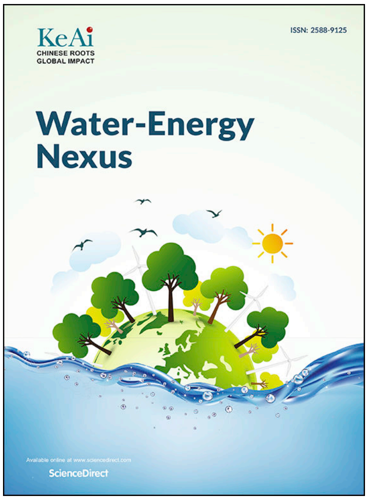

Review Article

A comprehensive review of production and characterization of biochar for removal of organic pollutants from water and wastewater

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A comprehensive review of production and characterization of biochar for removal of organic pollutants from water and wastewater

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Abstract

Biochar is produced by the pyrolysis of organic constituents at moderate to low temperatures and oxygen-deficient conditions. Various types of biomass wastes are used as the starting points for biochar production, which not only makes better use of the waste resources already available but also significantly lessens environmental harm. Biochar is extensively used as a soil amendment, biofuel, catalyst, energy storage, and carbon sequestration regulator because of its excellent efficacy, environmental friendliness, and affordable price. Biochar has lately received much interest in wastewater treatment due to its significantly expanded surface area, excellent pore volume, accessibility of functional charge, and environmental durability. It may also be recycled because of its exceptional therapeutic effectiveness and resource recovery capabilities. The ability of biochar to absorb major contaminants makes it a suitable treatment solution for wastewater. For the intent of developing biochar, the techniques of gasification, hydrothermal carbonization, and pyrolysis have been developed. Biochar was employed to absorb minerals, heavy metals (HMs), and organic pollutants to remove impurities from water and wastewater. The adsorption methods of organic contaminants, nutrients in wastewater and HMs were examined. Understanding the interactions among the biochar's structures, adsorption traits, and preparation parameters is crucial. The generation, characterization, and biochar exploitation for the elimination of organic and HMs were the main topics of the current review.

Keywords: Waste Biomass, Pyrolysis, Biochar, sustainability, Water and Wastewater Treatment.

1. Introduction

The growth in the global population over the past two decades has resulted in a greater demand for water for both human consumption and industrial use, which has increased the volume of wastewater dumped into the aquatic environment. Several contaminants, including carcinogenic heavy metals (HMs) (Park et al., 2016), phenols, pesticides (Safaei Khorram et al., 2016), polycyclic aromatic hydrocarbons (PAHs) (Flesch et al., 2019), organic dyes (Praveen et al., 2022), petroleum hydrocarbons (Zhang et al., 2019a), pharmaceuticals, and veterinary antibiotics (Kang et al., 2022) have been identified in wastewater streams. Literature has thoroughly covered a variety of pollution treatment methods. It is still thought to be challenging to create the most effective, practical therapeutic approaches. Chemical oxidation, reverse osmosis, adsorption, electrocoagulation, filtering, membrane separation, and biological treatment processes were found to be the most promising methods (Dey et al., 2024; Zeghioud et al., 2022). Adsorption is one of the most effective ways to remove a range of contaminants from wastewater and gaseous streams (Zeghioud et al., 2022). The contaminants are removed from the effluent during the adsorption process by being trapped on the energetically active regions on a solid substrate surface. The adsorption capacity is influenced by several factors, such as temperature, acidity, or the concentration of the liquid phase's adsorbate. The adsorbed molecule may be liberated from the interface and reabsorbed into the liquid phase if any of these parameters change (Nguyen et al., 2021a; Sun et al., 2019). Clays, zeolites, and active carbon are common adsorbents that are extensively employed for effective micro-pollutant removal, particularly in the potabilization of water. Further, advanced oxidation processes (AOPs) are a set of chemical treatment procedures designed to remove organic and inorganic pollutants from wastewater through oxidation reactions. These processes generate highly reactive species, such as hydroxyl radicals, which can effectively degrade complex contaminants (Dong et al., 2022). Common AOPs include ozone treatment, UV irradiation combined with hydrogen peroxide, and Fenton's reagent. AOPs are advantageous due to their ability to achieve high removal efficiencies and mineralize pollutants, making them a promising option for treating recalcitrant compounds in wastewater (Dong et al., 2022; Mishra et al., 2023).

