A comprehensive assessment of the method for producing biochar, its characterization, stability, and potential applications in regenerative economic sustainability – A review

Farah Amalina [a], Abdul Syukor Abd Razak [a], Santhana Krishnan [b], A.W. Zularisam [a], Mohd Nasrullah [a,*]

[a] Faculty of Civil Engineering Technology, Universiti Malaysia Pahang (UMP), Lebuhraya Tun Razak, 26300 Gambang, Kuantan, Pahang, Malaysia
[b] PSU Energy Systems Research Institute, Department of Environmental Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand

ARTICLE INFO

ABSTRACT

There is a rise of interest in various aspects of biochar derived from waste biomass to address the most pressing ecosystem challenges. This study contributes to understanding biochar's usage in the remediation of hazardous pollutants. The synthesis of biochar using a variety of different techniques has been explored. Numerous analysts have considered biochar as a strategy for enhancing their ability to remediate pollutants. Process factors are primarily responsible for determining biochar yield. Biochar-derived biomass is an exceptionally rich well-spring of carbon produced from biomass utilizing thermal combustion. Activating biochar is another field where biochar is increasingly used to remove specific contaminants. Closed-loop methods to produce biochar expand options. Distributed biochar manufacturing processes are an efficient method to develop businesses, manage waste, and increase resource proficiency in environmental applications. Additionally, this research discusses knowledge gaps and future directions in toxic pollutant remediation through biochar.

Contents

* Corresponding author.
  E-mail addresses: nasrul.ump@gmail.com, mnasrul@ump.edu.my (M. Nasrullah).

1. Introduction

Global energy consumption is increasing at times as a result of rapid urbanization. Energy is required in every country area (Chiappero et al., 2020). The primary source of energy is fossil fuels. However, the influence of atmospheric carbon dioxide on the environment and world energy challenges have necessitated the substitution of fossil fuels (Grobelak et al., 2019; Syuhada et al., 2018). Organic waste, the primary component of solid biomass, has a significant biochar production potential (Nidheesh et al., 2021). Agricultural wastes from farming, forestry, municipal solid waste, food, and animal manure are all acceptable biomass waste feedstock for biochar formation (Bedia et al., 2018; Ravindran et al., 2018). Fig. 1 summarises the most frequently used method for producing biochar from various biomasses. The biochar derived from biomass is a highly rich source of carbon produced from biomass using thermal combustion in an oxygen-deficient condition (Hu et al., 2021; Yaashikaa et al., 2020). Biochar's unique qualities, which include a large surface area, a high porosity, functional groups, a high capacity for cation exchange, and stability, meet appropriate for a wide variety of applications. The rapid and simple production, environmentally safe, recyclability, and cost-effectiveness of biochar are only a few benefits (Chen et al., 2019b; Thomas et al., 2019). Numerous researches have demonstrated biochar's efficacy in removing various pollutants (Bolan et al., 2021; Sun et al., 2021). The pyrolysis parameters, such as the reaction conditions (temperature, residence time, heating rate, pressure) and the feedstock type, significantly influence biochar yield and properties (Limmer and Burken, 2016; Santoso et al., 2020). Its basic structure and properties also vary according to the reactor type utilized throughout the carbonization method. Thermochemical conversion is a common technique for biochar production (Tang et al., 2019; Yu et al., 2017). Pyrolysis, hydrothermal carbonization (HTC), gasification, flash carbonization, and torrefaction are common thermochemical processes for producing biochar (Chiappero et al., 2020; Kumar et al., 2020). Pyrolysis is the most often used process for producing biochar. In an oxygen-deficient condition, the organic molecules in biomass degrade at a specific temperature. The thermal efficiency, residence time, biomass type, and heating affect the pyrolysis product (Leng et al., 2021; Sakhiya et al., 2020). Temperature is the primary factor influencing the properties of biochar (Godwin et al., 2019; Gopinath et al., 2021), while biochar is completely constituted of carbon and ash. Thus, biochar's role and efficacy in many areas depend on the biomass utilized to make it. Biochar characterization is critical for determining the material's elemental analysis, surface functional groups, stability, and structure. Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectroscopy (FTIR), Thermo Gravimetric Analysis (TGA), X-Ray Diffraction (XRD), Brunauer Emmett Teller (BET), Nuclear Magnetic Resonance (NMR), and Raman
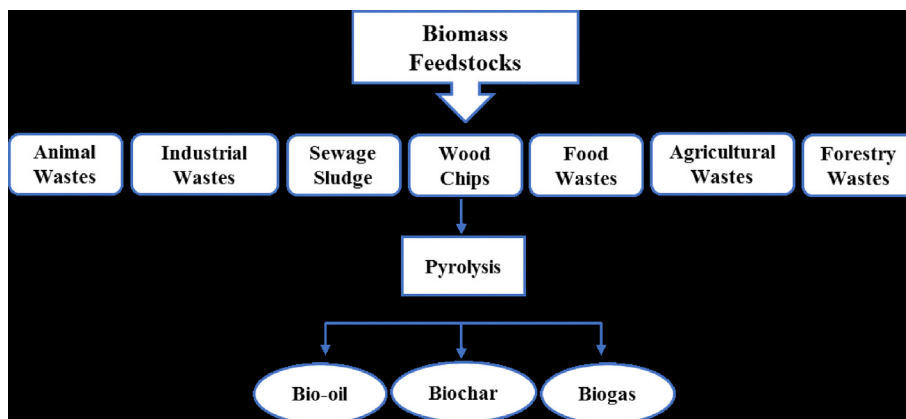

Fig. 1. Schematic diagram illustrating the processes involved in the synthesis of pyrolysis products from various feedstocks.

Table 1

Techniques of thermochemical conversion and their operating parameters with the proportion of biochar, bio-oil, and gas produced.

Process	Temperature (°C)	Residence time (s)	Yield of biochar (%)	Yield of bio-oil (%)	Yield of syngas (%)	Reference
Pyrolysis	Slow 300–700	<2 s	35	30	35	(Koyuncu and Koyuncu, 2017; Lee et al., 2020)
	Fast 500–1000	Hour–day	12	75	13	
Hydrothermal carbonization (HTC)	180–300	1–16 h	50–80	5–20	2–5	(Brown et al., 2020)
Gasification	750–900	10–20 s	10	5	85	(et al., 2017)
Torrefaction	290	10–60 s	80	0	20	(Daful et al., 2018)
Flash Carbonization	300–600	<30 min	37	–	–	(Liu et al., 2020)
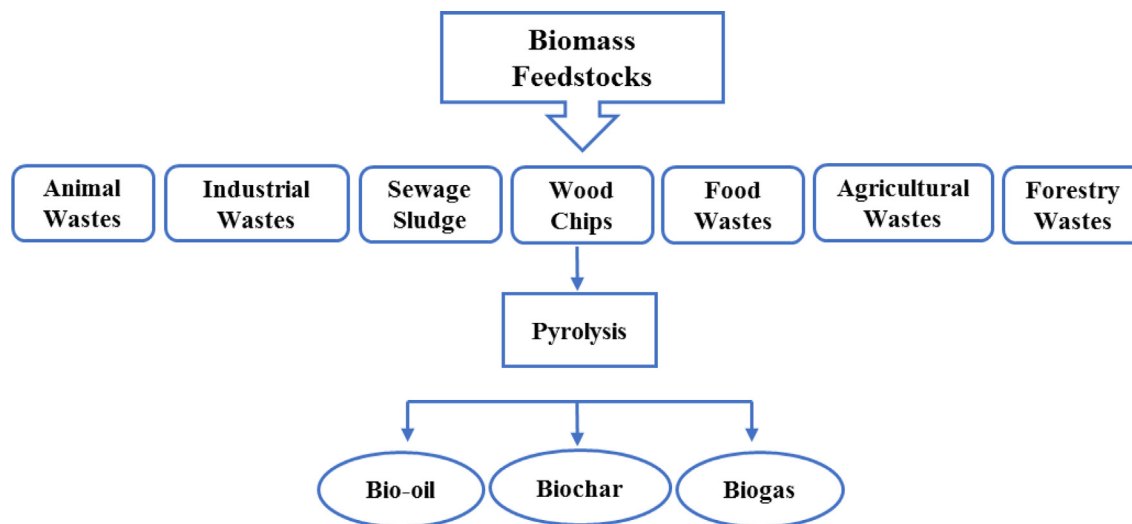
Fig. 2. Process of pyrolysis.

spectroscopy are some of the current technologies used to characterize biochar (Sonu et al., 2020; Zhang et al., 2020a). Recent research has concentrated on biochar characterization, with the primary goal of distinguishing biochar from other organic materials in soil (W. Chen et al., 2018; Zhou et al., 2020). For example, SEM can determine the morphology of the biochar, and FTIR may determine the functional groups (Oliveira et al., 2017; Papurello et al., 2019). Adsorption is the mechanism through which biochar binds hazardous heavy metals and other pollutants. Biochar's adsorptive efficiency is precisely linked to its physical and chemical properties, including functional groups, surface area, and cation exchange capacity (CEC). By exposing biochar to acid, alkali, or oxidizing chemicals, its physicochemical qualities can be enhanced (Daful et al., 2018; Wahi et al., 2017). Acid treatment can be used to modify the surface area. The extensive literature on biochar properties and strategies for evaluating and characterizing them will clear the path for understanding biochar's efficacy in various disciplines. Biochar has been used to resolve a variety of environmental issues due to its numerous benefits and eco-friendly nature, including adsorbing contaminants (You et al., 2017), reducing greenhouse gas emissions (Hamzah et al., 2019), composting (Akdeniz, 2019), wastewater treatment (Srivatsav et al., 2020), soil remediation (Abdullahi, 2015), energy production (Papurello et al., 2019), and catalyst (Cheng and Li, 2018). Biochar's capability for adsorption of organic and inorganic pollutants is based on its high surface-to-volume ratio and affinity for nonpolar groups (Nyoo et al., 2021). Additionally, biochar was used in agricultural fields to eliminate soil contaminants. Numerous agricultural wastes, including rice straw (Qin et al., 2020), wheat straw (Ravindran et al., 2018), waste wood (Papurello et al., 2019), sugar beet tailings (Fan, 2018), and maize cob (Shamsollahi and Partovinia, 2019), have been used to generate

biochar. These biowastes are mostly comprised of cellulose, hemicellulose, and lignin. These elements are thermally degraded at various temperatures throughout the pyrolysis process, and their mechanisms are explored in detail. This article focuses on a comprehensive review and assessment of hazardous pollutant treatment using biochar, the benefits, and the effect of process parameters, notably temperature, pressure, heating rate, etc. The synthetization of biochar was performed utilizing various processes, including pyrolysis, hydrothermal gasification, and torrefaction. Researchers investigated characterization approaches which included SEM, XRD, FTIR, TGA, and BET. Most importantly, the recent advances of biochar stability, its use in various applications such as the immobilization of organic and inorganic contaminations, carbon sequestration, and as a catalyst are perspicuously and detailly elucidated. Also, the topic of regenerative economic sustainability is included.

