



## Review

# A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy



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## ABSTRACT

There is an upsurge enthusiasm for utilizing biochar produced from waste-biomass in different fields, to address the most important ecological issues. This review is focused on an overview of remediating harmful contaminants utilizing biochar. Production of biochar utilizing various systems has been discussed. Biochar has received the consideration of numerous analysts in building up their proficiency to remediate contaminants. Process parameters are fundamentally answerable for deciding the yield of biomass. Biochar derived from biomass is an exceptionally rich wellspring of carbon produced from biomass utilizing thermal combustion. Activating biochar is another particular region for the growing utilization of biochar for expelling specific contaminations. Closed-loop systems to produce biochar creates more opportunities. Decentralized biochar production techniques serve as an effective way of providing employment opportunities, managing wastes, increasing resource proficiency in circular bioeconomy. This paper also covers knowledge gaps and perspectives in the field of remediation of toxic pollutants using biochar.

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## 1. Introduction

The global energy requirement is currently increasing owing to the increase in population. All sectors in the country require energy [1–3]. Fossil fuels are the main source of energy. But owing to the effect of CO<sub>2</sub> on the environment and global energy issues, the replacement of fossil fuels has become necessary [4–6]. Organic waste, as the main constituent of solid biomass, has a high potential for biochar generation [7–9]. Biomass waste materials appropriate for biochar production include crop residues from agriculture, forestry, municipal solid waste, food and animal manures, etc [10–12]. The biochar derived from biomass is a highly rich source of carbon produced from biomass using thermal combustion in an oxygen-limited environment [13,14]. The unique properties of biochar such as large surface area, high porosity, functional groups, high cation exchange capacity, stability make it suitable for various applications. The fast and ease of preparation,

eco-friendly nature, reusability, and cost-effective are few advantages of biochar [15,16]. Biochar has gained attention of many researchers in establishing its efficiency in removal of various contaminants. The process parameters are mainly responsible for determining the yield of biomass. The parameters include temperature, types of biomass, residence time, heating rate, pressure, etc [17,18]. Temperature is the main parameter affecting the characteristic of biochar [19–21]. The common thermochemical techniques used for biochar production include pyrolysis, hydrothermal carbonization, gasification, flash carbonization and torrefaction [22,23]. Of all these methods, pyrolysis is the most commonly used to produce biochar. The organic compounds present in the biomass decompose at a specific temperature in an oxygen-limited environment. The factors that affect the product from pyrolysis include process temperature, residence time, and type of biomass and rate of heating [24,25]. Though biochar is fully made of carbon content and ash, the elemental composition and characteristics differ based on the type of biomass, reaction conditions and type of reactors used during the carbonization process. Therefore, application and efficiency of biochar in various fields depends on the type of biomass used for producing biochar. The characterization of biochar is very important for determining biochar elemental composition, surface functional groups, stability and structure. The biochar characterization can be done using

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various modern techniques such as Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectrometer (FTIR), Thermo Gravimetric Analysis (TGA), X-Ray Diffraction (XRD), Brunauer Emmett Teller (BET), Nuclear Magnetic Resonance (NMR), Raman spectroscopy, etc [26,27]. Recent literature has been focused on biochar characterization and its main objective is to differentiate biochar from other organic matter in soil [28–30]. Different biochar properties can be identified using the above characterization techniques, for example, SEM for biochar morphology, FTIR for determining functional groups, etc [31,32]. The mechanism by which biochar sorbs toxic heavy metals and other contaminants are adsorption. The adsorptive efficiency of biochar is directly proportional to the physicochemical properties such as functional groups, surface area, cation exchange capacity, etc. The physicochemical properties of biochar can be improved by treating biochar with acid, alkali or oxidizing agents [33–35]. The surface area can be altered using acid treatment. The detailed literature regarding the biochar properties and its techniques for analyzing and quantifying will pave way for knowledge about the efficiency of biochar in various sectors. Owing to its vast advantages and eco-friendly nature, biochar has been utilized in resolving many environmental issues such as adsorbing pollutants [36], reducing greenhouse emission gas [37,38], composting [39], wastewater treatment [40], soil remediation [41,42], energy production [43] and catalyst [44–46]. The capacity of biochar in adsorbing organic and inorganic pollutants depends on the high surface/volume ratio and its affinity towards nonpolar groups [47,12]. Biochar has been employed in agricultural fields also for eliminating soil pollutants. Many agricultural residues have been utilized for producing biochar such as rice straw [48], wheat straw [49], waste wood [50], sugar beet tailings [51], corn cob [52], etc. These biomasses are composed of mostly cellulose, hemicellulose and lignin components. During the pyrolysis process, these components are thermally decomposed at different temperatures and their mechanisms are discussed in detail. This review focused on an overview of the remediation of toxic pollutants using biochar, advantages of biochar and the influence of process parameters such as temperature, pressure, heating rate, etc. Production of biochar using different techniques such as pyrolysis, hydrothermal gasification, torrefaction was conferred. The characterization techniques such as SEM, XRD, FTIR, TGA, BET, etc were explored. In addition to that, the stability of biochar, utilization of biochar in various applications such as organic and inorganic pollutants removal, sequestering carbon, and the catalyst was discussed.

## 2. Methods of biochar production

The developing interest in utilizing biochar for various applications has led to increased conversion of biomass to biochar. Thermochemical conversion is a common technique for biochar production. Thermochemical conversion method includes pyrolysis, hydrothermal carbonization, gasification and torrefaction [53,54]. For a maximum yield of biochar, the technique chosen for production must be appropriate depending on the biomass type

and also the process conditions such as heating rate, temperature, residence time, etc must be optimum. These conditions are crucial since they may affect the physical and chemical states of biochar during the production process. The morphology of biochar derived from plant biomass varies based on the process conditions since it involves weight loss of the biomass. Initially, the weight loss because of water loss around 100 °C continued by cellulose, hemicellulose and lignin degradation occurring above 220 °C. Finally, loss of weight occurs due to the burning of carbonaceous residues. The thermochemical conversion techniques and their process conditions are given in Table 1.

### 2.1. Pyrolysis

The process of thermal decomposition of organic materials in an oxygen-free environment under the temperature range of 250–900 °C is called pyrolysis [60]. This process is an alternate strategy for converting the waste biomass into value-added products like biochar, syngas and bio-oil. During the process, the lignocellulosic components like cellulose, hemicellulose and lignin undergo reaction processes like depolymerization, fragmentation and cross-linking at specific temperatures resulting in a different state of products like solid, liquid and gas. The solid and liquid products comprise of the char and bio-oil whereas the gaseous products are carbon dioxide, carbon monoxide and hydrogen and also syngas (C<sub>1</sub>–C<sub>2</sub> hydrocarbons). Various types of reactors such as paddle kiln, bubbling fluidized bed, wagon reactors and agitated sand rotating kilns are used for biochar production. The biochar yield during the pyrolysis process depends on the type and nature of biomass used. Temperature is the main operating process condition that decides the product efficiency [61]. Generally, the yield of biochar decreases and production of syngas increases when the temperature is increased during the pyrolysis process. The mechanism of the pyrolysis process is shown in Fig. 1. Pyrolysis can be classified as a fast and slow pyrolysis process depending on the heating rate, temperature, residence time and pressure.

**Fast pyrolysis:** Fast pyrolysis is deliberated as a direct thermochemical procedure that can liquefy solid biomass into liquid bio-oil with a high potential for energy application. Fast pyrolysis conditions are described by: (i) fast warming paces of biomass particles (>100 °C/min), (ii) joined with short times of the biomass particles and pyrolysis fumes (0.5–2 s) at high temperatures and (iii) moderate pyrolysis treatment temperatures (400–600 °C). A key distinctive component of fast pyrolysis innovation is the need to keep the fume residence time in hot zone to the base, to accomplish great bio-oil quality. This can be accomplished by guaranteeing fast extinguishing or cooling of the fumes [62]. **Slow pyrolysis:** In slow pyrolysis, the rate of heating is very less around 5–7 °C/min and possesses a longer residence time of more than 1 h [63]. The slow pyrolysis innovation has a better yield of char contrasted different pyrolysis and carbonization strategies. The biochar could be utilized as a dirt enhancer to improve soil quality. [64].