Biochar, a porous carbonaceous material, is produced when biomass degrades thermochemically without oxygen exposure (Xiang et al., 2020). Around 6% of the globe's energy production and 55% of all renewable energy sources come from modern bioenergy. By 2030, the Net Zero Emissions 2050 Scenario predicts a sharp rise in the utilization of bioenergy to substitute fossil fuels. The usage of modern bioenergy increased by approximately 7% annually between 2010 and 2021 and is currently growing (EIA, 2021). The distribution of contemporaneous bioenergy needs to be accelerated to fulfil the Net Zero Scenario, which demands a 10% yearly increase in deployment between 2021 and 2030. The development of bioenergy must be monitored to ensure that it has no negative social or environmental repercussions. According to the Net Zero Forecast, by 2030, no traditional biomass will be used, making it possible to achieve UN Sustainable Development Goal 7 on the availability of affordable, clean energy. By excluding traditional uses of biomass, the use of modern bioenergy roughly doubles from around 42 Exajoule (EJ) in 2021 to 80 EJ in 2030 (IEA, 2021). The data for global bioenergy from the years 2000-2018 are shown in **Fig. 1** (Statistics, 2020). Pyrolysis, carbonization, gasification, hydrothermal, torrefaction, and microwave heating are techniques for thermochemical degradation that range in thermochemical time and temperatures (Fang et al., 2018). Due to its multitude of surface functional groups and relatively large surface area, biochar is an efficient, inexpensive, and environmentally sustainable adsorbent. In addition to being used as an adsorbent and catalyst to remove environmental contaminants and lower greenhouse gas emissions, biochar may be utilized on soils to increase soil fertility and agricultural growth. It also has the potential to produce clean energy as a substitute for fossil fuels (Fang et al., 2018). As a result, biochar has become a remedy for various worldwide issues, such as soil erosion, environmental pollution, and climate change (Creamer & Gao, 2016).

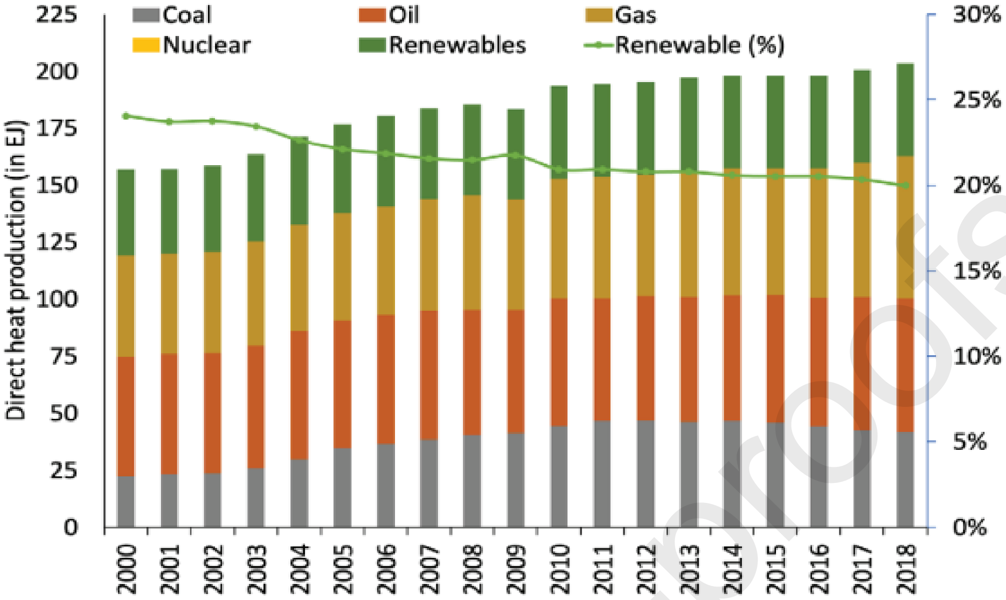


Fig. 1: Global bioenergy statistics worldwide (Adopted from (Statistics, 2020) (Statistics, 2020))