2. Biochar production methods

The strong demand for biochar for a spectrum of uses has resulted in converting biomass to biochar (Ukanwa et al., 2019). Thermochemical conversion is a frequently used approach for producing biochar. Pyrolysis, HTC, gasification, and torrefaction are all instances of thermochemical conversion methods (Brown et al., 2020; Iisa et al., 2019). To reach the optimum yield of biochar, the production methods should be compatible with the biomass source. The operating parameters, notably heating rate, temperature, residence time, etc., must be optimal (Gale et al., 2021). The mentioned variables are critical because they can influence the physicochemical properties of biochar across the development processes. The structure of biochar obtained from crop residues differs according to the preparation circumstances, as

weight loss occurs during the process (Sakhiya et al., 2020). At first, weight loss occurred since water loss was around 100 ℃, followed by cellulose, hemicellulose, and lignin degradation around 220 ℃. Eventually, weight loss leads to the combustion of carbonaceous wastes (Abo Omar and Abdallah, 2019). Table 1 summarises the thermal conversion procedures and their associated operating parameters.

2.1. Pyrolysis

Pyrolysis is a concept that describes the thermal breakdown of organic compounds in an oxygen-free condition at temperatures ranging from 250 to 900 ℃ (Wang and Wang, 2019). This is a different method of transforming biomass waste into valuation products such as biochar, syngas, and bio-oil. At specific temperatures, lignocellulosic compounds, notably cellulose, hemicellulose, and lignin, undergo reaction mechanisms including depolymerization, fragmentation, and linkage, corresponding to new various product states as an example solid, liquid, and gas (Jorge et al., 2021; Waters et al., 2017). Char and bio-oil are solid and liquid products, whereas carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H), and syngas are gaseous products (C^1-C^2 hydrocarbons) (Ha and Lee, 2020). Biochar is produced using various reactor types, including paddle furnaces, bubbling fluidized bed reactors, wagon reactors, and agitated sand rotating furnaces (Sakhiya et al., 2020). The biochar quantity extracted during the pyrolytic is based on the type and composition of the biomass utilized, pyrolysis conditions and temperature. Temperature is the key operational process condition that affects the efficiency of the product (Kumar et al., 2020). When the temperature of the pyrolysis process rises, the yield of biochar decreases, and the formation of syngas increases. The mechanism of pyrolysis is illustrated in Fig. 2. Pyrolysis may classify into three broad categories based on the operating conditions (heating rate, temperature, residence time, and pressure): (i) slow pyrolysis with temperature of 300 ℃ (Kameyama et al., 2019), (ii) intermediate pyrolysis at temperatures ranging from 300 to 500 ℃ (Oginni, 2018), and (iii) fast pyrolysis with heating rate is relatively more than 500 ℃ (Ha and Lee, 2020).

Fast pyrolysis is considered a rapid thermochemical process capable of liquefying carbon-based materials to a high-energy liquid bio-oil (Ha and Lee, 2020). Fast pyrolysis conditions are defined by the following characteristics: (i) rapid heating of biomass particles (>100 ℃/min) (Dhyani and Bhaskar, 2018), (ii) short heating time of structural and pyrolysis fumes (0.5–2 s) at elevated temperatures (Wahi et al., 2017), and (iii) moderate pyrolysis treatment temperatures (400–600 ℃) (Daful et al., 2018). A critical distinguishing feature of fast pyrolysis development is the requirement to minimize fume residence time in the hot zone to obtain high-quality bio-oil (Y. Wang et al., 2018). For instance, fast pyrolysis yields more bio-oil. This can be achieved by ensuring that vapors are quickly extinguished or cooled (Bedia et al., 2018).

Fig. 3. Hydrothermal carbonization of organic waste and biomass.

Slow pyrolysis occurs when the heating rate is relatively low, at 5–7 ℃/min. The residence duration is more significant than 1 h. Slow pyrolysis's productivity more char than other pyrolysis and carbonization processes (Shahbaz et al., 2020).

Cellulose, hemicellulose, and lignin comprise the majority of biomass. These elements are transformed into biochar in many ways and under a variety of reaction parameters and techniques.

2.1.1. Cellulose decomposition

The mechanism of cellulose decomposition is recognized by lowering the degree of polymerization, which results in two reactions: (i) slow pyrolysis, which results in cellulose decomposition over a longer residence time and lowers the heating rate, and (ii) fast pyrolysis, which results in rapid volatilization and the formation of levoglucosan (Kaur et al., 2018). Along with the solid biochar, levoglucosan is dehydrated to create hydroxymethyl furfural that could break down into a liquid or gaseous product, for example, bio-oil and syngas. Additionally, the hydroxymethyl furfural can undergo numerous techniques, including aromatization, condensation, and polymerization, to regenerate solid biochar (Bhardwaj et al., 2019). According to (Kandanelli et al., 2018), in thermal analysis, the degradation of cellulose occurred quickly, with the weight loss of cellulose at 315–400 ℃.

2.1.2. Hemicellulose decomposition

Hemicellulose decomposes similarly to cellulose (Liu et al., 2018a). When hemicellulose is depolymerized, oligosaccharides are formed. This can arise via various methods, including decarboxylation, intramolecular rearrangement, depolymerization, and aromatization, resulting in the formation of biochar or the decomposition of the chemical into syngas and bio-oil (A. K. Singh and Chandra, 2019). According to (Waters et al., 2017), thermal studies have shown that hemicellulose, cellulose, and lignin decompose over different temperature ranges; generally, hemicellulose decomposes at a lower temperature range (220–315 ℃) than cellulose (315–400 ℃), while lignin decomposes over a broad range of temperatures (150–900 ℃).

2.1.3. Lignin decomposition

As stated above, the decomposition temperature range was observed to be 150–900 ℃ for lignin (Shahbaz et al., 2020). Compared to cellulose and hemicellulose, the breakdown of lignin is a complicated and complex phenomenon. Its long decomposition temperature range can evidence compared to hemicellulose and cellulose that undergo decomposition quickly (Albadarin et al., 2017). The β-O-4 lignin connection breaks, releasing free radicals. These free radicals absorb protons from other molecules, forming degraded substances. The free radicals interact with other molecules, thereby spreading the chain (Zhang et al., 2020b).

