield and water-holding capacity.

4.6. Climate change mitigation

One of the most significant environmental problems of the twenty-first century is global warming, caused by increasing greenhouse gas (GHG) emissions, and the carbon (C) cycle plays a crucial role in both its cause and its mitigation [22]. Biochar has outstanding physical and chemical substances for use in different fields to improve eco-natural quality. Biochar can be utilized as a catalyst for the degradation of

Table 2
Summary of biochar types on contaminants removal from different factors.

S. N.	Biochar type	Contaminants	Proposed sorption mechanisms	Removal performance (%)
1.	Cattle manure, Rice straw, Secale cereale	Al	Surface adsorption/ coprecipitation and Al surface complexation with oxygen-containing functional groups	–
2.	Corn straw, Soybean straw, Canola straw, Hardwood, Peanut straw, Spartina alterniflora, Orchard prune residue, Wood clips, Broiler litter, Eucalyptus, green waste, Sewage sludge, Rice straw	Cu	Negatively charged inorganic components, chemisorption	~75
3.	Wastewater sludge	Fluoroquinolone	Sorption	~80–96
4.	Broiler litter	Deisopropylatrazine	Aromaticity and a large surface area cause sorption	~27
5.	Corn straw, Hardwood, Broiler litter, Eucalyptus, Orchard prune residue, Sewage sludge	Zn	Negatively charged inorganic components, chemisorption	~16
6.	Peanut straw	Methyl violet	Phenolic and carboxylic functional group interaction	~27
7.	Soybean stover, Peanut shells	Trichloroethylene	Sorption, Phenolic, and carboxylic functional group interactions	~27
8.	Pine needles, Switchgrass	U	Adsorption that is pH-dependent	~2
9.	Maize straw	Oxytetracycline	Biochar surface sorption	~27
10.	Rice husk, Orchard prune residue, Chicken manure, Pinewood, Sludge, Dairy manure, Eucalyptus, green waste, Rice straw, Oakwood, Wheat straw, Peanut shell	Pb	Phosphate-containing precipitation	~99
11.	Broiler litter, Orchard prune residue, Sewage sludge	Ni	Negatively charged inorganic components, chemisorption	~10
12.	Hardwood biochar,	As	–	

(*continued on next page*)

Table 2 (*continued*)

S. N.	Biochar type	Contaminants	Proposed sorption mechanisms	Removal performance (%)
	Eucalyptus, Rice, Maize			
13.	Algal biomass, Eucalyptus,	Methylene blue	Monolayer adsorption, both chemical and physical	~27
14.	Dairy manure	Atrazine	Dividing into organic C	~27
15.	Miscanthus saccharifloru, Broiler litter, Orchard prune residue, green waste, Sewage sludge, Rice straw, Cotton stalks, Eucalyptus, Quail litter, Peanut shell, Wheat straw	Cd	Negatively charged inorganic components, chemisorption	~21
16.	Sludge, Sugar beet tailing, Orchard prune residue, Chicken manure, Walnut shell	Cr	Conversion of Cr (VI) to Cr (III)	~27
17.	Wine manure	Parquet	Increased surface negativity causes sorption	~80–90

Source [28,49,52,55,70,83].

contaminants because gathers transition metals (Fig. 6) [76]. Appropriate management of organic wastes can indirectly reduce methane emissions from landfills, industrial energy usage, and other greenhouse gas emissions that are indirectly useful for mitigating climate change [11]. [68] reported that for the removal of 0.49 GtC per year from the atmosphere by application of biochar, practically 2.2 GtC of feedstock would need to be converted to biochar per year. The pyrolysis of animal manures or the use of appropriate biochars in lowering the leaching of phosphates and nitrates present in soil or co-applied manures may be beneficial in mitigating excessive nutrient export from agricultural watersheds (Fig. 7) [11,28]. The possibility of lowering greenhouse gas emissions demonstrates the necessity of viewing biochar management as a system rather than a discrete component. Biochar has less mineralization than the raw material from which it was created lowers system CO_2 emissions, and is essential for mitigating climate change [11,76]. Since, biochar is tightly bound to soil particles, resulting in decreased CO2 emissions [16]. The role of biochar has been investigated in two key areas of climate change mitigation, i.e., carbon sequestration and GHG reduction [28].