Biochar has been employed for thousands of years for various applications. The first indication of biochar's use in Western agriculture dates back to the mid-19th century, although its precise history may go back even further. Biochar's usage in water treatment has only recently drawn the interest of researchers due to water pollution and a lack of drinkable water as a result of wasteful consumption by the expanding population. Water shortage denotes a province's lack of freshwater deliveries to satisfy both societal and environmental requirements. Four billion people, or around two-thirds of the world's population, experience extreme water shortages for at least one month each year. It is predicted that by 2025, half of the people worldwide will live in areas with scarce water resources (Liu et al., 2017). Also, by 2040, one-fourth of all children worldwide will reside in areas with significant water deficiency (Unicef, 2017). It has been shown that biochar is a good absorber of a number of common contaminants found in animal effluent, including organic pollutants (OPs), heavy metals (HMs), nitrogen, and phosphorus. In contrast to commercially available activated carbon products, good magnetic biochar that is easily separated from liquid after magnetization seems to be more appropriate for animal effluent. Since biochar has a greater throughput for adsorbing N_2 and P, it may also be consumed as a slow-release fertilizer and has the qualities of an agricultural commodity that is beneficial to the environment (Dai et al., 2020). Recent studies reviewed specific uses for biochar and assigned preparation tools and functionalization procedures to specific biochar features to categorize the vast amount of information about the physicochemical properties of biochar and how they affect removal mechanisms (Patel et al., 2020; Wang et al., 2020b). Additionally covered are the applications of biochar and the analytical mechanism of contaminant adsorption (Deng et al., 2017). Understanding the biochar features and their probable influence on adsorption processes towards countless contaminants in the water is crucial to deciding what actions should be made to improve biochar features through many treatments, including functionalization and activation. **Table 1** provides a general summary of the characteristics, uses, pollutant adsorption capabilities, and pertinent biochar synthesis parameters.

Table 1. A comprehensive summary of the characteristics, use, and adsorption of pollutants by biochar, along with the pertinent production factors.

Biochar Property	Functionality	Application/ Mechanism involved	Paremets of biochar generation
SSA*, porosity	Sorption capacity	Immobilization of contamination from solid, liquid and gaseous media	Residence time, higher temperatures
Ion-exchange properties on surface	Electrostatic interactions with polar or non-polar groups	adsorption of organic pollutants	Post functionalization
High mechanical and chemical stability	-	-	High temperatures.
Surface functional groups	Chemical bonding with assured molecules	Absorption and immobilization of certain toxins and drugs	Low temperature production, post treatment (functionalization)
pH	Negatively or positively charged surface	Attraction/repulsion of ionically charged molecules	Feedstock (high ash content biomass leads to high pH biochars), post functionalization

*SSA= Specific surface area

This current review article investigated biochar generation techniques, physical and chemical features, factors influencing biochar properties, biochar adsorption abilities, and biochar application in the elimination of organic pollutants (OPs), HMs, and nutrients from the water. The adsorption mechanism of biochar linked with major pollutants was deliberated concerning the organic carbon structure (OCS), surface characteristics, surface electrical properties, and essential minerals. The review's objectives are to improve and commercialize biochar-based adsorption technology to satisfy the cleaning of water and wastewater, as well as to assist researchers interested in the thermochemical conversion of feedstock into biochar and its application in the adsorption process. The current review paper concentrated on articles that were published during the last ten years (excluding a few) to demonstrate its potential comparability with other published material.

2. Biochar preparation methods and characteristics

2.1. Preparation methods

A wide range of methods are employed in the synthesis of biochar, some of them being pyrolysis, hydrothermal carbonization, and gasification. They are discussed in detail below.

2.1.1. Pyrolysis

Pyrolysis is the thermal degradation of organic constituents at moderate (350-900 °C) temperatures in an oxygen-deprived environment (Deng et al., 2017). This is an effective process for transforming waste materials into valuable products (biochar, syngas, and bio-oil). A variety of products in the form of solid, liquid, and gas are produced throughout the process, as hemicellulose, cellulose, and lignin undergo reaction processes such as depolymerization, fragmentation, and cross-linking (Yaashikaa et al., 2020). For the design and manufacturing of biochar, a multitude of reactor designs are employed, including agitated sand rotating kilns, wagon reactors, bubbling fluidized beds, and paddle kilns. The quality and nature of the biomass are used to alter the throughput of biochar during pyrolysis. Temperature is a dynamic process that influences product efficiency (Wei et al., 2019). In general, as the temperature is raised during the pyrolysis process, the output of biochar falls, and the production of syngas rises. Pyrolysis can be majorly ordered into three broad categories: slow, rapid, and flash pyrolysis. As per scientific studies, lower pyrolysis temperatures and reduction in heating rates play a crucial role in the synthesis of solid products. Slow pyrolysis is deduced to be the overriding technique for biochar generation, as in this method, the solid product concentration was able to reach 35% (Kambo & Dutta, 2015).