2.2. Hydrothermal carbonization (HTC)

HTC is an economic practice of developing biochar since it may be conducted at temperatures ranging from 180 to 250 ℃ (Gale et al., 2021). Hydrochar is the term used to refer to the product created by the hydrothermal process to distinguish it from the effect produced by dry methods such as pyrolysis and gasification (Liu et al., 2020). The biomass is dissolved in water and deposited in a closed reactor during the process. To maintain stability, the temperature is gradually increased (Brown et al., 2020). At various temperatures, the following products are generated: HTC produces biochar at temperatures <250 ℃, hydrothermal liquefaction produces bio-oil within 250–400 ℃, and hydrothermal gasification produces synthesis gas like carbon monoxide, carbon dioxide, methane, methylene at temperatures >400 ℃ (Wei et al., 2019). The process depicted in Fig. 3 is hydrothermal carbonization. The hydrolyzed product undergoes several dehydration, fragmentation, and isomerization methods to provide the intermediates 5-hydroxymethylfurfural and its constituents (Liu et al., 2018a).
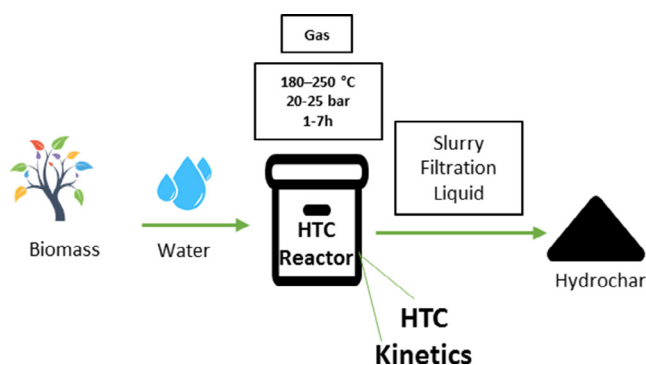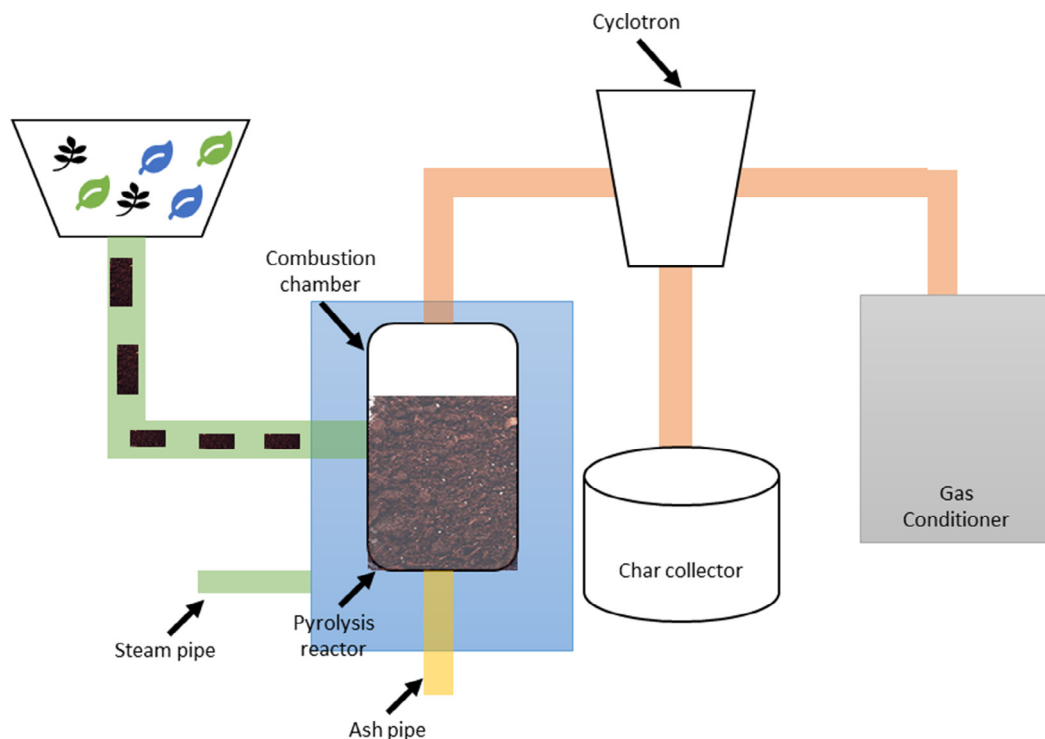
Fig. 4. Gasification process.
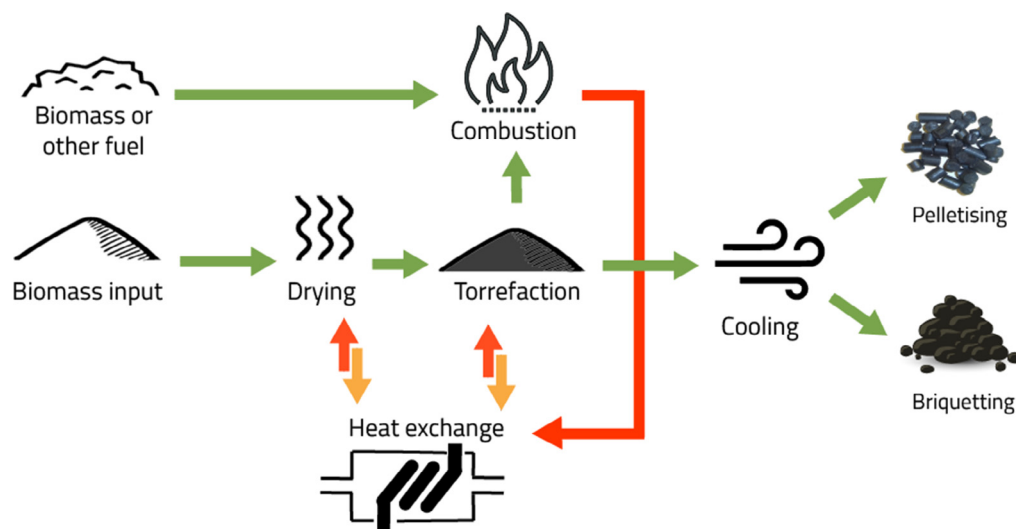
Fig. 5. Torrefaction Basics.

The reaction produces hydrochar via condensation, polymerization, and intramolecular dehydration (Chu et al., 2018). Due to lignin's high molecular weight and complex structure, the mechanism is complicated. The lignin degradation begins with a dealkylation and hydrolysis reaction that produces phenolic compounds such as phenols, catechols, and syringols (Yaashikaa et al., 2020). Eventually, char is synthesized by depolymerizing and cross-linking intermediates. Parallel to pyrolysis, the lignin components that are undissolved in the liquid phase are converted to hydrochar.

2.3. Gasification

Gasification is a thermochemical process that converts carbonaceous material into gaseous products, namely syngas composed of CO, CO_2, CH_4, H_2, and traces of hydrocarbons, in the presence of gasification agents like oxygen, air, or steam (You et al., 2017). It is emphasized that an essential element affecting the formation of syngas is the reaction temperature. Carbon monoxide and hydrogen production increased as temperature increased, whereas other components such as methane, carbon dioxide, and hydrocarbons declined (Ge et al., 2021; Sakhiya et al., 2020). The direct result of this process is syngas, whereas the char is considered a product with a lower yield (Zuber et al., 2019). Fig. 4 demonstrates the gasification process. The gasification process can be broken down into numerous steps as follows:

Drying: Without energy recovery, the moisture content of the biowaste is entirely lost during drying. The moisture content of various biomass materials varies. Drying is performed separately from the gasification process (Zhang, 2019).

Oxidation/Combustion: The primary energy source for the gasification process is the oxidation/combustion activities of the gasification agents. These gasification agents interact with the gasifier's combustible molecules to create CO_2, CO, and water (Korpe and Rao, 2021).

2.4. Torrefaction and flash carbonization

Torrefaction is a relatively recent technology for producing charcoal. It uses a slow heating rate; hence it is considered as intermediate pyrolysis (Waters et al., 2017). Torrefaction is a type of inadequate pyrolysis that arises when the temperature is between 200 and 300 ° C, residence duration < 30 min, a heating rate < 50 °C/min, and no oxygen (Hassan et al., 2020). The operation of the dry torrefaction is separated into several parts, including heating, drying, torrefaction, and cooling. Once again, drying could be categorized into two phases: pre-drying and post-drying (Ge et al., 2021). According to (Dhyani and Bhaskar, 2018; Machrouhi et al., 2019), the oxygen, moisture, and carbon dioxide in the feedstock were eliminated by inert ambient air in the oxygen-free environment at a temperature of 300 °C by a multiplicity of breakdown processes. Torrefaction modifies the properties of biomass, including the size of the particles, moisture content, surface area, heating time, and energy density. The torrefaction operation is illustrated in Fig. 5. Torrefaction is a process that can be conducted; (i) steam torrefaction: Steam is used to treat the biomass in this process, with a maximum temperature of 260 °C and a residence period of around 10 min (Drahansky and Paridah, 2019). (ii) Wet torrefaction, also known as HTC, occurs when biomass is in contact with water at a temperature of 180–260 °C for 5–240 min (Hamzah et al., 2019). (iii) Oxidative torrefaction: This process utilizes oxidizing agents like gases used in the burning process to generate heat energy (Enaime et al., 2020; Yaashikaa et al., 2020). This thermal energy is utilized to raise the temperature to the desired level.

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3. Factors affecting biochar properties

The parameters of the reaction through the pyrolytic are essentially involved in the formation of biochar. The properties of biochar are essentially determined by the feedstocks, the temperature, the particle size, and the heating rate. These elements directly affect the quality of biochar (Ao et al., 2018). Meanwhile, the yield of biochar is influenced by the type and conditions of pyrolysis. A thorough understanding of biochar property analysis is critical for selecting biochar usage. Various biomass sources, including natural, agricultural residues, wood, solid waste, etc, can produce biochar (Senthil and Lee, 2021). Biochar is produced in greater quantities from solid and animal waste than other material resources, including wood biomass, crop residues, etc.

3.1. Feedstocks

Biomass is a multi-component solid made up of biological, organic, or inorganic substances originated from living or non-living organisms (Zafar, 2019). Woody and non-woody biomass are the two forms of biomass. The term "woody biomass" refers to tree and forestry residues (Leng et al., 2021; Yang et al., 2016). Wood biomass has a low moisture content, a low detritus content, a low voltage, a high density, and a high calorific value (Danish and Ahmad, 2018). Non-woody biomass includes animal manure, agricultural and industrial biowastes.

Non-woody biomass has high debris, moisture, high voltage, low density, and poor calorific value (Tomczyk et al., 2020). Moisture content is one of the many features of biomass resources that substantially impact biomass productivity. Moisture in biomass can take on various states, such as liquid water, water vapor, and humidity adsorbed inside the pores of the biomass. Excessive moisture content in biomass significantly reduces char production and boosts the energy needed to reach the pyrolysis temperature (Nidheesh et al., 2021; Oliveira et al., 2017). Low moisture content biomass is advantageous for biochar production. The dramatic reduction in heat energy and time during the pyrolytic makes biochar production commercially feasible compared to high moisture content feedstock.

3.2. Temperature

As mentioned in the previous section, pyrolysis is a very well technique for transforming biomass to biochar via a thermochemical decomposition process in an oxygen-depleted ambient at elevated temperatures. The temperature at which biochar is pyrolyzed influences its physicochemical qualities and structure, including its elemental composition, pore structure, surface area, and functional groups (Jawad et al., 2019). The impact of pyrolysis temperature on these products results from the influx of volatiles at elevated temperatures. The removal of various elements (carbon, hydrogen, and oxygen) through gases and volatiles results in a decrease in the O/C and H/C atomic ratios and a corresponding increase in aromaticity and carbon content, which improves the stability of the biochar (Han et al., 2018). This tendency becomes more pronounced as the temperature of pyrolysis rises. Increased pyrolysis temperature (> 500 °C) results in increased hydrophobicity, surface area, and micropore volume (Sakhiya et al., 2020), all of which render the resulting biochar extremely amenable to organic pollutant removal. However, a lower pyrolysis temperature (< 500 °C) resulted in biochar with smaller pore size, a smaller surface area, and more oxygen-containing functional groups (Senthil and Lee, 2021) more suitable for the removal of inorganic contaminants. Increased pyrolysis temperature also results in a rise in the pH of biochar due to the addition of ash (Leng et al., 2021; Oliveira et al., 2017).