**Table 1**  
Thermochemical conversion techniques and their process conditions.

Technique	Temperature (°C)	Residence time	Yield of biochar (%)	Yield of bio-oil (%)	Syngas production (%)	References
Pyrolysis	300–700 (slow)	< 2 s (slow)	35 (slow)	30 (slow)	35 (slow)	[55]
	500–1000 (fast)	Hour-day (fast)	12 (fast)	75 (fast)	13 (fast)	
Hydrothermal carbonization	180–300	1–16 h	50–80	5–20	2–5	[56]
Gasification	750–900	10–20 s	10	5	85	[57]
Torrefaction	290	10–60 min	80	0	20	[58]
Flash carbonization	300–600	< 30 min	37	–	–	[59]

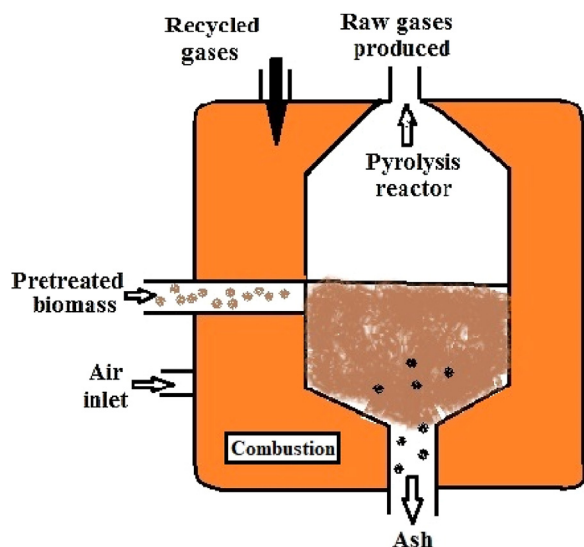


Fig. 1. Mechanism of pyrolysis.

The majority of biomass is composed of cellulose, hemicellulose and lignin. These components are converted into biochar using different reaction conditions and mechanisms.

### 2.1.1. Cellulose decomposition

The mechanism of cellulose decomposition is identified by reducing the degree of polymerization constituting of two reactions: 1) By slow pyrolysis, comprising of cellulose decomposition at longer residence time and less heating rate 2) By fast pyrolysis, occurring at a high heating rate through rapid volatilization resulting in the development of levoglucosan. In addition to solid product biochar, the levoglucosan also undergoes the dehydration process to produce hydroxymethyl furfural that can decompose either to produce liquid and gaseous products like bio-oil and syngas respectively. Besides, the hydroxymethyl furfural can also proceed through several reactions like aromatization, condensation and polymerization to produce solid biochar again.

### 2.1.2. Hemicellulose decomposition

The decomposition mechanism of hemicellulose is similar to those of cellulose. The hemicellulose undergoes depolymerization to form oligosaccharides. This can proceed through a series of reactions including decarboxylation, intramolecular rearrangement, depolymerization and aromatization to produce either biochar or the compound decomposes to syngas and bio-oil [65].

### 2.1.3. Lignin decomposition

In contrast to the decomposition mechanism of cellulose and hemicellulose, the lignin decomposition mechanism is complex [66]. The  $\beta$ -O-4 lignin linkage breaks resulting in the production of free radicals. These free radicals capture the protons from other species resulting in the formation of decomposed compounds. The free radicals move to other molecules conducting chain propagation.

## 2.2. Hydrothermal carbonization

Hydrothermal carbonization is considered to be a cost-effective method for biochar production as the process can be performed at a low temperature around 180–250 °C [67]. The product using the hydrothermal process is referred to as the hydrochar to differentiate the product produced from dry processes such as pyrolysis and

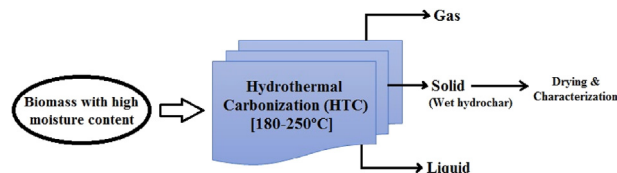


Fig. 2. Hydrothermal carbonization procedure.

gasification [68]. During the process, the biomass is blended using water and is placed in a closed reactor. The temperature is slowly increased for maintaining stability. At different temperatures, the products are produced as follows: biochar at a temperature below 250 °C referred to as hydrothermal carbonization [69], bio-oil between 250–400 °C known as hydrothermal liquefaction and gaseous products syngas such as CO, CO<sub>2</sub>, H<sub>2</sub> and CH<sub>4</sub> produced at a temperature above 400 °C referred as hydrothermal gasification [70]. Fig. 2 represents hydrothermal carbonization procedure. The hydrolysed product proceeds through series of reactions such as dehydration, fragmentation and isomerization to form intermediate product 5-hydroxymethylfurfural and their derivatives. Furthermore, the reaction proceeds through condensation, polymerization and intramolecular dehydration to produce the hydrochar [71]. The high molecular weight and complex nature of lignin make the mechanism complicate. The lignin decomposition starts through dealkylation and hydrolysis reaction producing phenolic products like phenols, catechols, syringols, etc [72]. Finally, the char is produced through repolymerization and cross-linking of intermediates. The lignin components that are not dissolved in liquid phase are transformed into hydrochar similar to pyrolysis reaction.

## 2.3. Gasification

Gasification is a thermochemical method of decomposition of the carbonaceous material into gaseous products i.e., the syngas comprising CO, CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub> and traces of hydrocarbons in presence of gasification agents such as oxygen, air, steam, etc and high temperature. It is noted that the reaction temperature is the most significant factor in determining the production of syngas. It was found that as temperature increased carbon monoxide, hydrogen production increased while other contents such as methane, carbon dioxide and hydrocarbons were decreased [73].

The major product of this process is syngas and the char are referred to as the by-product with less yield. The gasification process was shown in Fig. 3. The gasification mechanism can be sub-divided into many steps as follows:

### 2.3.1. Drying

During this process, the moisture content in the biomass is completely evaporated without energy recovery. The moisture content varies from different biomass material. Drying is employed as a separate process during the gasification process when the biomass contains high moisture content.

### 2.3.2. Oxidation/Combustion

The oxidation and combustion reactions of gasification agents are the main energy sources for gasification process. These gasification agents react with the combustible species present in the gasifier to produce CO<sub>2</sub>, CO and water.

## 2.4. Torrefaction and flash carbonization

Torrefaction is a newly emerging technique for biochar production. It employs a low heating rate thus referred to as mild

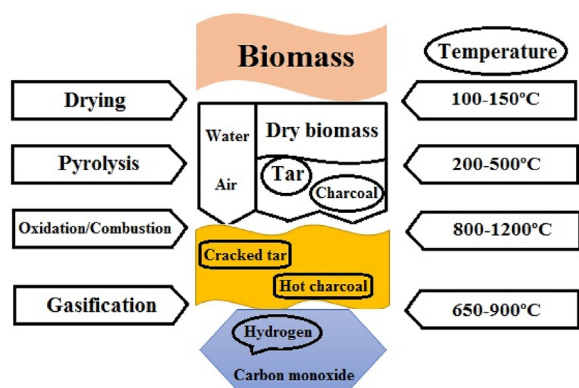


Fig. 3. Process of gasification.

pyrolysis. The oxygen, moisture and carbon dioxide present in the biomass removed using inert atmospheric air in absence of oxygen at temperature of 300 °C using various decomposition processes [74]. The torrefaction process modifies the biomass properties such as particle size, moisture content, surface area, heating rate, energy density, etc. The steps involved in torrefaction process are represented in Fig. 4. The process of torrefaction can be performed (a) Steam torrefaction: The biomass is treated using steam in this process with temperature not more than 260 °C and residence time of around 10 min. (b) Wet torrefaction: It is also called hydrothermal carbonization proceeds with the contact of biomass with water at temperature 180–260 °C and residence time of 5–240 min. (c) Oxidative torrefaction: This process is carried out by treating biomass with oxidizing agents like gases that are utilized for combustion process for generating heat energy. This heat energy is used to produce required temperature.