2.1.2. Slow pyrolysis

A viable carbon-negative process is slow pyrolysis, which turns resistant carbon into a variety of products and lowers the amount of CO_2 in the atmosphere while producing biochar from different bio-stuffs (Mohamed Noor et al., 2012). According to Mohamed Noor et al. (2012) and Ok et al. (2015), slow pyrolysis is carried out at temperatures between 350-400 °C and 600-700 °C, with a heating rate of 5 °C min^{-1} (Mohamed Noor et al., 2012; Ok et al., 2015). The breakdown of cellulose and hemicelluloses requires the presence of heat. The pyrolysis can be performed on agricultural residues (Mohamed Noor et al., 2012). The solid product of biochar is maximized through slow pyrolysis, which can be done in a lab setting with a slow pyrolysis apparatus (Yu et al., 2017). To obtain a moisture-free product, the entire grounded product is lifted to apply a pre-drying treatment following grounding. During pyrolysis, the heating efficiency is reduced when the product contains moisture. The grounded materials are dried out by being baked at 105 °C in a traditional oven until the sample's weight does not change (Mohamed Noor et al., 2012). Pre-treatment is performed on the material during the torrefaction process to get carbon-rich products. Hydrothermal pyrolysis yields a high hydrochar yield, while slow pyrolysis yields a char yield. Before solid decomposition to produce a product, pre-pyrolysis takes place during slow pyrolysis (Yu et al., 2017). Steel kilns, earthen, and bricks are examples of conventional biochar extraction methods that release different volatiles into the environment and contribute to air pollution. Slow pyrolysis yields 30-35% biochar, 40-45% liquid product, and 20-25% gaseous product from 1 kg of wood. Retorts, converters, and kilns are examples of reactors used in slow pyrolysis (Sakhiya et al., 2020). Many researchers have used slow pyrolysis techniques to produce biochar from agricultural wastes such as wood sawdust, rice waste (Gupta et al., 2018), and corn stover (Karimi et al., 2020). A systematic presentation of the different conversion techniques and their properties is listed in **Fig. 2.**

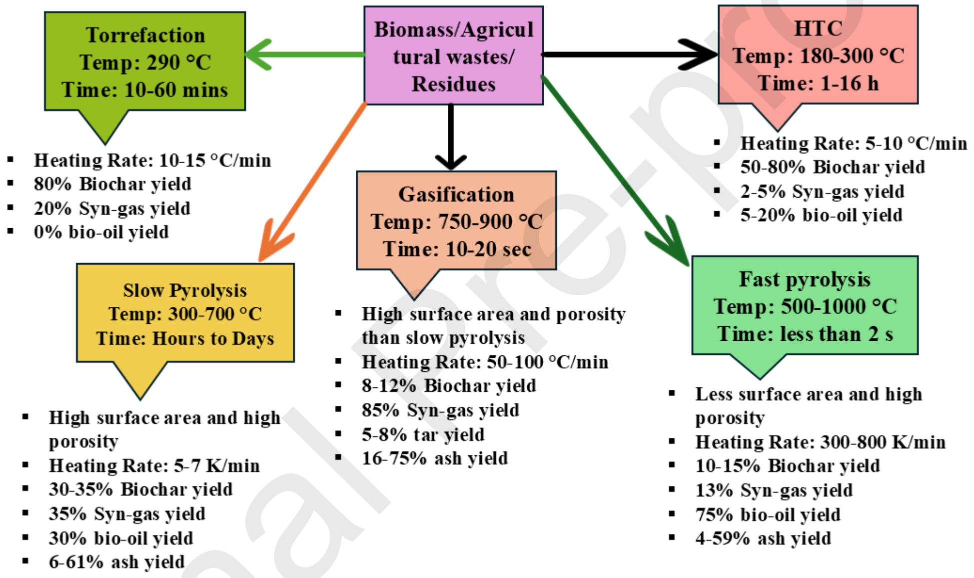


Fig. 2. Biochar yields and characteristics obtained from several biochar production techniques: rapid, slow, torrefaction, hydrothermal carbonization (HTC) pyrolysis, and gasification.