3.3. Residence time

Extending the residence period at a low pyrolysis temperature (300 °C) resulted in a gradual reduction in biochar productivity and increased biochar pH and iodine adsorption. Nevertheless, increasing residence period at a higher pyrolysis temperature (600 °C) have a more negligible impact on biochar production or pH, while decreasing biochar iodine sorption capacity (Manyà et al., 2020; Zhou et al., 2020).

3.4. Pre-treatment

Pre-treatment of material prior to pyrolysis affects the characteristics of biochar. Pre-treatment is the initial stage in producing biochar from a variety of source materials. Generally, these pre-treatment approaches can be physical, chemical, or biological (Xiang et al., 2020). The most often used pre-treatment procedures include immersing simple ingredients insolvent and lowering biomass particle size. The reduction in the size of the biomass particles results in the high production of biochar (Yaashikaa et al., 2020). For example, pine wood biomass was pre-treated by immersing it in a dilute acidic solution (Yaashikaa et al., 2020). Nitrogen and metal doping can affect the development and stabilization of biochar. Pre-treatments like immersing or steaming may affect biochar's elemental constitution and characteristics (Li et al., 2020). Corrosive chemicals such as acid, alkali, and oxidant have also been used to pre-treat biomass to generate engineered biochar with higher surface area, unique pore structure,

enriched surface functional groups, etc. (Yang et al., 2019). The feedstock's inherent properties determine the physical pre-treatment of biomass feedstock. For instance, dewatered sludge is frequently dried overnight in an oven, crushed, sieved, and kept in sealed containers prior to use in accordance to control the moisture contents (Wang et al., 2017). In bacterial treatment, particularly anaerobic digestion or biofuel processes, biomass feedstock has been proven to be an effective and biologically activated' biochar with enhanced properties (Gopinath et al., 2021). Pre-treatment with anaerobic digestion would result in biochar with a higher specific surface area and improved adsorption ability (Chu et al., 2018). Pre-treatments vary depending on feedstock and biochar use, including physical, chemical, and biological methods. Meanwhile, biochar is post-treated by either physical or chemical modification methods to increase its specific surface area, pore-volume, surface chemistry, and functional agents, including surface functional group and composited nanoparticles (Yang et al., 2019). However, in current technologies, post-treatment techniques including magnetic, ball milling, and corrosive provided comprehensive technologies for biochar treatment (Li et al., 2020).

4. Biochar properties and characterization

4.1. Properties of biochar

4.1.1. Functional groups

Carboxylic (COOH), hydroxyl (OH), amine, amide, and lactonic groups are all vital functional groups on the biochar surface that contribute to its adsorption capacity (Yaashikaa et al., 2020). Biochar's surface functional groups are controlled mainly by biomass and temperature (Rashid et al., 2019). Moreover, as other qualities like pH, surface area, and porosity are increased, the functional groups in biochar might be reduced. Biochar properties can also be affected by feedstock pre-treatments and biochar post-treatments (Xiang et al., 2020).

4.1.2. Surface area and porosity

Generally, biochar with a high surface area and porosity will have a higher adsorption capacity. Biochar develops a porous surface during the pyrolysis process due to increased water loss during the dehydration process (Sigmund et al., 2017). As stated by the International Union of Pure and Applied Chemistry, categorized the pores in biochar as micropores (<2 nm), mesopores (2–50 nm), or macropores (>50 nm) (W. Chen et al., 2018; Samsami et al., 2020). Biochar with a smaller pore size is incapable of adsorbing pesticide molecules regardless of their polarity or charge. SEM images of biochars indicated that diverse processes and temperatures resulted in significant modifications to the surface morphology of the initial particles; they retained the visible shape to a large extent (Papurello et al., 2019). Likewise, the expansion of pores in biochar experiments with increasing temperature may excessively increase the pore characteristics of biochar. Additionally, it is probable that as the temperature of pyrolysis increases, the crystallinity of mineral segments increases, resulting in the formation of highly desirable sweet-smelling structures in biochar (Singh et al., 2021).

The surface area of the biochar is a vital parameter since its sorption and ion exchange properties are directly related to its surface area (Leng et al., 2021), and bulk is responsible for contaminant reduction from the soil and aquatic ecosystem (Sigmund et al., 2017). The exposed surface area is measured in two distinct ways, depending on the size and accessibility of pores; internal and external surface area. The outer surface area includes all prominences, larger cracks, and pores (mesopores and macropores). In comparison, the inner surface area has only the walls of more profound and less open cracks and cavities (micropores) (Senthil and Lee, 2021). Since mesopores and macropores contribute very little to the total porous structure of biochar, especially in terms of adsorption ability (they serve as conduits for adsorbate to reach the micropores), the internal surface area is prominently recorded.

When raw samples are compared to their biochar alternatives, a considerable rise in the BET surface zone is observed following pyrolysis. The natural biomasses lacked physical micropores, but the char was generated with new micropores during pyrolysis. Porosity results for both biomass types, comprising BET surface territory and micropore region, increased with power level improved from 2100 to 2400 W, as indicated by a rapid rate of residual unstable discharge and enlarged development of micropores at increased heating rates (Khan et al., 2018; Xiao et al., 2018). Due to the emission of many
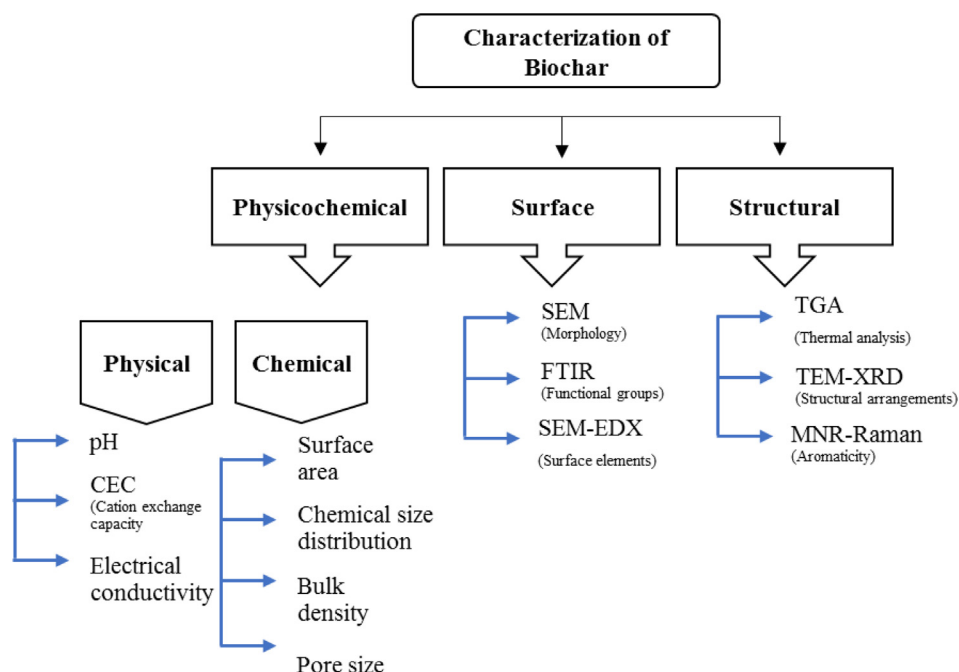

Fig. 6. Physicochemical, surface, and structural biochar characterization.

volatile materials, biochar develops a high porosity with various pore structures and a low density.

The surface area of natural resources that have been treated and those that have not been treated may differ (Banna et al., 2019). Commercially available activated biochar has a greater surface area. Without activation, biochar has a limited surface area and is less porous (Esteves et al., 2020). Thus, activation is used during the biochar synthesis process to enhance the porosity and surface area of the biochar. The treatment process may entail both physical and chemical activation.

4.2. Characterization of biochar

Biochar characterization is performed to determine the ability to remove pollutants or other applications. The structural and elemental assessment also assists in anticipating the ecological impact of biochar (Li et al., 2016). Furthermore, the metals interact with biochar which is a function of pH like (i) the function of biochar differs with pH (ii) metal contaminant ion speciation varies with pH. These properties of biochar demonstrated its efficacy to operate as a very effective biosorbent to remove the bulk of soil contaminants (Ahmed et al., 2016). The biochar characterization techniques are based on the structure, surface functional groups, and elemental analysis (Gopinath et al., 2021; Leng et al., 2021). Different technological characterization methods, which include SEM, FTIR, XRD, NMR, BET, thermogravimetric analysis (TGA) (Singh et al., 2021), proximate and ultimate analysis, and Raman spectroscopy (Shukla et al., 2020), by described in Fig. 6.

4.2.1. Fourier-transform infrared spectroscopy (FTIR)

FTIR technology is a vibrational technology employed to analyze the functional groups present on the surface of biochar (Chen et al., 2019a). At various temperatures, the surface functional groups of biochars varied dramatically. As increasing the temperature, substantial improvements occur in the composition and auxiliary arrangements of biochar. These advancements might be examined using a nondestructive FTIR instrument (Yaashikaa et al., 2020). The spectra revealed a constant loss of aromatic groups at 650–800 °C (Singh et al., 2021). The sample is modified to pellet form for DRIFTS (Diffuse reflectance infrared Fourier transform spectroscopy) by employing potassium bromide (KBr). The pellet sample is brought into contact with an ATR crystal, and the functional groups are identified using ATR-FTIR (Stawinski et al., 2013). In addition to FTIR, NMR can determine the surface functional groups in biochar (Rehman et al., 2019).

4.2.2. Scanning electron microscopy (SEM)

The surface structures of biochar were characterized utilizing SEM (Waqas et al., 2018; Yin et al., 2018). SEM can be utilized to quantify the pore size of biochar, and biochar's surface area can be determined via BET analysis. SEM images provide a complete description of the microporous and mesoporous distributions and pore configurations found in biochar. SEM may be used to anticipate the surface morphology before and after the adsorption. SEM and EDX are used to examine the composition of biochar (Sun et al., 2021). SEM-EDX analysis can be used to determine the various components present on the surface of biochar. SEM-EDX has been utilized in many investigations on biochar applications to characterize the surface of the biochar once it has adsorbed pollutants. The limitation is that SEM-EDX is incompatible with organic pollutants (Burk, 2017; Jawad et al., 2019).