The mechanism of torrefaction process is an incomplete pyrolysis process and the process proceeds as following reaction conditions: temperature – 200–300 °C, residence time – less than 30 min, heating rate – less than 50 °C/min and in absence of oxygen. The process of dry torrefaction process can be classified into various phases such as heating, drying, torrefaction and cooling. Again, drying can be classified as pre-drying and post-drying process.

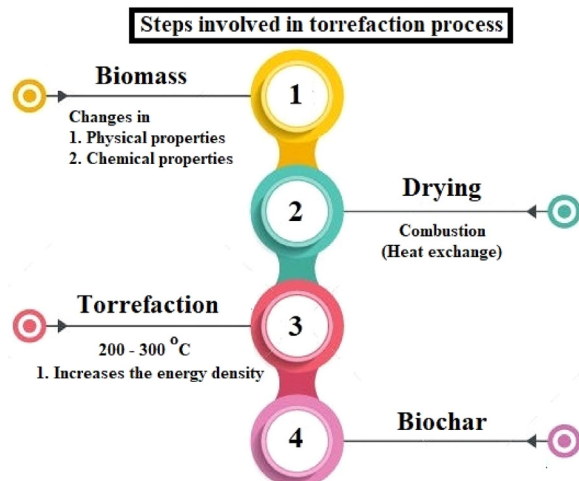


Fig. 4. Steps involved in torrefaction process.

### 2.4.1. Heating

During this process, the biomass is heated till the desired drying temperature is maintained and the moisture content of the biomass evaporates.

### 2.4.2. Pre-heating

This process occurs at a temperature of 100 °C until the moisture content present in the biomass evaporates completely.

### 2.4.3. Post-drying

The temperature is increased up to 200 °C and the water content completely evaporates. The mass content is lost due to increased temperature.

### 2.4.4. Torrefaction

This process is the main stage of whole torrefaction process. It takes place at a 200 °C and a stable temperature is obtained during the process.

### 2.4.5. Cooling

After product formation, the temperature is allowed to cool before it gets contact with the air and room temperature is obtained.

The flash fire is ignited on the packed bed of biomass at high pressure and the biomass is converted into solid-phase and gas-phase products. The whole process is carried out at temperature 300–600 °C and reaction time less than 30 min. About 40 % of biomass is converted into solid products and the process decreases with increasing pressure. The process of flash carbonization is very limited to literature and not used commonly.

## 3. Factors affecting biochar properties

The reaction conditions during the pyrolysis process are mainly responsible for producing biochar. The factors such as feedstocks, temperature, size of the particle, heating rate, etc mainly influence biochar properties. These factors have a direct effect on the yield of biochar rather than its quality. The detailed knowledge of analyzing biochar properties is important for determining the biochar application. Various biomass from different sources such as plant materials, agricultural residues, biomass from wood, solid wastes, etc has been used for producing biochar [75]. Pyrolysis is a commonly used method for biochar production, which is generally carried out at 400–1000 °C. Solid wastes and animal wastes produce more biochar compared to other biomass materials such as wood biomass, agricultural residues, etc.

### 3.1. Feedstocks

Biomass is considered as a complex solid material, composed of biological, organic, or inorganic material which was derived from living or living organisms. Biomass is characterized into two types (i) Woody biomass and (ii) Non-woody biomass. Woody biomass essentially includes tree residues and forestry residues [76]. The attributes of wood biomass are low dampness, low debris, less voidage, high density and calorific value. Non-woody biomass comprises animal waste, industrial and agricultural solid wastes. The attributes of non woody biomass are high debris, high dampness, high voidage, low density and calorific value. Among different attributes of biomass feedstock, moisture content has great impact on biomass formation. The moisture in the biomass can exist as different forms such as liquid water, water vapor and adsorbed within the pores of biomass. Higher moisture content in biomass majorly inhibits formation of char and raises amount of energy needed to attain the pyrolysis temperature [77]. Low moisture content in the biomass is preferable for biochar



formation because of the impressive decrease in the heat energy and the reduction of time needed for the pyrolysis process which makes that biochar formation economically feasible when compared with biomass with high moisture content.

### 3.2. Carbonization temperature

Pyrolysis is the most famous method for exchanging biomasses over to biochar through thermochemical decay process under an oxygen-denied environment at the raised temperature. Contingent upon the conditions, pyrolysis cycles can be grouped into three fundamental classifications: (i) Slow pyrolysis (temperatures <300 °C), (ii) moderate pyrolysis (temperatures of 300–500 °C) and (iii) quick pyrolysis (temperatures more prominent than 500 °C). Pyrolysis temperature influences physicochemical properties and structure of biochar, for example, elemental components, pore structure, surface area and functional groups [78]. The impact of pyrolysis temperature on such properties can be attributed to the influx of volatiles at high temperatures.

### 3.3. Residence time

Expanding the residence time at low pyrolysis temperature (300 °C) brought about a slow decrease in biochar yield and reformist expansion in pH and iodine adsorption number of biochars. Nonetheless, expanding residence time at high pyrolysis temperature (600 °C) had little impact on biochar yield or pH, while it diminished iodine adsorption number of biochars [79].

### 3.4. Pre-treatment of biomass

Pre-treating the biomass before pyrolysis influences biochar characteristics. The common pre-treatment methods available are immersing the raw materials in solution and particle size reduction of biomass. The reduction of biomass particle size results in high biochar yield. For example, pine wood biomass was pre-treated by immersing the biomass in a dilute acidic solution. Pre-treatment methods such as nitrogen and metal doping can influence biochar production and solution pre-treatment such as soaking or steaming can influence the elemental composition and properties of biochar while the baking method can increase the carbon content and reduce the oxygen and moisture content of biochar.

The potential biomass for biochar generation, utilized either independently or as mixes. Contingent upon the innovation utilized, the practical execution is as often as possible restricted

by the moisture or mineral substance of the biomass. For example, the presence of chlorine and soluble base metals can cause consumption. Because of various production technologies and biomass, the properties of the produced biochar can go broadly. While components, for example, hydrogen (H), O, nitrogen (N), and sulfur (S) are volatilized during pyrolysis, minerals, for example, phosphorus (P), K, calcium (Ca), magnesium (Mg), and silicon (Si) remain and their concentrations increment in the resultant biochar. The occurrence of harmful compounds or components in biochar can either be an outcome of polluted biomass during pyrolysis/gasification [80].

## 4. Characterization of biochar

Biochar characterization is performed to determine the ability to remove pollutants or other applications. The structural and elemental analysis also helps to predict the impact of biochar on the environment. In addition, the metals interact with biochar which is a function of pH like 1) the function of biochar differs with pH 2) metal contaminant ion speciation varies with pH. These characteristics of biochar showed the ability to act as a highly efficient adsorbent for removing most of the soil pollutants. The biochar characterization techniques are based on the structure, surface functional groups and elemental analysis [81]. Currently, numerous modern characterization techniques have been reported for characterizing biochar such as Scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), Thermo-gravimetric analysis (TGA), Nuclear magnetic resonance spectroscopy (NMR), Brunauer-Emmett-Teller (BET), proximate and ultimate analysis, Raman spectroscopy, etc as shown in Fig. 5.

### 4.1. Functional groups

The essential functional groups present at surface of biochar that increase its sorption properties include carboxylic (–COOH), hydroxyl (–OH), amine, amide and lactonic groups. The main factors that influence surface functional groups of biochar are biomass and temperature [82]. In addition, when other properties such as pH, surface area and porosity are increased there is a chance of reduction in biochar functional groups. The surface functional groups are characterized using Fourier Transform Infrared Spectroscopy (FTIR). The biochar produced at different temperatures showed a significant difference in their surface functional groups. Apart from FTIR, NMR (Nuclear Magnetic Resonance) can also be used for determining surface functional groups present in biochar.