4.7. *Carbon sequestration*

Biochar was initially suggested as a soil amendment to store carbon in the soil, enhancing carbon sequestration since its carbon component is generally stable [22]. A relatively stable form of carbon known as “biochar” has the potential to serve as an effective long-term carbon store and have a significant impact on the reduction of greenhouse gas emissions. It may be possible to store organic carbon that would otherwise be burnt or composted away to create minerals over a long period when biomass is used in conjunction with waste management techniques and strategies. Consequently, it might be a good substitute for existing waste disposal systems [68]. Compared to virgin biochar, certain biochar-based composites may improve biochar’s stability and biomass carbon retention [7]. Creating biochar from leftover biomass from the agriculture and food processing industries can aid in long-term carbon sequestration and positively affect soils and environmental quality [28].

4.8. *Mitigate greenhouse gas emissions*

According to some estimates, using biochar on a global scale might reduce greenhouse gas emissions by 12% [7]. According to a recent study, deploying biochar composites in the soil rather than virgin biochar might help mitigate climate change in two ways, even though biochar alone can cut world GHG emissions [7,11]. First, it has been hypothesized that combining biochar and compost will improve decomposing capability by increasing the amount of stable carbon contributed and producing a valuable byproduct (biochar-compost mix) that would balance out any potential drawbacks of the pyrolysis biochar

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

Sr. no.	Crops	Biochar feedstock	Soil type	Application rate	Yield response	Other effects	References
1.	Maize	Corncob	Alfisols	2% w/w	Induce crop production	–	[92]
2.	Peanut	Hardwood	Fine, Rhodic, kaolinitic, Thermic	0, 89.6, 22.4, and 44.8 Mg/ha	No change	Significant decrease in the amount of (As) contamination in the foliage	[55,92]
3.	Soybean	Acacia wood	Clayey	50 + 50 Mg/ha	Increase seasonal yield	–	[92]
4.	Mustard	Chicken manure & green waste	Loamy	–	Increase in crop yield	Cd, Cu, and Pb levels are reduced	[55]
5.	Cotton	Rice husk	Sandy	–	–	Decrease in free Cu, Pb, and Cd contents; discovery of functional groups with high Cu adsorption affinity	[28]
6.	Paddy	Wheat straw	Loamy	–	Increase crop production	Increase in CH4 emissions	[28]
7.	Corn	Pine chips	Loamy sand	30,000 kg/ha	No change	–	[92]
8.	Amaranthus	Domestic organic waste	Fluvisols, Calcareous	10 t/ha	Induce crop yield by 17–64%	–	[92]
9.	Wheat	Birch	Loamy	–	–	Reduce N2O and CO2 emission	[28,93]
10.	Maize	Acacia wood	Clay	50 + 50 Mg/ha	Increase in seasonal yield	–	[92]
11.	Lettuce	Chicken manure	Sandy and Silty loam	10-30 t/ha	Induce crop yield	Improves Cr (VI) reduction to Cr in soil (III)	[55,92]
12.	Cotton	Corn straw	Inceptisol	10-20 t/ha	Induce crop yield by 8.1–18.6%	–	[92]

technology (such as poor macronutrient content, the composting system, and emissions of CH_4 capacity) [28]. Second, increases in soil organic matter and a decrease in the emission of GHGs with a high global warming potential, such as CH_4 and N_2O, have been linked to biochar [7,28]. In reality, more plant growth or lower soil greenhouse gas emissions may be required for a biochar system to have a better emission balance than using biochar as a charcoal fuel [11]. According to a study [90], biochar plays an important role in reducing methane emissions from rice fields by encouraging methanotroph (methane-consuming bacteria) communities and decreasing the variety of methanogens (methane-producing bacteria).