4.2.3. X-ray diffraction (XRD)

The technique of XRD is extensively applicable for determining the crystallinity and structure of biochar (Singh et al., 2021). In XRD, the diffractogram has indicated particular attributes of nebulous material created over 350 °C and is reliable (Zoroufchi et al., 2020). A computerized XRD system is comprised of a monochromator, a radiation source, and a stepping motor. The nanocrystals generated have a crystalline structure that is similar to the sharp and robust XRD peaks. The diameter of the particles increases as time passes (Hajialigol and Masoum, 2019; Kazemi et al., 2020). Thus, XRD patterns allow for the rapid and non-destructive development of high-quality biochar with a substantial sorption capacity.

4.2.4. Thermal analysis

The thermal analysis used TGA to determine materials' physiochemical properties due to temperature rise (Chen et al., 2019b; Jean et al., 2019). TGA has frequently been used to depict and examine the heat behavior of countless examples. The purpose of this experiment was to identify the ignitibility of biochar and biomass/biochar mixtures using thermogravimetric analysis (Labiadh and Kamali, 2020). Further, the expected weighted average of each component was analyzed to determine whether the synergic activity occurred between the blends' segments. The results may support a complete understanding of the heating process and instance features from a macro perspective and testing analysis (Santoso et al., 2020). The heating of charcoal commences at room temperature and is escalated to 1000 °C during this process. Other researchers have reported employing temperatures ranging between 10 and 20 °C/min, 10 K/min, and less than 1000 °C (Hamzah et al., 2019).

4.2.5. Nuclear magnetic resonance spectroscopy (NMR)

NMR spectroscopy can be used to determine the structural composition of biochar (Yaashikaa et al., 2020). Nuclear magnetic resonance spectroscopy (NMR) involves an attracting solid field and radio frequency (RF) pulses to study the structure of particles by examining the reverberation frequencies of centers within the atom. Solid-state methods can be used to determine the total quantity of carbon functional groups in biochars, the estimated level of aromatic ring formation, and the overall structure of char molecules (Sun et al., 2021). NMR spectroscopy can be used to determine the aliphatic and aromatic hydrocarbon composition. NMR can be used to compare the stability and carbonization of various biochars (Goldberga et al., 2018). The primary disadvantage of employing NMR spectroscopy is that the existence of ferromagnetic minerals in biochar might interfere with the NMR signals, and biochar formed via high-temperature pyrolysis has a low signal-to-noise ratio (Chiappero et al., 2020).

4.3. Biochar stability

The stability or resistance of biochar to biotic and abiotic soil degradation has been used to evaluate its capacity for carbon sequestration (Jones et al., 2018). Various research has been conducted to determine the stability of biochar. The temperature employed in the pyrolysis process is utilized to assess the stability of biochar (Yoo et al., 2018). Methods for determining the stability of biochar can be classified into three categories: (a) direct or indirect qualification or quantification of biochar C structures such as aromaticity; (b) quantitative or qualitative qualification of stable C via thermal, chemical, or thermochemical methods mainly chemical oxidation, thermal degradation, etc.; and (c) incubating biochar in soil and modeling C mineralization (Leng et al., 2019). The last technique, Incubation, and modeling are biological techniques for assessing the stability of biochar and serve as a basis for the first two strategies. The results produced using the first two procedures are comparable to indirect stability values obtained using the incubation and modeling methods (Hristov et al., 2019). The presence of a C structure composed of crystalline and amorphous phases is a well-defined characteristic of biochar. The stability of biochar can be determined by examining the carbon content of biochar or stable carbon structures.

Consequently, the C structure is the decisive factor in determining the stability of biochar. Aromatic condensation and aromaticity are the primary indications of biochar C structure (Leng et al., 2019). Biochars with a high degree of aromatic condensation and aromaticity exhibit
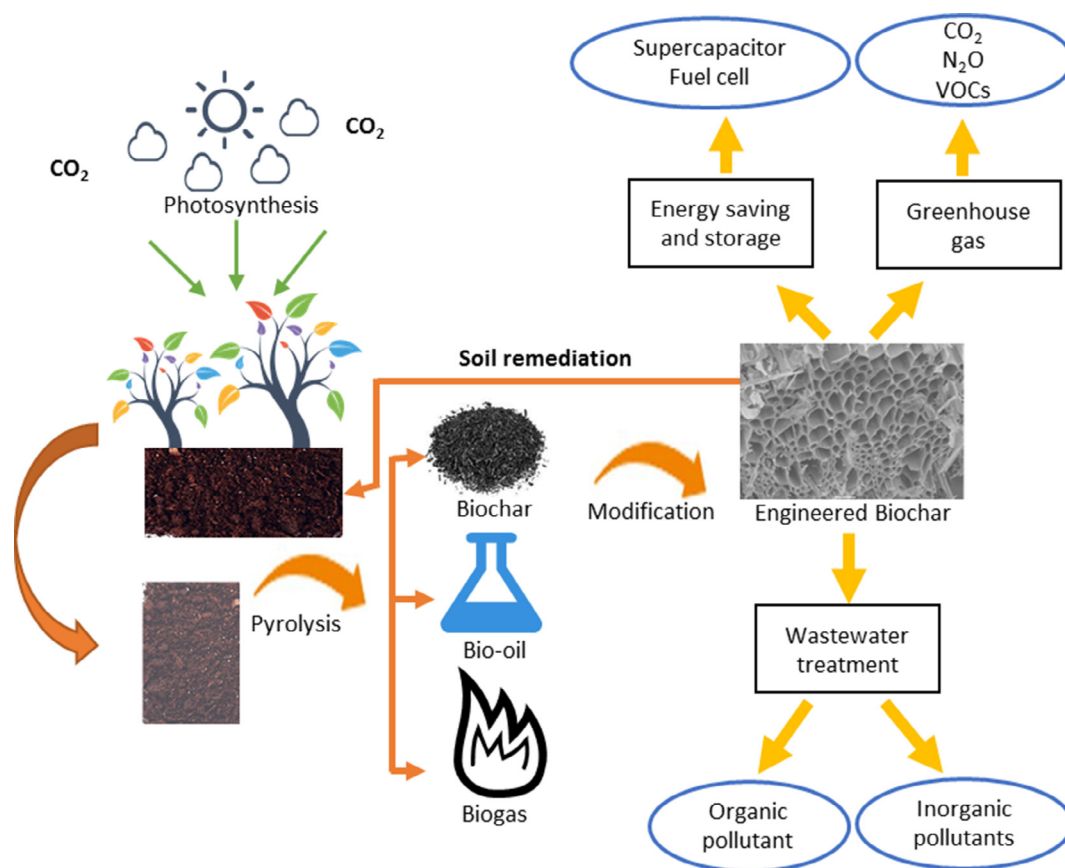
Fig. 7. Biochar development for environmental sustainability.

Table 2
The benefits and drawbacks of various biochar applications.

Applications	Aim	Benefits	Drawbacks	Reference
Catalyst	Assist in the catalysis of direct reactions.	Easily available, reusability/recyclability (can be used several times), highly efficient, no toxicity and environmentally friendly nature	Costly, reduce the efficiency.	(Enaime et al., 2020; Mishra et al., 2021; Talaiekhozani et al., 2021)
Energy storage	Utilization of materials as electrode materials.	Price-effective, stable, reusability, long-term effects, highly efficient	Poor performance.	(Bolan et al., 2021; Senthil and Lee, 2021; Thomas et al., 2019)
Soil amendment	Increasing the fertility and quality of soils, as well as carbon sequestration.	Low cost, reduces GHG emissions, aids in the retention of nutrients and water, and regulates nutrient loss.	Heavy metal and polyaromatic hydrocarbon contamination remain.	(El-naggar et al., 2019; Irfan, 2017)
Adsorbents	Organic and inorganic contaminants are removed from the soil and aquatic systems.	The min. cost and increased oxygen groups in biochar improve in the adsorption of contaminants.	Pollutant removal effectiveness is limited.	(Hassan and Carr, 2021; Talaiekhozani et al., 2021)
Composting	Enhancing the microbial population's structure and carbon mineralization.	Porous, which reduces GHG, has a large surface area and retains nutrients.	There is a possibility that heavy metals and other toxins will infiltrate the soil.	(Diacono et al., 2019; Kandanelli et al., 2018)

resistance to thermochemical and biological degradation, conferring on them a high degree of stability. Biochar's fundamental structure reflects C–C bonds or aromaticity (Iisa et al., 2019). Biochar stability is further influenced by the pore structure, pH, minerals, sorption process, surface area, and particle size of the biochar (Han et al., 2020). Due to the direct and reliable results acquired via incubation and modeling, the evaluation of biochar stability is regarded as a critical class. This method produces values for longevity that persist after incubation. These numbers are derived via data modeling. The optimal biochar stability can be determined by incubating the biochar in the soil until complete degradation occurs and then determining the degradation time (Alkharabsheh et al., 2021). Because biochar

degrades over centuries, calculating its longevity is impossible. However, this process of incubation and modeling is costly and time-intensive (Han et al., 2020).

5. Biochar and environment

While biochar could be used for various applications, its impact on the environment must be thoroughly investigated to minimize unwanted consequences. Prior to application, the primary factor that must be considered is stability (Han et al., 2020; Leng et al., 2019). Biochar forms the carbon structure. Thus, biochar stability is related to the strength of the carbon structure (Tang et al., 2019). The aro-

Table 3
Removal of organic contaminations from water and wastewater.