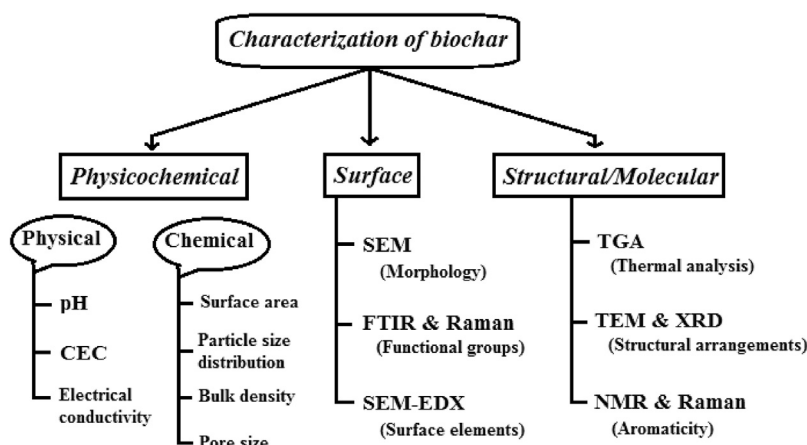


Fig. 5. Physicochemical, surface and structural characterization of biochar.

#### 4.2. Surface area and porosity

Usually, biochar with increased surface area and high porosity will possess high sorption property. The porous surface in biochar is formed during pyrolysis process when there is an increase in water loss during dehydration process. According to the International Union of Pure and Applied Chemistry, the pores present in biochar may be micro (<2 nm), meso (2–50 nm) and macro (>50 nm). The biochar with less pore size cannot adsorb the pesticide molecules despite their polarity or charges. The pore size of biochar can be characterized using SEM (Scanning Electron Microscopy). The surface area is the keynote for determining biochar sorption capacity while temperature plays a major role in biochar formation. The surface area may vary between treated and untreated raw materials. Commercially, activated carbon possesses more surface area. The biochar produced without activation process possesses a low surface area and is less porous [83]. Hence during biochar production, activation process is involved to increase porosity and surface area of biochar. The physical and chemical activation process may be involved in activation process.

#### 4.3. Scanning electron microscopy (SEM)

The surface structures of biochar identified by SEM. SEM pictures of biochars demonstrated that various procedures and temperatures caused generous changes in the surface morphology of the first particles; they to a great extent held the visible shape. Additionally, the improvement of pores in biochar tests upgrading with expanding temperature may bring about huge improvement in the pore properties of biochar. It is likewise conceivable that crystallinity of mineral segments increments and exceptionally requested sweet-smelling structures structure in biochar with expanding pyrolysis temperature [84]. SEM images gives detailed description regarding the microporous and mesoporous distributions and also pore arrangement present in the biochar. The surface morphology before and after adsorption process can be predicted using SEM. Scanning electron microscopy along with EDX (Energy dispersive X-ray spectroscopy) is utilized for examining the elemental composition of biochar. The numerous elements present on the surface of biochar can be determined using SEM-EDX. Most of the studies on biochar applications have utilized SEM-EDX for determining the biochar surface after it adsorbs contaminants. The main drawback is SEM-EDX is not suitable for organic contaminants.

#### 4.4. Fourier transform infrared spectroscopy (FTIR)

FTIR spectroscopy is a vibrational technique for investigating the functional groups present on the surface of biochar. While expanding the temperature, huge changes happened in biochar in concoction and auxiliary arrangements. These progressions could be viably observed by non-damaging FTIR system. In the higher temperature scope of 650–800 °C, the spectra uncovered the continuous loss of aromatic groups. In DRIFTS (Diffuse reflectance infrared Fourier transform spectroscopy) the sample is converted into pellet form using potassium bromide. The pellet sample is made to contact with ATR (attenuated total reflectance) crystal and the functional groups are predicted in ATR-FTIR [85].

#### 4.5. X-ray diffraction (XRD)

X-ray diffraction is a broadly relevant strategy to determine the crystallinity and structure of biochar. In XRD, The diffractogram has indicated particular attributes of nebulous material which was created over 350 °C and reliable. The XRD that is computerized is equipped with a monochromator, radiation source and a stepping

motor [86]. The crystalline nature of the formed nanocrystals resembles the sharp and strong XRD peaks. With increase in time, the particle diameter gets increased. Thus, XRD patterns help in producing high quality, fast and non-destructive biochar with high sorption efficiency.

#### 4.6. Thermo-gravimetric analysis (TGA)

TGA is applied for thermal analysis to observe the physical and chemical properties of materials which are measured as a function of a temperature rise. Thermogravimetric analysis (TGA) has been generally utilized to portray and think about the warm conduct of various examples. This examination planned to look at the ignition attributes of biochar and the biomass/biochar mixes by thermogravimetric examination. Additionally, the normal weighted average of the individual part was inspected whether synergic activity happened between the segments of the blends. The outcomes may assist with bettering comprehend the warm procedure and attributes of the examples from a major perspective and for the examination of tests [87]. During this process, the heating of biochar initiates from room temperature and is increased up to 1000 °C. Many researchers have reported using different temperature such as 10 and 20 °C/min, 10 K/min and less than 1000 °C.

#### 4.7. Brunauer-Emmett-Teller Analysis (BET)

The surface area of biochar can be examined using BET analysis. The study of surface area is important because this property of biochar is mainly responsible for pollutant removal from soil and aqueous environment. Contrasting the crude examples with their biochar counterparts demonstrates a huge increment BET surface zone after pyrolysis. Most eminently, the crude feedstocks have no material micropores, while new micropores were created in the char during pyrolysis. For both feedstock types, porosity results, including BET surface territory and micropore region, improved as force level increments from 2100 to 2400 W, inferable from the quicker rate of remaining unstable discharge, and expanded improvement of micropores at the raised warming rates [88]. The release of a huge quantity of volatile matter results in biochar with high porosity with various pore structures and low density.

#### 4.8. Nuclear magnetic resonance spectroscopy (NMR)

The structural composition of biochar can be examined using a specific spectroscopic technique NMR. Nuclear magnetic resonance spectroscopy (NMR) utilizes a solid attractive field and radio recurrence (RF) pulses to contemplate the structure of particles through the reverberation frequencies of explicit cores inside the atom. To portray biochars, solid-state methods can be utilized to decide general amount of carbon functional groups, the surmised level of the build-up of aromatic rings, and the general structure of char molecules. The aliphatic and aromatic hydrocarbon content can be investigated using NMR spectroscopy. The comparison of stability and carbonization of different biochar can be examined using NMR [89]. The major drawback of using NMR spectroscopy is that presence of ferromagnetic minerals in biochar may interrupt the NMR signals and also the biochar produced by pyrolysis using high-temperature results in a low signal-to-noise ratio.

#### 4.9. Raman spectroscopy

Raman scattering is one of the most significant and utilized types of sub-atomic spectroscopy. It depends on the vibrational advances of the atoms while illuminating with electromagnetic radiation. Raman radiation is the light dispersing with a moved recurrence of the incident radiation because of the misfortune or

the ingestion of vibrational vitality in the atom. Build up a technique for dependably estimating the degree of synthetic/nanostructural changes that have happened during the carbonization of biomass. Have the option to utilize this strategy to quickly gauge the heat treatment temperatures (HTTs) utilized in the generation of a given biochar sample. High sensitivity, less sample preparation and lower interference make Raman spectroscopy suitable for biochar characterization but its cost makes it less applicable [90].

#### 4.10. X-ray photon spectroscopy

The biochars were portrayed utilizing X-ray photoelectron spectroscopy (XPS) to enlighten the structure and arrangement of the biochars which were gotten from the diverse warm temperatures and biomass. XPS can be utilized to distinguish and measure functional groups and fundamental components on the biochar. The alteration in oxygen-containing functional groups refers to short-term biochar stability. XPS is also be used to determine the elemental O/C molar ratio that may be considered as a representation for biochar stability [91].