2.1.3. Fast pyrolysis

Fast pyrolysis of biomass is a thermal decomposition process conducted at high temperatures (typically 500°C or greater) in the absence of oxygen, with rapid heating rates and short residence times (Elkhalifa et al., 2019). This process converts biomass into bio-oil, syngas, and char, with bio-oil being the primary product. The rapid heating and cooling in fast pyrolysis maximize liquid yields, making it an efficient method for producing renewable biofuels and chemicals (Elkhalifa et al., 2019). Fast pyrolysis is considered a promising technology for sustainable energy production due to its ability to convert a wide range of biomass feedstocks into valuable products. Fast pyrolysis can increase bio-oil production by up to 75% when it is carried out at 800 ◦C to 1300 ◦C at a heat rate of 200 ◦C/min for no more than 10 s (Elkhalifa et al., 2019). This approach uses circulating beds, ablative reactors, rotating-cone reactors, and bubbling fluidized beds as reactors (Zhang et al., 2019c). The liquid product is maximized by fast pyrolysis (Mohamed Noor et al., 2012; Yu et al., 2017). The most liquid product is produced when softwood is used, together with hardwood, grass, and other agricultural wastes. Fast pyrolysis involves the anaerobic decomposition of biomass at 10 °C to 100 °C in 0.5-2 s (Sakhiya et al., 2020). Vacuum, ablative reactors, spinning cones, entrained flow, and fluidized beds are among the reactor types used in fast pyrolysis beds (Elkhalifa et al., 2019). 60-75% liquid, 10-20% gaseous, and 10-20% solid components make up the final product (Elkhalifa et al., 2019; Sakhiya et al., 2020). The various pyrolysis processes and their corresponding product yields are listed in **Table 2.**

Table. 2. Different types of pyrolysis techniques and their products (Mohan et al., 2006).

Process	Temp. (°C)	Pressure	Residence time	Products yield (wt.%)		
				Pyrolysis oil	syngas	char
Fast pyrolysis	400-600	atmospheric	2-5 sec	75	13	12
Slow pyrolysis	350-900	atmospheric	Min to an hour.	30	35	35
Intermediate pyrolysis	450-700	atmospheric	10-30 min	45-50	30-35	28-35
Gasification	700-1500	atmospheric	Second to min.	5	85	10

2.1.4. Hydrothermal carbonization

Hydrothermal carbonization (HTC) is regarded as a profitable technique since it may produce biochar at a low temperature (180-250 °C) (Lee et al., 2018). The biomass is blended with water during the process and then put in a sealed reactor. To preserve stability, the temperature is gradually raised. The following compounds are created under varying temperature conditions: Biochar yielded below 250 °C is known as HTC (Zhang et al., 2017), liquid oil formed between 250 and 400 °C is acknowledged as HTL (Safaei Khorram et al., 2016), and syngas, including CO, CO_2, H_2, and CH_4 generated beyond 400 °C is known as hydrothermal gasification (Bakraoui et al., 2020). The intermediate product, 5-hydroxymethylfurfural (5HMF), and its derivatives are produced through a sequence of processes involving the hydrolysed product, including dehydration, fragmentation, and isomerization. The process also involves condensation, polymerization, and intramolecular dehydration to form the hydrochar (Bakraoui et al., 2020). It is challenging to synthesize potentially dangerous stimulants because HTC practices water as the reaction medium under extreme pressure and temperature situations. As such, biochar produced utilizing this routine is exceptionally equipped for the adsorption of contaminants in water (Regmi et al., 2012; Zhang et al., 2013c). The ideal temperature range for biochar is 180 to 250 °C, together with 2 to 10 MPa of pressure and water (Parmar et al., 2014). Compared to HTC, dry pyrolysis causes the carbonization and breakdown of lignin, cellulose, and hemicelluloses at low temperatures, which are mostly caused by the aqueous substrate (Parmar et al., 2014; Zhang et al., 2019c). HTC is, therefore, especially well-suited for processing feedstocks or waste residues with high moisture values, such as algae and aquatic plants (Cheng & Li, 2018). Through the processes of dehydration, polymerization, hydrolysis, aromatization, and decarboxylation, a hydrocarbon is broken down into smaller pieces, yet it always maintains its similarity to lignite, the end substrate. Levulinic acid, glucose, hydromethyl furfural, organic acid, and other organic acids are among the chemicals used in this process. Intermediate products have a variety of uses in the industrial sector. Removing microbes and organic pollinators lessens the dangerous qualities of different compounds (Parmar et al., 2014; Zhang et al., 2019c). Biochar, liquid products, and gaseous products are produced by HTC, which is carried out in water at pressures lower than 10 bars. At lower energy levels and temperatures, it can deliver more substantial output quality more quickly (Yu et al., 2017). It is the most economical method at 180-250 °C underwater and is very suitable for small-scale, farm-based biochar production. This process involves multiple parameters that impact its final production; the yield in the end is approximately 40-70% of biomass **(Fig. 3)** (Zhang et al., 2019c). Regrettably, this technique is constrained by the reaction parameters, as well as the expensive reactor's precondition for high pressure and temperature. The practical implementation is challenging to commercialize owing to its high preparation cost (Regmi et al., 2012).