Adsorbates	Initial concentration (mg/L)	Adsorbents	Pyrolysis temperature (°C)	Applied dose (g/L)	Removal efficiency (%)	Reference
Microcystin-LR	0.2	Chicken manure	600	0.15	100	(Gwenzi et al., 2017)
Tetracycline	200	Sewage sludge	800	1	26–60	(Malaysian Sewage Industry, 2016)
Norfloxacin	10	Corn stalks	500	4	97.62	(Mbarki et al., 2019)
Sulfamethoxazole	20.3	Pinus radiata sawdust	650	2	100	(Wang and Wang, 2019)
Methylene blue	50	Mangosteen peel	800	3	80	(Machrouhi et al., 2019) (Nyoo et al., 2021)
Ibuprofen	2	Cool Planet LLC Organic	550	1	<6	(Gwenzi et al., 2017)
Sulfamethoxazole	64	Farms LLC	500	1.25	<10	(Danish and Ahmad, 2018)
Bisphenol A		Corncob			n.a.	
salicylic acid	500	Waste Douglas fir	900–1000	0.4	100	(Burk, 2017)
4-nitroaniline benzoic acid		Corn straw				(Kameyama et al., 2019; J. Wang and Wang, 2019)
Atrazine	30		500	4	100	
Sulfamethoxazole	1	Wood	850	40 mg/L	20–30	(Zhu et al., 2018)
Polychlorinated biphenyls	1	Corn straw	700	50 mg/L	n.a.	(Kameyama et al., 2019)
Sulfamethazine	50	Sicyos angulatus	700	1	46–95	(Feng et al., 2021)
Tetracycline	5	Rice-husk	500	0.4	~90	(Wang et al., 2018)
Trichloroethylene	20	Buffalo-weed	700	1.2	88.47	(Wang and Wang, 2019)
Gatifloxacin	100	Sludge	550	5	>9	(Malaysian Sewage Industry, 2016)
Trichloroethylene	20	Soybean stover Peanut	700	0.3	~55	(Thomas et al., 2019)
Tetracycline	1000	shell	500	5	~55	(Wu et al., 2019)
		Rice husk			n.a.	
Methyl violet	816.06	Canola straw	350	8	n.a.	(Gwenzi et al., 2017)
Phenanthrene	1	Soybean Stalk	700	0.33	99.5	(Liu et al., 2020)

maticity and aromatic condensation of biochar are the primary indicators of its carbon structure. Biochar's dissolved organic matter retains a high level of aromaticity, resilience, and stability. As biochar is used to treat industrial effluents, the carbon content of the water increases because of the substances released by the biochar, biochar generated from heavy metal-containing sludge might accumulate through the treatment system, resulting in heavy metal contamination (Mahmoud et al., n.d; Godwin et al., 2019).

Consequently, once biochar is applied as a catalyst, its stability steadily decreases over repeated use. Biochar's instability could potentially be a result of structural deterioration. As a result, biochar's stability is critical in terms of environmental concerns. Additionally, prior to application, the toxicity of biochar to terrestrial organisms should be determined (Rajasulochana and Preethy, 2016). Since biochar's physical and chemical properties change based on biomass, it is critical to investigate its hazardous impacts on the surroundings thoroughly. Bacteria could conduct various toxicity tests, algae, or fish (Jesudoss et al., 2020; Reza et al., 2020). As a critical breakthrough, biochar has been extensively applied to agricultural soils to help mitigate global environmental issues and synthesized through the thermochemical breakdown of natural build-ups in an oxygen-limited environment (Aziz et al., 2020). The growth of biochar was documented to modify the soil permeability, moisture content, pH, and labile C and N pool sizes, affecting soil CO_2 emissions significantly (Diacono et al., 2019). Biochar modifications to the agricultural ground may act as a viable instrument for mitigating environmental change, with fewer CO_2 emissions and increased dry issue output (Tomczyk et al., 2020).

6. Applications of biochar

Biochar is a hot topic of research regarding its eco-friendliness, abundant resources, readily available materials, and simpler production from diverse biomass employing thermochemical processes for addressing a wide variety of environmental applications (Waqas et al., 2018). Biochar plays an important role in removing contaminants and pollutants from wastewater and that's depend on the type of biomass and pyrolysis temperature (Ahmed et al., 2016; Devi and

Saroha, 2016). Because of its enhanced attributes like porosity, surface area, pH, low dissolved carbon content, and hydrophobic nature, carbon-rich biochar synthesized at high pyrolysis temperatures has a higher removal rate of organic contaminants (Bolan et al., 2021). Similarly, biochar formed at a lower temperature has oxygen-containing functional groups, a high concentration of dissolved organic carbon, and is less porous, allowing it to eliminate inorganic contaminants (Weerasundara et al., 2021). Other parameters, such as pH and residence period, also influence biochar's absorption rate (Gale et al., 2021). Biochar has an enormous potential in addressing these global issues and can act as a catalyst in achieving sustainable development goals (SDGs) for environmental sustainability (Fig. 7). Additionally, biochar can be utilized as a catalyst, wastewater treatment, composting agent, energy source, carbon sequestration, and soil amendment. Table 2 summarises the benefits and drawbacks of various biochar applications.

6.1. Water and wastewater decontamination

Recent surveys have reported that biochar may adsorb contaminants from water and wastewater by adsorption, including organic and inorganic pollutants (Grobelak et al., 2019). Antibiotics have evolved into a pervasive organic contaminant in the environment (Chen et al., 2019a; Liu et al., 2018b; Wang and Wang, 2019). It was established that biochar generated from sludge was an economic and recyclable adsorbent for antibacterial drug removal (Saha and Basak, 2020).

Table 3 summarised the decontamination of suspended contaminants from water by biochar via sorption. The ability of biochar to adsorb pollutants in water is based on the bioactive components of the contaminants and the type of biochar used. For instance, sawdust-derived biochar may eliminate 20.3 mg/L of sulfamethoxazole by applying 20 mg/L adsorbent dose (Vijayaraghavan and Won, 2009), whereas wood-derived biochar had a substantially lower sulfamethoxazole removal efficiency (20–30%) at room temperature (Shimabuku et al., 2016). Biochar obtained from natural farms had the most deficient sulfamethoxazole sorption capacity (<6%) (Liu

Table 4

Removal of metals and metalloids from water and wastewater.

Adsorbates	Initial concentration	Adsorbents	Pyrolysis temperature	Applied dose (g/L)	Removal efficiency (%)	Reference
Cu^{2+}	1 mM	Corn straws	800	1	97	(Kazemi et al., 2020)
Cd^{2+}	1 mM				88.1	
Cd^{2+}	20 mg/L	Rape straw	600	1.25	100	(Yaashikaa, Kumar, Varjani, and Saravanan, 2019)
Pb^{2+}	150 mg/L	Sawdust and swine manure	400	0.4	100	(Tomczyk et al., 2020)
Cd^{2+}	50 mg/L				83	
Cd^{2+}	50 mg/L	Mangosteen peel	800	3	80	(Machrouhi et al., 2019) (Nyoo et al., 2021)
Cd^{2+}	20 mg/L	Corn straw	400	20	99.24	(Mbarki et al., 2019)
Pb^{2+}	20 mg/L				98.62	
Pb^{2+}	400 mg/L	Celery	500	5	97.7	(Dawood et al., 2017)
Cd^{2+}	0.04 mg/L	Scots pine Silver birch Scots pine	450	140	~23	(Khanh et al., 2021)
Cu^{2+}	0.5 mg/L	Scots pine			~25	(Jaya and Amir, 2015)
Zn^{2+}	0.4 mg/L	Water hyacinths			~20	
Pb^{2+}	0.1 mg/L		600	2	~22	
$Cd2þ$	100 mg/L				~60	
Pb^{2+}	100 mg/L	Sugar cane bagasse			100	(Bhardwaj et al., 2019)
Pb^{2+}	6e233 mg/L	Orange peel	~500	1	~80	
					30–40	
Cu^{2+}	10 mg/L	Macroalga	500	0.1	~80	(Matthews et al., 2019)
$Cr6^{+}$	200 mg/L	Peanut hull	450–650	2	10–70	(Wu et al., 2019)
Cd^{2+}	100 mg/L	Wheat straw	650–700	0.2 g	100	(Zhou et al., 2020)
Cu^{2+}	100 mg/L				100	
Zn^{2+}	100 mg/L				100	
As^{5+}	50 mg/L	Pinewood	600	2.5	~35	(Zoroufchi et al., 2020)
As^{5+}	0.09 mg/L	Sewage sludge	300	4	53	(Malaysian Sewage Industry, 2016)
Cd^{2+}	30 mg/L	Hickory wood	600	2	95.9	(Ahmed et al., 2020)
Cu^{2+}	30 mg/L				93.2	
Pb^{2+}	100 mg/L				98.5	
As^{5+}	50 mg/L	Pinewood	600	2.5	~35	(Zoroufchi et al., 2020)
Cr^{6+}	0.16 mg/L	Rice husk			89	(Wang et al., 2018)
Cr^{6+}	100 mg/L		450e500	1	~100	
Cu^{2+}	5 mM	Dairy manure	350	5	62.4	(Wang and Wang, 2019)
Zn^{2+}	5 mM				49.4	
Cd^{2+}	5 mM				51.1	
Cu^{2+}	50 mg/L	Spartina alterniflora	400	10	100	
Pb^{2+}	0.1 mM	Anaerobic digested sludge	600	2	99	(Gopinath et al., 2021)
Cu^{2+}	0.1 mM				98	
Ni^{2+}	0.1 mM				26	
Cd^{2+}	0.1 mM				57	
Cu^{2+}	1 mM	Hardwood	450	1	6.2	(Zhu et al., 2018)
Cu^{2+}	1 mM	Corn straw	600	10	95	(Kazemi et al., 2020)
Zn^{2+}	1 mM				90	

et al., 2018a; Ma et al., 2018). For biochar generated from rice husk, varying the pyrolysis temperature resulted in changing tetracycline removal efficiencies. When pyrolysis was carried out at 800 °C, and the initial concentration of tetracycline was 200 mg/L, the sorption capacity of tetracycline was around 26–60% (Ren et al., 2018). While other research conducted by (Xiao et al., 2018), the removal efficiency was almost 90% when the pyrolysis temperature was 500 °C, and the starting tetracycline concentration was 5 mg/L.