#### 4.11. Biochar stability

The stability or resistance of biochar to both biotic and abiotic soil degradation has been utilized for determining carbon sequestration capability of biochar. Numerous studies have been investigated for assessing/evaluating biochar stability. The temperature used in the pyrolysis process is considered as an indication of biochar stability. This prediction is inaccurate and simple. The proximate examination has long been utilized to survey nature of coal, moisture, charcoal, ash and fixed carbon. The proximate examination requires high temperatures (900 °C for assurance of volatile matter and 750 °C for ash determination) for an expanded period; this has disadvantages and can prompt an exaggerated estimation of carbon by underestimating ash content [92]. Assessing methods for biochar stability can be divided into three classes: (a) direct or indirect qualification or quantification of C structures of biochar like aromaticity; (b) quantification or qualification of stable C by thermal or chemical or thermochemical methods like chemical oxidation, thermal degradation, etc. and (c) incubating biochar in soil and modeling of C mineralization [93]. The last method Incubation and modeling is a biochemical technique for measuring biochar stability and it is the base of the first two methods. The outcomes obtained from the first two methods resemble indirect stability results that are in correlation with the results obtained from the incubation and modeling method. A well-defined property of biochar is the presence of C structure comprising a crystalline phase and an amorphous phase. The biochar stability assessment can be done by evaluating the C present in biochar or stable C structures. Therefore, C structure is the determining element in assessing biochar stability. The main indicators for biochar C structures are aromatic condensation and aromaticity. Biochar possessing a high degree of aromatic condensation and aromaticity are resisted thermochemical and biological degradation thus having high stability. The elemental composition of biochar represents C—C bonds or aromaticity. The biochar properties such as pore structure, pH, minerals, sorption mechanism, surface area and particle size also contribute to biochar stability. The evaluation of biochar stability by incubation and modeling is considered a major class owing to the direct and accurate results obtained. This method gives longevity values that remain under incubation conditions. These values are based on the modeling of data. The ideal biochar stability can be acquired by biochar incubation in the soil until complete degradation and calculating the time of degradation. It takes hundreds of years for

complete degradation of biochar hence calculation of longevity value is impossible. However, this incubation and modeling process is expensive and time-consuming [94]. The utilization of radioactive  $^{14}\text{C}$  isotopes is another new approach for analyzing biochar stability.  $^{14}\text{C}$ -labeled complex C substrates were used to determine the impact of biochar and straw on microbial SOC turnover. The assessment of thermochemical oxidation stability permits for biotic and abiotic degradation. However, biochar can be used as a tool for various applications, the present techniques available for determining biochar stability does not provide accurate results. Hence developing new methods for evaluating biochar stability will enhance the application of biochar for climate change mitigation.

### 5. Biochar and environment

Though biochar is utilized for various purposes, its influence on the environment must be analysed properly to avoid its negative impacts. The main factor that must be focused on prior application is stability. Biochar constitutes the carbon structure. Hence, stability of biochar relates to the stability of carbon structure [95]. Aromaticity and aromatic condensation are the main measures of biochar carbon structures. The dissolved organic matter released from biochar maintains a high degree of aromaticity, resistance and stability. When biochar is utilized for treating wastewater, the carbon content of water increases due to the release of carbon by biochar. The biochar produced from sludge containing heavy metals may percolate during the treatment process thus causing heavy metal contamination [96]. Similarly, when biochar acts as a catalyst, the stability gradually decreases on reusing biochar several times. The instability of biochar may be due to structural damage also. Hence stability of biochar plays an important role in environmental concern. In addition, the toxicity of biochar to soil microbes must also be investigated before application [97]. Since the physicochemical properties of biochar vary with different biomass, it is important to study in detail the toxic effect(s) of biochar on environment. A different toxicity test can be performed using bacteria, algae, fish, etc [98]. Biochar, as a key innovation, has been broadly added to farmland soils to moderate worldwide environmental change. Created by the thermochemical discussion of natural build-ups in an oxygen-restricted condition. The expansion of biochar has been archived to change the soil porosity, dampness content, pH, labile C and N pool sizes, which would notably affect soil  $\text{CO}_2$  emanations. Biochar alterations in farming soil may fill in as a potential instrument for environmental change alleviation, with lower  $\text{CO}_2$  emanations and higher dry issue generation.

### 6. Applications of biochar

The eco-friendly, inexpensive and ease of preparation from various biomass using thermochemical techniques for addressing vast environmental applications makes biochar an intensive area of interest among researchers. Biochar plays an important role in removing contaminants and pollutants from soil and aqueous environment, which can be determined using the type of biomass and pyrolysis temperature. The carbon-rich biochar produced using high pyrolysis temperature has more removal efficiency of organic pollutants due to its enriched properties such as porosity, surface area, pH, less dissolved carbon content and hydrophobic nature. Similarly, the biochar produced using lower temperature possess oxygen-containing functional groups, high dissolved organic carbon and less porous so these types of biochar are more suitable for removing inorganic pollutants. Other factors like pH and residence time also contribute to the removal capacity of biochar. Biochar can also be used for other applications such as

**Table 2**  
Advantages and limitations of different applications of biochar.

Applications	Aim	Benefits	Limitations	References
Catalyst	Act as supporting materials for direct catalysis	Low cost, more functional groups, large surface area	Efficiency may be less	[99,100,101]
Energy storage	Utilizing as electrode materials	Low cost, highly porous, large surface area	Performance is low	[102]
Soil amendment	Enhancing soil fertility and quality and carbon sequestration	Low cost, minimize emission of greenhouse gases, helps to retain nutrients and water, controls nutrient loss	Contamination of heavy metals and poly aromatic hydrocarbons may persist	[27,12]
Adsorbents	Removal of organic and inorganic pollutants in soil and aqueous system	Low cost and more oxygen groups present in biochar enhances adsorption of pollutants	Removal efficiency of pollutants is undetermined and heavy metals retains in soil	[103]
Composting	Improving structure of microbial population and carbon mineralization	Porous, reducing emission of greenhouse gases, large surface area and retains nutrients	There may be chance of heavy metals and other contaminants invading into soil	[104]

catalysts, wastewater treatment, composting, energy storage, carbon sequestration and soil amendment. The advantages and limitations of different applications of biochar were listed in Table 2.

### 6.1. Remediation of pollutants

#### 6.1.1. Organic pollutants

Recent biochar applications focus on utilizing biochar for removing organic pollutants from soil and water. Biochar when applied to soil, adsorbs organic pollutants present in the soil. Few organic contaminants include agricultural chemicals such as insecticides, herbicides, pesticides, fungicides like atrazine, simazine, carbofuran, etc., industrial chemicals such as PAHs (polycyclic aromatic hydrocarbon) including phenanthrene, catechol, pyrene, naphthalene, anthracene, etc., antibiotics and drugs like acetaminophen, tetracycline, ibuprofen, sulfamethazine, tylosine, etc., cationic dyes such as methylene blue, rhodamine, methylene violet, etc., and volatile organic compounds such as butanol, benzene, furan, trichloroethylene, etc [105]. The degradation and adsorption of organic pollutants in soil were increased by increasing the biochar concentration. The pesticidal content such as carbofuran was minimized due to adsorption or degradation of biochar when its concentration is increased in soil. Degradation of carbofuran that has dense on the biochar surface during pyrolysis prompts an expansion in porosity and adsorption of certain pesticides. Pesticide might be adsorbed on the surface of biochar, because of the quality of carboxylic and phenolic functional groups. The uptake of pesticides by growing plants in the soil also decreased. Hence, the biochar quantity must be optimized related to a specific area of application to facilitate enhanced adsorption of pollutants. The mechanism of removal is directly related to the interaction between biochar and pollutants. Mechanism occurs through physisorption (electrostatic attraction/repulsion, pore diffusion, H-bonding and hydrophobic) and chemisorption (electrophilic interaction) processes in presence of various functional groups such as OH, COOH, etc. Other removal mechanisms include chemical transformation, partitioning and biodegradation [106]. The main factors that affect biochar-organic pollutant interactions are temperature, pH, type of biomass and ratio of pollutant and applied biochar. Biochar application was also found to decrease the bioavailability of soil organic pollutants and their uptake by plants and microbes. For example, the biochar derived from hardwood at high pyrolysis temperature was found to decrease the bioavailability of pesticides in soil due to biochar surface area and porosity to adsorb organic pollutants compared to the biochar produced using low temperature. Diffusion, partitioning and electrostatic attraction were the main adsorption mechanisms contributing to this removal. The removal efficiency was compared between the

soil amended with biochar and unimpeded soil. It was found that the biochar amended soil reduced the availability of pollutants in the soil for plants uptake whereas the plants grown in unamended soil increased pesticidal absorption. The pollutant removal increased with an increase in biochar concentration. The properties of biochar influence organic pollutant sorption. Biochar possessing small particle size possess large surface area and show better removal results and also the removal time required was found to be less. Apart from biochar properties, soil conditions also contribute to adsorption or degradation of pollutants. For example, pesticidal sorption occurs at low pH only. Adsorption was found to be a significant mechanism for removing organic pollutants when combined with degradation and immobilization of organic content. Similar to pesticides, cationic dyes such as methylene blue, rhodamine, methyl violet, etc., are removed using an electrostatic attraction/repulsion process. Pollutants removal mechanism using various biomasses is listed in Table 3.