2.1.5. Gasification

Gasification is employed to transform carbon-rich materials into syngas (CO, CO_2, CH_4, H_2, and remnants of hydrocarbons). Gasification is operated at higher temperatures (> 900 ^{o}C) in the occurrence of O_2 air, steam, etc. It has been shown that the reaction temperature has the greatest impact on syngas synthesis. Higher temperatures increased carbon monoxide and hydrogen production but decreased methane, carbon dioxide, and hydrocarbon production(Zhang et al., 2013a). The gasification of feeds frequently uses fluidized-bed, fixed-bed, and entrained-flow-bed gasifiers. The raw material materials serve as the route through which the gas travels in fixed-bed gasifiers, whereas the gasifier zones are located at the location of the reaction. These gasifiers are further divided into three categories based on their direction of gas flow: updraft, downdraft, and crossflow fixed beds (Zhang et al., 2013a). Considering that the gasifying agent suspends the biomass feedstock in a fluid-like state, fluidized-bed gasifiers benefit from increased solid-gas interaction, uniform temperature distribution, and higher heat transfer rates (Zhang et al., 2013a). **Fig 2** depicts a visual representation of biomass transformation and end products.

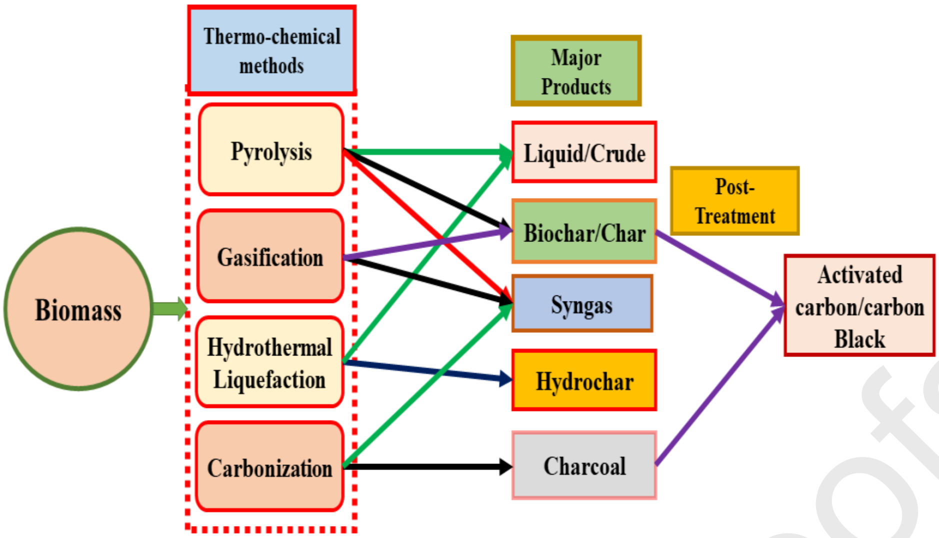


Fig. 3. Pictorial presentation of thermochemical conversion of biomass and their end products.