Therefore, it is established that pyrolysis temperature substantially impacts biochar's adsorption capability. Along with pyrolysis temperature, additional variables like the pyrolysis time can influence the physicochemical characteristics of biochar, hence affecting its adsorption capability.

Heavy metal pollution is a significant ecological hazard that requires immediate attention (Haziq et al., 2020). Adsorption is a highly effective method for heavy metal removal from aquatic environments (Wang et al., 2018). The elimination of heavy metal ions by biochar is detailed in Table 4. As with organic contaminants, the removal of toxic substances by biochar relies on the type of heavy metal and adsorbent used. Biochar has a more insufficient removal capability for Cd^{2+} and As^{5+} than other heavy metals like Pb^{2+} and Zn^{2+}.

The temperature at which biochar was pyrolyzed had a significant effect on its adsorption capability (Lember et al., 2019). For example, corn straw-derived biochar exhibited a variable ability for adsorption of Cu^{2+}. At an 800 °C pyrolysis temperature, 1 g/L biochar was needed to eliminate 1 mM Cu^{2+}. 20 g/L of biochar was required to remove 20 mg/L Cu^{2+} at 400 °C of pyrolysis temperature (Carolin et al., 2017). The biochar produced from water hyacinths demonstrated a different remove capacity for Cd^{2+} and Pb^{2+}, demonstrating that the removal rate of biochar differed according to the heavy metals targeted (Liu et al., 2020). It should be highlighted that the functional groups certainly influenced the adsorption energy of the functional group-modified biochar. For instance, the amino-modified biochar improved the Cu(II) adsorption through robust complexation (Leng et al., 2021; Zhang et al., 2020b). (Wang and Wang, 2019) discovered that biochar prepared at high temperatures was effective at removing Cr (VI).

Along with heavy and organic metals, a systematic review concluded that sludge-derived biochar is capable of completely removing ammonium via monolayer chemisorption's (Tang et al., 2019), signifying that highly competitive biosorption existed when biochar was used as an adsorbent for heavy metals and organic contaminations removal in the existence of ammonium.

Table 5
Comparative analysis of biochar-based and non-biochar-based catalysts.

Catalyst	Tar compound	Reaction condition	Tar removal efficiency (%)	Reference
Pine-bark biochar	Toluene	900 °C; H_2O	94	(Sakhiya et al., 2020)
Fe/pine-bark biochar	Toluene	800 °C; H_2O	100	(Sakhiya et al., 2020)
Switchgrass biochar	Toluene	800 °C	84	(Alkurdi et al., 2019)
Commercial biochar	Phenol	900 °C; H_2O and CO_2	55	(Wang et al., 2018)
Dolomite	Phenol	700 °C; H_2O and CO_2	90	(You et al., 2017)
Pinewood biochar	Naphthalene	900 °C; H_2O and CO_2	94	(Zoroufchi et al., 2020)
Olivine	Naphthalene	900 °C; H_2O and CO_2	55	(You et al., 2017)

Besides adsorption, biochar can stimulate microbes, hence increasing the rate of organic waste removal. (Arrebola et al., 2020) discovered that the fraction of Archaea was significantly greater in the presence of fruitwood-derived biochar, which reduced ammonia and acid stress on microorganisms, hence enhancing microbial activity. (Oliveira et al., 2017) also discovered a similar phenomenon. Additionally, the inclusion of biochar improved the redox-active moieties' clearance of tetrabromobisphenol A and expedited the transformation of adsorbed tetrabromobisphenol A (Zhang et al., 2020a). It is highlighted that when biochar is used in environmental treatment, recycling and reuse should be considered. The magnetic modification of the biochar enables it to be recycled. The magnetic properties of corn stalk-derived biochar were significantly enhanced when added a mixture of $ZnCl_2$ and $FeCl_3$ (Nyamunda et al., 2019).

According to the interim analysis, biochar performed well in batch trials to remove specific contaminants. However, in practice, several pollutants cohabit in drinking water treatment. Competitive adsorption may develop, leading to findings that differ from those obtained in the laboratory. Further, actual flow conditions may influence biochar's ability to adsorb contaminants. As a result, additional research should be conducted in the laboratory to imitate real-world requirements and determine the efficacy of biochar in removing impurities.

6.2. Catalyst and catalyst support

Biochar can perform as a versatile catalyst in various uses, notably agriculture, ecology, and energy (He Zhang et al., 2018). Biochar's characteristics make it an attractive catalyst potential. The wide surface area is critical for biochar catalytic performance because it contains different functional groups (Liu et al., 2018b). For instance, the functional group O—H is responsible for norfloxacin sorption, while the functional groups C=O and OH—groups are ideal for ammonium adsorption.

More significantly, the activated and functionalized biochars can obtain large surface area and abundant surface functional groups, thus displaying remarkable roles as catalysts or catalyst supports for various chemical transformations and adsorption/sorption/enrichment of low-concentration pollutant streams. Along with the application of biochars as catalysts/catalyst supports in the degradation of organic pollutants, it can also be applied in biorefinery for the production of a range of value-added products (Mishra et al., 2021). As a catalyst, biochar has a wide range of applications, including biodiesel synthesis, energy generation, tar removal, waste management, biogas generation, electrodes in microbial fuel cells, chemical development, and contaminant removal (Adejumoke et al., 2018; Raud et al., 2019; Samer, 2015).

6.2.1. Energy production

During the biomass gasification process, the development of tar is undesirable because it contaminates and clogs downstream activities, reducing energy efficiency (Zhang, 2019). Catalytic tar transformation can turn tar into hydrogen and carbon monoxide. These two gases are critical syngas components (Zubair et al., 2021). The char formed from various biomasses, including maize and rice straw char, affects the tar

Table 6
Biochar as a soil contaminant remover.

Adsorbents	Adsorbates	Removal rate (mg g^{-1})/ Removal efficiency (%)	Reference
Rice straw	Al^{3+}	0.450	(Kołtowski et al., 2017)
	Cd^{2+}	6.34	
Sugar beet tailing	Cr^{3+}	123	(Rangabhashiyam and Balasubramanian, 2019)
Sludge	Pb^{2+}	30.88	(Chen et al., 2019a)
Hickory wood	Cu^{2+}	15.5	(Enaime et al., 2020)
	Pb^{2+}	17.8	
	Zn^{2+}	1.5	
	Ni^{2+}	0.8	
Poplar catkins	U^{6+}	71.85	(Sakhiya et al., 2020)
	Co^{2+}	10.17	
Rice straw	Pb^{2+}	100%	(Shokry et al., 2020)
	Cd^{2+}	97.1%	(Wang and Wang, 2019)
Sugar beet tailing	Cr	88.5%	(Chen et al., 2019b)
Sludge	Zn^{2+}	51.2%	(Yunus, 2017)
Hardwood	As	0%	(Rahman and Hasegawa, 2011)
Switchgrass	U	90%	(Li et al., 2020)

treatment process. Therefore, char variations affect the efficiency of tar removal. The efficiency of tar removal diminishes as the particle size of the char increases. This is because the surface area and active site affect the removal effectiveness (Cheng and Li, 2018). Biochar increases hydrogen production during the gasification/pyrolysis operation. The efficacy of biochar as catalysts for tar cracking is compared in Table 5, as is the removal efficiency of various tar components contained in syngas.

6.2.2. Waste management

Different biochemical compounds synthesized in the laboratory exhibit high resistance to microbial breakdown and are bio recalcitrant. These synthetic substances are carcinogenic to people, microorganisms, crops, and other organisms. Bio-recalcitrant chemicals can be destroyed using a prospective approach known as the catalytic ozonation process (COP) (De Gisi et al., 2016). Biochar generated from biomass with a porous structure and functional groups like phenolic and hydroxyl was used as an inexpensive catalyst in the COP to degrade a refractory organic molecule, reactive red 198 dye (Toczyłowska-Maminska, 2017).

6.2.3. Control of air pollutants

Biochar was already extensively studied as a relatively low-temperature selective catalytic reduction catalyst (Waqas et al., 2018). Researches on biomass such as sewage sludge and paddy hulls were conducted to create biochar and employ it as low-temperature catalysts in conjunction with ammonia as a solvent (Chen et al., 2018; Li et al., 2020). The char was activated physically or chemically, and the efficiency with which they were removed was determined.

Chemical activation was more effective at removing contaminants than physical activation. This revealed that chemical characteristics, including functional groups and adsorption sites, have a significant role in determining removal efficiency (Ichinohe, 2018; Mukhlisin, 2011). Sulphate and free radicals were supplied via charcoal catalysis. The surface of biochar is oxygen-explicit, containing catalytic activity complexes with varying reactions. Due to the biochar, the combination enhanced the catalyst's catalytic activity (Benkhaya et al., 2020; 2021).

6.3. Soil amendment

An inadequate mechanism for managing agricultural fields ended in higher CO_2 emissions and accelerated the decomposition of organic molecules in the soil. Numerous studies have increased soil conductivity by combining biomass from crops and animal dungs (Irfan, 2017; Yu et al., 2017). Not only did biochar assist isolate carbon in the soil, but it also improved its quality by balancing the soil pH, boosting the soil's CEC, and enhancing microbial development in soil. The functional groups in biochar interact with hydrogen ions in the soil, lowering the concentration of hydrogen ions and increasing the soil pH. Carbonates, bicarbonates, and silicates in biochar react with H+ ions to bring the pH of the soil to a neutral state (Akdeniz, 2019; Hamzah et al., 2019). As a result of its surface features and basic structure, biochar has gained considerable interest in soil remediation in agricultural sectors. Biochar can be used in agriculture for the following purposes: a) improving soil fertility and structure (Barnossi et al., 2020); b) enhancing the CEC of soil and decreasing aluminium toxicity (Saha and Basak, 2020); c) promoting carbon sequestration and mitigating the effect of GHG (Sizmur et al., 2017); d) increasing productivity by retaining water (El-naggar et al., 2019); and e) increasing microbial activity by alleviating nutrient stress (Jones et al., 2018).