#### 6.1.2. Inorganic pollutants

Inorganic pollutants such as metals are toxic and non-biodegradable when present at higher concentration hence it poses a serious threat to human life and environment. The more carcinogenic and toxic are heavy metals like copper, zinc, cadmium, lead, nickel and mercury. These inorganic pollutants are released into the environment either by industrial effluents or municipal wastewaters [123]. In contrast to organic pollutants, the biochar produced using low temperature is suitable for sorbing inorganic contaminants. The biochar produced using low temperature possesses many functional groups, high organic carbon content and porous. Ion-exchange is the dominant mechanism for removing inorganic pollutants specifically heavy metals. The physicochemical characteristics of biochar influence the adsorption of porous structure and enhance the reduction of heavy metal. Biochar also possesses immobilization properties that will assess chemical modification in heavy metals including surface functional groups, pH and cation exchange capacity. Biochar characterization techniques such as SEM, FTIR, TEM and XRD analyses showed that biochar possesses strong adsorption efficiency for heavy metals. The zeta potential and cation exchange capacity of biochar decreased with an increase in soil pH. The biochar amended soil possesses more potency for the immobilization of heavy metals. For example, the concentration of heavy metals such as lead, cadmium and copper were potentially reduced in biochar amended soil. The biomass utilized for producing biochar for removing inorganic pollutants are agricultural products such as corn cob, sugar beet, soybean straw, switchgrass, etc., animal waste and sewage sludge. Among heavy metals, copper possesses a strong affinity towards OH and COOH groups and its removal mainly depends on type of biomass and pH. Another factor pH also



**Table 3**  
Pollutants removal mechanism by various biomass.

Biomass	Pollutants	Pyrolytic temperature (°C)	pH	Mechanism	References
Bamboo	Fuel oil	700	7.0	Acid-base interaction	[107]
Pig manure	Methylene blue	525	6.5	–	[108]
Paper and pulp sludge	Methyl orange	750	8.0	Complexation	[109]
Maple wood	Crude oil	400	Sea water conditions	Pore-filling	[110]
Pecan nutshell	Methylene blue	800	6.0	Chemical adsorption	[111]
	Reactive red 141		3.0		
Woody tree	Crystal violet	500	8.0	H-bonding and electron donor/acceptor interaction	[112]
Rice husk	Crude oil	450	Sea water conditions	Hydrophobic interaction	[113]
Post-harvest residue	Diesel oil	200–600	6.5	Physical sorption	[114]
Straw	Sunset yellow	500, 700	–	Spectrometer exchange	[115]
	Methylene blue				
Saw dust	Crude oil	450	Sea water conditions	$\pi$ - $\pi$ interactions	[113]
Maize straw	Thiacloprid	500, 700	–	$\pi$ - $\pi$ interactions and hydrophobic interactions	[116]
Sugarcane bagasse	Dimethoate	500	–	Intraparticle diffusion and Physical sorption	[117]
Swine manure	Tetracycline	700	9.0	$\pi$ - $\pi$ electron donor/acceptor interaction, H-bonding	[118]
Eucalyptus sawdust	Dimetridazole	500	7.0	Physisorption and Chemisorption	[119]
	Metronidazole				
Chitosan	Ciprofloxacin	450	3.0	$\pi$ - $\pi$ electron donor/acceptor interaction, hydrophobic interaction, H-bonding	[120]
Swine manure	Imidacloprid	600	–	Pore-filling	[121]
Peanut shells	Doxycycline hydrochloride	450	8.0	Electrostatic interaction and complexation	[122]
Rice straw	Tetracycline	700	9.0	$\pi$ - $\pi$ electron donor/acceptor interaction, H-bonding	[46]

contributes to removal efficiency but the process depends on the metal. At pH 6.0–7.0, the removal was by ion-exchange while at higher pH 7.0–9.0, the removal mechanism was by surface complexation and electrostatic attraction. For example, Cr removal was found to be maximum at pH 2.0 while Pb removal was found high at pH 2.0 and 5.0. At higher pH, the solubility of metal reduces that hinders metal mobility in soil. The dosage of biochar also contributes to heavy metal removal [124]. Higher removal efficiency can be obtained with increased biochar dosage which also increases surface area and pH. Apart from using biochar as sorbent material for removing organic pollutants in soil, it can also be used for removing inorganic pollutants from an aqueous environment also. Biochar possesses potency to remove dissolved pollutants present in groundwater. Uranium can be effectively removed from groundwater using biochar. Many factors contribute to removal efficiency. Biochar dosage is the key factor. Many literature studies support that increased biochar dosage enhanced the removal of heavy metals. The biochar porosity also affects metal sorption. The functional groups responsible for the removal of Pb and Cr are hydroxyl and carboxylate. The competition for metals binding among various metals exists since the functional groups for metal adsorption are chemically the same. The effect of biochar immobilization on heavy metals and inorganic contaminants in polluted soils are still needed to be analysed [125]. Table 4 shows adsorption of organic and inorganic contaminants and their removal percentage using different biomass.

## 6.2. Catalyst

Biochar can act as catalyst that finds vast application in various fields such as agriculture, environment, energy, etc [126]. The properties of biochar make it potent as a promising catalyst. The large surface area is important for biochar catalytic activity since more functional groups are present at the surface. For example, the functional group O–H is responsible for adsorption of norfloxacin

and C=O and OH– groups are suitable for ammonium adsorption. As a catalyst, biochar finds vast application such as biodiesel production, energy production, removal of tar, waste management, syngas production, and electrodes in microbial fuel cells, production of chemicals and removing environmental contaminants [127].

### 6.2.1. Energy production

During the biomass gasification process, the formation of tar is unpleasant as the tar condensation results in contamination and clogging of downstream operations and also a reduction in energy efficiency. The catalytic transforming of tar possesses the capability of converting the tar to hydrogen and carbon monoxide. These H<sub>2</sub> and CO are considered as the important components of syngas. The char produced from different biomass such as corn straw char, rice straw char influences removal of tar. Thus, removal of tar efficiency is affected by char types. The tar removal efficiency decreases with an increase in particle size of char. This is because of the surface area and active site affects removal efficiency. During the gasification/pyrolysis process, the production of hydrogen is enhanced by biochar.

### 6.2.2. Biofuel production

Biofuel is a perfect substitute for petroleum product as it is biodegradable, nontoxic, renewable, and shows a comparable fuel property to fossil fuel. Biofuel can be created from the transesterification of vegetable oils or the esterification of free unsaturated fats (FFAs) with alcohols. Biochar catalysts are used for producing biofuels through transesterification and esterification reactions. The biochar-based catalysts can be classified into two types: (i) Solid acid catalysts and (ii) Solid alkali catalysts

Acid functionalized biochar catalysts are generally arranged by sulfonating biochar with vaporous SO<sub>3</sub> or liquid H<sub>2</sub>SO<sub>4</sub>. Poor quality or waste oils for the most part contain a lot of FFAs, which are probably going to bring down the reaction rate and biodiesel