5. Advantages of biochar application

Compared to the standard carbon activation process, most biochar engineering techniques are more practical or affordable [94]. Biochars are also used for producing fuel cells and super-capacitors and as support in catalysis for producing new composites such as metallic nanoparticles [95]. Due to its cheap cost and the availability of abundant feedstock materials, such as agriculture and forestry wastes, biochar is emerging as a practical alternative remediation agent for various environmental contaminants, including heavy metallic ions, organic pollutants, and even nutrients [96]. Biochars are carbon-rich compounds that improve soil conditions and raise crop productivity [97]. Biochars are manufactured with raw materials from agro-industrial residues consisting mainly of hemicellulose, cellulose, lignin, and some inorganic minerals [95]. Biochar can maintain water and nutrients in the top layer of soil for an extended time, preventing nutrient loss from the crop root zone and directly enhancing crop output (Table 3) [98]. Biochar has been utilized to promote sustainability in the energy, environmental, and agricultural fields [94]. One emerging technology, biochar production, can enhance national food security and sequester carbon to slow climate change [99]. Biochar is also used to support the ZVI (zerovalent iron) particles, which are environmentally and economically beneficial [100]. Biochars can be produced from locally available materials like wood products, agricultural wastes, manure, etc., which are not costly [97].

6. Disadvantages of biochar application

The applied biochar in the soil causes agrochemical binding and deactivation, such as herbicides and soil nutrients [99]. Many biochars assessed here slowed the net CH oxidation rate in the soil and decreased the creation of soil and N_2O [101]. Some phytotoxic substances in biochar may affect plant germination [99]. Biochar influences soil physiochemical characteristics: it increases porosity and bulk density while decreasing the porous structure [30]. The excess biochar applied to the soil impacts the germination and biological processes in the soil due to EC and pH [95,99]. Biochar's poor mechanical strength and dusty nature are issues, especially when used in agricultural soil where considerable volumes are routinely lost to wind or rain due to soil application circumstances [102]. Once applied to the soil, biochar gets adsorbed in the soil and cannot be removed [99,101]. Because of its fine-grained nature, biochar cannot be utilized in combined heat and power plants to produce energy because it would be challenging to distribute the amount of biochar consistently fed into thermal energy systems [102]. There is always the chance of potentially releasing hazardous substances, such as heavy metals and PAHs, available in biochar [99]. Not all organic waste can be converted into biochar, which is useful in agriculture. It is because some production processes and feedstocks result in biochar that cannot efficiently store nutrients and is vulnerable to microbial degradation [98,99].

7. Conclusion

The manufacturing procedure of biomass gives heterogeneous physical and chemical properties, usually pyrolyzed at different conditions. The utilization of biochar in improving the composition and texture of the soil, soil productivity, and sorption of nutrients, directly enhances crop production. Biochar also helps to remove toxified soils, enhances photosynthesis in plants, improves carbon sequestration, minimizes greenhouse gas emissions, and reduces the island effect. Furthermore, biochar is cost-effective compared with chemical fertilizers and can be easily transported. Thus, greater emphasis must be placed on collaboration among farmers, soil scientists, researchers, and concerned authorities to utilize biochar in concerned fields promptly.

Authors' declaration

The authors declare that there is no conflict of interest regarding the publication of this paper. Equal contributions from each author were made throughout the entire writing process. Similarly, all contributors agreed on the final draft of the manuscript.

Authors' contribution statement

Shubh Pravat Singh Yadav, Sujan Bhandari, Dibya Bhatta, Anju Poudel, Susmita Bhattarai, Puja Yadav, Netra Ghimire, Prava Paudel, Pragya Paudel, Jiban Shrestha and Biplov Oli collected information and wrote the paper.

Declaration of competing interest

The authors declare that there is no irreconcilable circumstance. Every authors has contributed for the final preparation of the manuscript.

Data availability

Data will be made available on request.

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