Additionally, biochar has been touted as a possible solution for remediating soil contaminated with harmful contaminants such as heavy metals, pesticides, and hydrocarbons. Biochar with a large pore volume, surface area, and functional group has been shown to have an outstanding ability for absorbing heavy metals (Table 6). The biomass utilized to create biochar is primarily composed of basic cations.

When biochar is added to soil, these cations are transported into the ground. This activity improves soil CEC by increasing the surface area available for the adsorption of additional cations (Gu, 2021). Moreover, increasing the pH of the soil raises the CEC. The presence of a high concentration of calcium, potassium, nitrogen, and phosphorus in biochar contributes nutrients to the ground or acts as a source of minerals for the soil's microscopic population (Pan et al., 2021). When biochar is used as a soil supplement, the pore fraction of the soil increases. Microbial development takes place in the pore fraction, extending the residence time of moisture, air, and nutrients, promoting microbe proliferation, survival, and activity, contributing to plant growth (Sakhiya et al., 2020; Yaashikaa et al., 2020). Due to the difficulty of degrading biochar created at high temperatures, it remains in the soil for a more extended period than biochar synthesized at low temperatures (Zhang et al., 2020b).

Furthermore, research has been performed upon these harmful impacts of biochar on the soil. For example, hydrochar put to soil inhibited plant growth, demonstrating that optimizing biochar prior to application is critical to avoiding harmful vegetation impacts (Alkharabsheh et al., 2021). The use of biochar as a soil amendment helps climate change mitigation. The direct combustion of biowaste emits CO_2 into the atmosphere. This carbon is potentially transformed into biochar via gasification or pyrolysis and then reintroduced into the soil (Ha and Lee, 2020).

6.4. Carbon sequestration

Climate change has sparked an increased interest in lowering carbon dioxide emissions into the atmosphere. As a significant carbon sink, soil plays a critical part in the global carbon cycle, directly impacting climate change (Diacono et al., 2019). Carbon sequestration has been presented to minimize carbon dioxide emissions in soil. Due to the highly condensed aromatic structure of biochar typically has a solid resistance for biodegradation (Aksu, 2005). Thus, it is believed that biochar has a beneficial influence on soil carbon sequestration.

Numerous researches have been undertaken to determine how biochar affects soil carbon sequestration. Nevertheless, no definitive conclusion has been reached because both increasing and decreasing carbon dioxide emissions have been reported (Tomczyk et al., 2020; Wang et al., 2017). For instance, adding carbon from burning to soil increased soil organic carbon turnover (Masciandaro et al., 2013). However, adding biochar made from wood sawdust to soil inhibited carbon mineralization, resulting in increased carbon sequestration (Ha and Lee, 2020; Jones et al., 2018), demonstrating that biochar's carbon sequestered due to carbon derived from biochar rather than carbon generated from soil fertility.

Hassan et al. (2020) conducted a systematic review and meta-analysis of the decomposition and priming impacts. They discovered that, subsequently, biochar mineralization of soil organic matter was more remarkable in low-fertility soils than in high-fertility soils. Consequently, carbon mineralization was better in soils with low organic carbon content than soils with high organic carbon concentration (Han et al., 2018). Also, the incubation duration had an apparent impact on the activation of biochar (El-naggar et al., 2019).

Carbon in biochar can be classified as liable carbon or recalcitrant carbon (Enaime et al., 2020). When biochar is introduced to the soil, soil microbes may easily consume available carbon, increasing carbon mineralization (Mitter et al., 2021). This clarified why the inclusion of biochar enhanced carbon mineralization. Indeed, the proportion of resistant carbon in biochar is significantly more significant than labile carbon (Diacono et al., 2019). Recalcitrant carbon can persist in soil for an extended period. Thus, the carbon input from biochar is more than the carbon emissions from the mineralization of relevant carbon.

By and large, the impact of biochar addition on carbon sequestration remained unknown. The priming impact changes according to the feedstock type and pyrolysis circumstances, indicating the need to investigate the link between biochar effects and material source. Given the significant influence of pyrolysis conditions on biochar's physical and chemical characteristics, it is also necessary to investigate the correlation between pyrolysis parameters and biochar's effect on carbon sequestration. Additionally, while evaluating biochar-induced carbon sequestration, soil constituents should be examined.

7. Environmental concern of biochar

Together with the widespread use of biochar, we must consider its detrimental impact on the environment. Stability is an essential condition to consider when biochar is used in the ambient. Biochar is primarily composed of carbon. Biochar stability, notably, refers to the stability of the carbon structure. Aromaticity and condensation degree indicate biochar's carbon structure (Kumar et al., 2021; Li et al., 2019). Although it has been observed that biochar formed from grass and wood residues functions as a sink for PAHs rather than a source of PAHs (Kołtowski et al., 2017), biochar stability must be considered since diverse biochars have varying physicochemical properties.

(Bhattacharjee et al., 2020) discovered that organic material from biochar might dissolve during the complex formation of toxic substances, implying that dissolved organic materials from biochar may be present in solution due to biochar's instability. Additionally, dissolved organic materials might retain a significant level of aromaticity, stability, and resistance. When biochar is in the treatment of water and wastewater, the carbon content of the watercourse often arises due to the carbon released from the biochar. Further, biochar, primarily composed of sludge, includes heavy metals that can leach out during water

and wastewater, resulting in toxicity. When biochar is utilized as catalyst support, the stability of the catalyst often degrades after multiple cycles of use. The structural degradation of biochar could be one factor contributing to the catalyst's decreased stability. Thus, the strength of biochar is directly proportional to the quality of drinking water treatment.

To summarize, the stability of biochar has a significant impact on its environmental applicability. As a result, a comprehensive assessment is required to analyze the stability of biochar in the future. Since pyrolysis parameters can potentially change biochar's carbon content and structure, it is vital to explore the relationship between biochar stability and pyrolysis operations. Along with stability, the possible hazardous effects of biochar on microbes are necessary to be considered. (Ambaye et al., 2020) indicated that biochar increased the enzymatic activity of soil microbes at a low dose, implying that a small amount of biochar posed no harm to bacteria. As discussed above, different types of biochar have varying physicochemical properties. Additional investigations are required to establish the possible toxicity of biochar to the surroundings to enable its practical deployment. It is mentioned that toxicity testing may be performed on fish, algae, water fleas, and luminous bacteria.

8. Biochar – an ideal approach for regenerative economic sustainability

The thermochemical techniques used to produce biochar, mainly in rural areas, aid in developing that region and assist small and medium-sized industries in producing sufficient energy, improving farmer income, and giving solutions for agricultural waste management. This allows for the connection of small-scale production systems to larger systems, so establishing closed system models in which waste from one process can be used as an input for another, resulting in positive social, economic, and ecological consequences in regenerative economic sustainability. Similar interactions between various biochar production and waste reuse technologies are required for the development of new prospects. By utilizing waste from one agro-processing industry to shed light on hazardous pollutant issues in another and incorporating the by-product into soil application, economic sustainability has been established, allowing for new product and procedure development and the possibility for new product and procedure development the formation of new corporates. Strategies that strike a balance between ease of use, energy efficiency, and constrained discharges could be integrated into the local network to enable the feasible generation of biochar, taking both technical and financial considerations into account, as well as recouping the biochar and heat generated.

Economic strengths are as follows: (i) economic benefit from cost savings associated with waste disposal; (ii) reduced greenhouse gas emissions. This regenerative economic sustainability application minimizes wastes using a variety of processes and techniques, thereby enhancing their value. The rationale for this concept was that a multiunit model would usually be beneficial in decomposing approaches to increasing productivity, upgrading activities, and allocating environmental loads rationally to achieve ecological benefits.

9. Conclusions and prospects

Biochar production reveals a diverse array of biomass used as feedstocks and pyrolyzed via various processes to manage water contamination. The pyrolysis temperature, feedstock, and pyrolysis process all have a massive impact on the characteristics of the resulting biochar. Biochar has the potential to be a considerable resource for the elimination of harmful contaminants. Biochar's primary reason for removing pollutants is functional groups like hydroxyl and carboxyl groups on its surface. While the efficiency of biochar varies according to the type

of biomass and pyrolysis operations, future development of biochar will focus on perfect biochar features. As a result, biochar appears to be a promising method of pollution removal. Socioeconomic and sustainability considerations should be explored while developing recoverable biochar for a variety of environmental applications. The interaction between diverse waste management and power generation methods varies depending on the characteristics and processes used to generate it and economic, social, and ecological constraints. Regardless of how the proposed method is implemented in practice, the closed framework establishes distinctions between the linear and circular models of waste organization. Increased energy recovery is possible with this economic sustainability concept. This review article highlighted current situation information that might be used to identify new avenues for scientific innovation in biochar research.

However, additional study is required to explore novel activation strategies and adsorption and desorption mechanisms for various contaminants. The following studies must be thoroughly examined:

- The study of microbial population and the interaction
- The growth and development of microbes in the presence and the influence of biochar properties on microbial community
- Microbial activity during mineralization process and soil remediation
- The mechanism of contaminants removal during wastewater treatment
- The performance of biochar supercapacitors

While biochar has a plethora of benefits, a few issues remain. In biochar, toxic chemicals such as dioxins, chlorinated hydrocarbons, and polycyclic aromatic hydrocarbons may be present, depending on the biomass utilized. To determine the economic benefits and environmental consequences of biochar, a life-cycle study must be conducted. Biochar characterization procedures have improved because of advancements in methods. Optimizing the characteristics and activation of biochar is critical for maximum efficiency. Economic viability and accessibility have an impact on the adoption of innovative techniques. Given the emergence of biochar as a substitute source, conventional characterization processes must be performed to understand biochar's features better.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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