**Table 4**  
Adsorption of organic and inorganic contaminants and their removal percentage using different biomass.

Type of contaminants	Contaminant	Biomass used	Biochar dosage (%)	Removal efficiency (%)	References	
Organic	Poly aromatic hydrocarbons	Hardwood	10	32	[126]	
		Paper mill waste	5	37.9	[127]	
	Polychlorinated dibenzo-p-dioxins	Wood chips	1	40	[128]	
		Corn Stover	1	52.3	[128]	
	Perfluoro octane sulfonate	Willow	0.12	41	[129]	
		Maize straw	0.12	70	[129]	
	Atrazine	Green waste	1	19	[130]	
	Carbofuran	Wood chips	1	51	[131]	
	Trifluralin	Wheat straw	1	13	[132]	
	Simazine	Green waste	2	95	[130]	
	Phenanthrene	Wood	0.1–5	50	[133]	
	Pentachlorophenol	Rice straw	2	96	[134]	
	Trichloroethylene	Peanut shells	0.03	70	[135]	
		Soybean Stover	0.03	67	[135]	
	Inorganic	Isoproturon	Wood	2	49.8	[136]
			Cd <sup>2+</sup>	Rice straw	20	97.1
		Cd <sup>2+</sup>	Tree bark	10	>99	[138]
			Wheat straw	40	93.6	[139]
			Sludge	8	99.9	[140]
Pb <sup>2+</sup>		Rice straw	5	100	[141]	
		Chicken manure	5	93.5	[142]	
		Soybean Stover	20	90	[143]	
Zn <sup>2+</sup>		Sugarcane straw	5	50	[144]	
		Sludge	5	51.2	[145]	
		Hardwood	5	56.7	[146]	
Cr		Corn straw	5	67	[146]	
		Sugar beet tailings	0.8	88.5	[147]	
As		Hardwood	47	0	[148]	
U		Switchgrass	0.5	90	[149]	

yield. In this manner, the improvement of catalyzes fit for simultaneously catalyzing esterification and transesterification is alluring. The solid catalysts were obtained from biomass using two main processes namely sulfonation and carbonization. Biofuels production is an emerging technology and is considered to be an alternate strategy to petro-fuels. Biodiesel is considered to be an alternate source for petroleum diesel owing to its benefits such as renewability and ease of storage. Biodiesel is composed of fatty acid alkyl esters produced by transesterification or esterification of animal fat, vegetable oil and microalgal oil [128]. Another sort of biochar-based catalysts for biofuel production is biochar-upheld alkali catalysts or biomass-determined solid alkali catalysts. CaO/biochar, K<sub>2</sub>CO<sub>3</sub><sup>-</sup> or KOH<sup>-</sup> functionalized biochar was additionally utilized as catalysts for biofuel production. These ease catalysts showed a high biofuel yield and decent reusability, making them an appealing option in contrast to existing transesterification catalyst frameworks [129]. Calcium oxide is a commonly used catalyst because of its vast availability and low cost. Though its disadvantages such as loss of activity and less surface area make it unsuitable. Hence biochar-based catalyst is more preferably used for producing biofuels because of its high efficiency, porosity and less cost. Studies have been reported on utilizing a magnetic biochar-based catalyst for biodiesel production owing to its recyclability and ease of recovery. On reusing these catalysts, biochar showed a high rate of reaction signifying its potency to act as an acid catalyst for producing biodiesel.

### 6.2.3. Waste management

Many artificially produced chemical compounds possess strong resistance to biological degradation and are bio-recalcitrant. These synthetic chemicals are carcinogenic to humans, microbes, plants and other species in the environment. The degradation of bio-recalcitrant compounds can be done using a promising technique named catalytic ozonation process (COP). The biochar derived from biomass containing porous structure and functional groups such as

phenolic and hydroxyl was utilized as a low-cost catalyst for degrading a resistant organic compound namely reactive red 198 dye in the catalytic ozonation process.

### 6.2.4. Control of air pollutants

The utilization of biochar as low temperature selective catalytic reduction catalysts has been reported in literature. Studies have been reported on biomass like sewage sludge and rice straw for producing biochar and utilizing as low-temperature catalysts where ammonia is used as a reducing agent. The char was modified physically or chemically and their removal efficiency was determined. The chemical activation showed higher removal efficiency than physical activation. This indicated that chemical properties such as functional groups, adsorption sites are main factors for higher removal. Sulfate and free radical were delivered under the catalysis of biochar. The surface of the biochar explicit oxygen including catalytic activity complexes with different responses. Because of biochar, the complex improved the catalytic activity of the catalyst [130,131].

### 6.2.5. Energy storage and supercapacitors

Energy storage in electrical products is important for consumer usage in electrical and electronic devices. Supercapacitors are energy storage devices that pave attention due to its fast charge and discharge capacity, high power density and long cycle stability while rechargeable batteries possess high energy density and less rate of charge/discharge [132]. Lithium ion batteries are also used as energy storage devices. The electrode materials predict the performance of energy storage device. These electrode materials consist of high surface area and porous structure that provides required active sites for oxidation process. Commonly used electrode materials are carbon nanotubes, activated carbon, graphene, etc. The cost of these carbon materials is expensive hence the utilization is limited. Owing to this drawback, the application of biochar as electrode is gaining interest. Similar to

carbon material, biochar also possesses high surface area and more porous and of less cost. Biochar can act as electrode for microbial fuel cells and supercapacitors [133].

### 6.3. Soil amendment

Defective system in managing agricultural fields resulted in emission of increased quantities of CO<sub>2</sub> and has enhanced the degradation of organic compounds in soil. Many researches have been preceded in increasing the organic carbon content in soil by incorporating biomass into crops and animal wastes [134]. The biochar application in soil not only helped in isolating carbon in soil, it also enhanced the quality of soil by neutralizing the soil pH, increasing soil cation exchange capacity and strengthening the microbial growth in soil. The functional groups such as carboxylic, hydroxyl and phenolic groups present in biochar interacts with hydrogen ions in soil and reduces concentration of hydrogen ion thus increasing soil pH. Carbonates, bicarbonates and silicates in biochar reacts with H<sup>+</sup> ions and neutralizes soil pH [135]. Hence biochar application in remediating soil in agricultural fields has increased interest owing to its surface properties and elemental composition. Biochar can be applied in agricultural field as follows: a) enhancing the fertility and structure of soil [136]; b) increasing the cation exchange capacity of soil and minimizing aluminium toxicity [137]; c) Supporting carbon sequestration and reducing the effect of greenhouse gases [138]; d) improving productivity by maintaining water retention; e) enhancing microbial activity by alleviating nutrient leaching [139]. In addition, biochar utilization has been considered as promising method for remediating contaminated soil with toxic pollutants including heavy metals, pesticides, hydrocarbons, etc. The biomass used for producing biochar consists of basic cations. These cations are transferred into soil when biochar is applied into soil. This activity enhances soil's cation exchange capacity by increasing the surface area of soil for adsorbing more cations. In addition, increase in pH also increases CEC of soil. The presence of high concentration of Ca, K, N and P in biochar adds nutrients to soil or may be used as nutrient source to microbial community in soil. The pore fraction of soil increases when biochar is utilized as soil amendment. The microbial growth occurs in the pore fraction increasing the moisture, air and nutrients residence time thus enhancing the growth, survival and activity of microbes which contributes to plant growth also. The biochar produced at high temperature is difficult to degrade and thus present in the soil for longer time compared to biochar produced at low temperature. Studies have also been reported on negative effects of biochar in soil. For example, hydrochar applied in soil limited the plant growth which showed that prior to application optimization of biochar is important for avoids its negative effects on plants. The application of biochar as soil amendment reduces emission of global warming gases. The direct combustion of biomass releases carbon in the form of CO<sub>2</sub> into environment. This carbon can be converted into biochar through gasification or pyrolysis process that can be restored in soil.

### 6.4. Carbon sequestration

Climatic change has increasing concern in minimizing the CO<sub>2</sub> emission into atmosphere. Soil plays a crucial role in carbon cycle that directly influences climate change. Carbon sequestration is a promising method of reducing CO<sub>2</sub> emission in soil [140]. Biochar is barely resistant to degradation by microbes owing to presence of aromatic structure thus biochar shows positive result on carbon sequestration in soil. Many literatures have been reported on sequestering carbon by biochar. However, no ideal results were observed since both positive and negative effects were obtained. Both increased and decreased carbon emissions were observed

[141–143]. The mineralization of organic matter present in soil was found to be higher in low fertile soil compared to soil with high fertility and also in soils containing high carbon content, the carbon mineralization was higher compared to low carbon content soil [8]. The carbon content in biochar can be classified into two types namely liable and recalcitrant carbon. Liable carbon is utilized by microbes easily during biochar application hence results in increased carbon mineralization at the initial stage itself. Thus, biochar application restored carbon mineralization. In contrast, recalcitrant carbon is present in the soil for longer time [144]. Therefore, the carbon fixation due to biochar application is more than the carbon released due to liable carbon mineralization. The influence of biochar on sequestering carbon is still not clear. The effect differs with the biomass type and pyrolytic conditions. Since pyrolysis conditions have major effect on physicochemical properties of biochar, it is mandatory to determine the association between reaction conditions and the influence of biochar on carbon sequestration.