3.2.6. Microwave assists pyrolysis

Microwave pyrolysis is an advanced thermal decomposition process where microwaves are used to heat biomass or other feedstocks in the absence of oxygen, resulting in the production of bio-oil, syngas, and char (Lam & Chase, 2012). Unlike conventional pyrolysis, microwave pyrolysis provides rapid and uniform heating, which enhances reaction rates and can improve the quality and yield of the products (Luo et al., 2023). The process involves converting microwave energy into thermal energy within the material, leading to efficient and controlled decomposition. This method is gaining interest because of its potential to process diverse feedstocks and for its energy efficiency and scalability in producing renewable energy and value-added chemicals (Luo et al., 2023). Abas and Ani (2014) and Yu et al. (2017) have identified microwave-assisted pyrolysis as a very efficient thermochemical method (Abas & Ani, 2014; Yu et al., 2017). Although pre-treatment is required before heating in a microwave, ordinary pyrolysis is carried out as a standard heating procedure. Heath water is a liquid product and a non-compressible gas, while pyrolyzed gas is the typical byproduct (Yu et al., 2017). Avoiding the development of secondary reactors eliminates the drawbacks of traditional biochar manufacturing and improves the quality of the product. It is also referred to as an electric volumetric heating technology, and it operates at 2.45 GHz and 915 MHz frequencies as required by international agreement. It has great efficiency, produces little emissions, and saves energy (Abas & Ani, 2014).

2.2. Characteristics of biochar

Biochar has a variety of aromaticity oxygen-containing functional groups due to its high carbon content and void structure (Tomczyk et al., 2020). The physicochemical properties of biochar are significantly influenced by the kinds of raw materials used, feedstock size, the pyrolysis process, the temperature, the pyrolysis period, and the circumstances under which it is modified (Tan et al., 2015). Although a variety of factors may affect the structure of biochar, in general, the material has a good number of surface functional groups (SFG) (hydroxyl, carboxyl, carbonyl, and methyl) (Sharma et al., 2021), a developed pore structure, a sizable specific surface area, and a stable molecular structure (Tomczyk et al., 2020), which makes it suitable for adsorbing effluents from livestock wastewater.

2.2.1. Physical properties

The bulk density, particle size distribution, specific surface area (SSA), pore size, and pore volume distribution are examples of physical attributes (Ding et al., 2021; Zeghioud et al., 2022). These variables (reactor temperature and residence duration) are closely related to the circumstances that affect the formation of biochar. The addition of oxygen-rich media throughout the course (air, oxygen, CO_2, and steam) and/or post-production processing alters the result (Hu et al., 2021). Five diverse biochars from diverse feedstocks were used to adsorb the fungicide epoxiconazole (EPC) (Xiong et al., 2020). The findings demonstrated a tight relationship between total pore volume and SSA and the adsorption ability of these biochars towards EPC (Xiong et al., 2020). The sorptive biochar potential toward ciprofloxacin or acetaminophen, the biochar surface area, and the total pore volume all showed favourable correlations (Patel et al., 2021). In addition to the overall surface area, biochar surface heterogeneity is crucial to the sorption behavior. In order to investigate the impact of biochar adjustment on SSA (**Fig. 4**), or to assess the impact of pyrolysis temperature on the SSA of generated biochar, Brunauer-Emmett-Teller (BET) analysis is used. SSA and total pore volume increase as pyrolysis temperature rises. The SSA was further enhanced in the attendance of acid due to the buildup of the inorganic component and the emergence of new minerals at the surface of the biochar (Liu et al., 2021).