### 6.5. Wastewater treatment

Biochar is a solid material with high surface region and high porosity, properties that makes it an appealing alternative in wastewater treatment. Biochar has been accounted for to be a successful media for catching supplements from wastewater and that can be connected in soil as an alteration. Biochar is accounted for to emphatically build toxins expulsion in wastewater because of its high porosity and high adsorption properties that enables poisons to aggregate on its surfaces bringing about a clean effluent and supplement rich biochar. There is a rising pattern on the utilization of carbonized materials and crude biowaste in wastewater treatment. Many researchers played out a meta-examination to think about the ecological and monetary exhibition of biochar and activated coal in evacuation of toxic contaminants. The examination revealed that evacuation execution of biochar to that of activated coal. It is in this manner supported that while huge surface territory of activated coal favours toxins adsorption by pore filling, there are different elements, including surface functional groups that clarify the removal execution of biochar. Creation of activated coal includes high natural effect, confirm by lower greenhouse gases emission of biochar. Likewise, generation of activated coal (97 MJ/kg) requires surprisingly higher vitality request than biochar (6.1 MJ/kg). Therefore, biochar could be more good than activated coal in removal of toxic contaminants from wastewater while thinking about the GHG discharge, vitality request and along these lines creation cost.

## 7. Biochar – an ideal approach for improving circular economy

This examination is centred on the idea of a circular bio-economy through use of biochar to deliver a feasible answer for its compelling administration. The larger particles of organic materials begin to break down to yield smaller atoms, which are discharged from the procedure stream as gases, condensable fumes (oils) and strong burn during pyrolysis process. The extent of each finished result relies upon the temperature, time, warming rate, and weight, sorts of forerunners and reactor plan and arrangement [2]. The thermochemical methods employed for producing biochar particularly in rural areas enhances development of that specific region and also small and medium enterprises producing enough energy thus increasing farmer's income, providing solutions for managing waste in agricultural sector. Through this, small-scale production systems can be connected with other systems creating a closed system models so that waste from one process can be utilized as an input for the other with high social, economic and ecological outcomes in circular economy

[145]. Similar interactions between different methodologies of biochar production and reusing waste are required for developing new opportunities. By using the waste from one agro-processing industry to illuminate toxic pollutant issues in another and the by-product going into soil application, a circular bio-economy has been set up new product and procedure advancement and potential for formation of new businesses. Because of high moisture content, significant items become fluids and if there is a low degree of water, there is a high hazard that the procedure produces a higher amount of residue rather than oil. Anyway at higher temperature that is more than 800 °C when the warming rate is high then bigger division of debris and vaporous items are created. Bio-oil can be delivered applying middle of the road temperature utilizing moderately high warming rates. During the start of the procedure around temperature 250–300 °C, unstable materials are discharged at very nearly multiple times faster than the ensuing advance. Methodologies in a balance between ease of use, energy proficiency, and constrained discharges could be incorporated into the local network for the feasible generation of biochar noting both specialized and financial viewpoints, recouping additionally the biochar and heat produced [146].

The following environmental benefits can be obtained:

- Less emission of greenhouse gases;
- Economic benefit by reducing the cost with respect to waste disposal.

This application in circular economy reduces wastes by various processes and techniques thus increasing their value. It displays an open door for the advancement of a Circular Economy (CE) utilizing an inventive combination of methodologies and beneficial strategic approaches to address the usage of wastes from agriculture, co-products, and by-products. The proposed framework could be a keen manageable rural energy foundation, in provincial cultivating networks, fit to the circular economy guideline. Both anaerobic digestion and gasification framework with farms providing yield and slurry and industry providing food waste can produce power and manure, which would then be able to be utilized by the nearby community, rather concentrating on the social advantages that a change from a linear to a Circular economy would involve [147,148]. Life cycle assessment (LCA) is a broadly utilized and standardized ecological appraisal approach to measure environmental performance of products. The outcomes featured that the environmental performance of pyrolysis can shift as per numerous elements, including (a) biomass feedstock, (b) pyrolysis process, (c) co-products yield, and (d) identification of peripheral innovations. The diverse life-cycle phases of bio-oil creation by pyrolysis process and production of bio-oil have been additionally distributed into five unit measures: (i) feedstock readiness and drying, (ii) pyrolysis reactor, (iii) extinguish condenser, (iv) char recuperation, and (v) heater cycle. The basis for this methodology were that a multiunit model would be generally helpful in breaking down approaches to improve productivity, upgrade activities, and give a sensible commission of environmental burdens to enhance ecological enhancements.

## 8. Knowledge gaps and future perspectives

Biochar is considered as a renewable resource for addressing many environmental problems such as remediation of contaminants from soil, aqueous and gaseous medium. Activating biochar is another specific area for expanding the application of biochar for removing particular pollutants. Further research is required for identifying new methods of activation and also adsorption and desorption mechanisms of various pollutants. The study of microbial population and their interaction with biochar present

in soil is still to be studied in detail yet. The growth and development of microbes in presence of biochar and the influence of biochar properties on microbial community must be examined in detail. The biochar when amended with soil not only helps in remediation and maintaining soil fertility but also aids in providing micro and macro nutrients whenever required. More research is needed on analyzing microbial activity during mineralization process and soil remediation. The interaction of biochar with soil and their binding mechanisms must be studied in detail. The mechanism of contaminants removal during wastewater treatment is still unclear. Current studies have observed the possibility of electrochemical conversion of a solid carbon material to electricity in direct carbon fuel cell. The problem is examining the mechanism of reaction kinetics and oxidation at anode/electrode interface. The interaction of solid carbon and electrolyte/electrolyte interface is much limited hence this field requires more attention. Though biochar provides vast benefits, few concerns still exist. The toxic compounds such as dioxins, chlorinated hydrocarbons and polycyclic aromatic hydrocarbons may be present in biochar depending on biomass used for producing. The performance of biochar that is utilized as supercapacitors still requires more attention. To evaluate the economic advantages and environmental impacts, life-cycle analysis of biochar must be done. The biochar characterization methods have progressed due to developments in new techniques. Optimizing biochar properties and activation is important for obtaining maximum efficiency. The utilization of new techniques is affected by economic viability and accessibility. Since biochar has emerged as an alternate source, standard characterization procedures must be implemented for better understanding of biochar properties.

## 9. Conclusions

Production of biochars uncovers a wide variety of biomass that have been utilized as the feedstocks and pyrolyzed by various procedures to handle water pollution. The properties of resultant biochar are significantly influenced by pyrolysis temperature, feedstock, and pyrolysis technology. Biochar can be utilized as major source for removal of toxic pollutants. Pollutant removal by biochar occurs mainly due to presence of functional groups such as hydroxyl, carboxyl groups on surface of biochar. Though the efficiency of biochar depends on type of biomass and pyrolysis conditions, the development of biochar in future is focused on fine sharpening on biochar properties. Thus, biochar appears as a highly promising option for pollutant removal. Economic impacts and recyclability should be considered in developing recoverable biochar for wide environmental applications. Relationship among various solutions for waste management and energy production differs on parameters and multiple techniques for its production as well as economic, social and ecological constrains. Disregarding the way that the proposed method might be used in regular practice, the closed framework sets up differentiations from the straight to a circular model of waste organization. In this circular economy idea, higher energy recuperation could be accomplished. This review paper summarised state-of-art information that would be helpful to find new opportunities in scientific innovation in field of biochar research.

## Declaration of Competing Interest

The authors report no declarations of interest.

## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.btre.2020.e00570>.



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