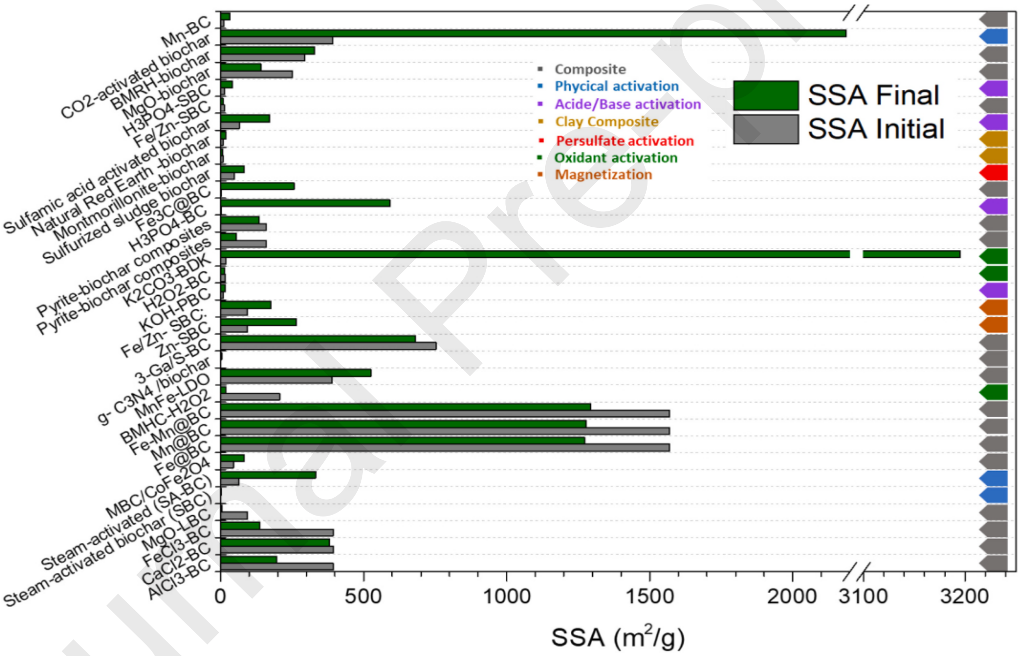


Fig. 4. The development of biochar's specific surface area (SSA) in some published papers according to various modification strategies (Adopted from Zeghioud et al. (2022) (Zeghioud et al., 2022)).

2.1.2. Chemical properties

Cation exchange capacity (CEC), electrical conductivity (EC), point of zero charges (PZC), and surface functional group (SFG) are among the chemical characteristics of biochar. It's crucial to conduct a structural and elemental study to forecast how biochar will affect the environment (Mishra et al., 2022c; Xiang et al., 2021). The O/C atomic ratio, the conformation and disposition of the elemental components at the surface, the relationship between the parameters used to prepare the biochar and its final characteristics are all revealed by combining the Scanning electron microscope (SEM) approach with energy-dispersive X-ray spectroscopy (EDX or EDS). The O/C ratio indicates the biochar's level of carbonization and aromaticity, which are indicators of its stability and, in turn, its capacity to trap carbon (Ma et al., 2016; Mishra et al., 2022a). Instead of elemental analysis, EDX is indicated as a suitable approach for measuring the direct O/C ratio (Mishra et al., 2022a). The H/C and O/C ratios in biochar demonstrated a positive relationship with the concentrations of hydroxyl, carboxyl, and carbonyl groups, as well as the cation exchange capacity (CEC) (Wiedner et al., 2013). The degree of aromatization of carbonization is indicated by the elemental ratios of H/C (Chen et al., 2008). X-ray photoelectron spectroscopy (XPS) analysis is an exceptionally effective evaluation method for detecting the functional groups on the surface of biochar and the metallic state of products before and after the synthesis of a biochar composite (Shen et al., 2020). Chemical information is present in the XPS spectral lines C 1s, O 1s, and N 1s photoelectron lines**.** The confined electronic situation of the photo-emitting atom is replicated in their exact positions on the energy axis; a distinctive move for the carbons C-O, C=O, COO^-, and CO^{2}_{3} is distinguished (Leng et al., 2019). Most of the C 1s and O 1s spectrum's peak intensities are reduced due to the adsorption of methylene blue (Vickers, 2017). However, the presence of N 1s in the biochar/FexOy-MB XPS spectrum indicated that N-electrostatic attraction might be involved in the adsorption (Vickers, 2017). Additionally, XPS may be used to assess the elemental O/C molar ratio, which might help identify the extent of stability of biochar (Spokas, 2010). Fourier Transform Infrared spectroscopy (FTIR) is frequently used to characterize the surface of biochar. This approach evaluates the efficacy of metal binding throughout surface treatment or the alteration of surface functional groups post-adsorption of contaminants, and it offers specific data on the oxygen-rich charge located on the biochar surface (Liu et al., 2019a). The classification of various instruments used in biochar characterization is listed **in Fig. 5.**

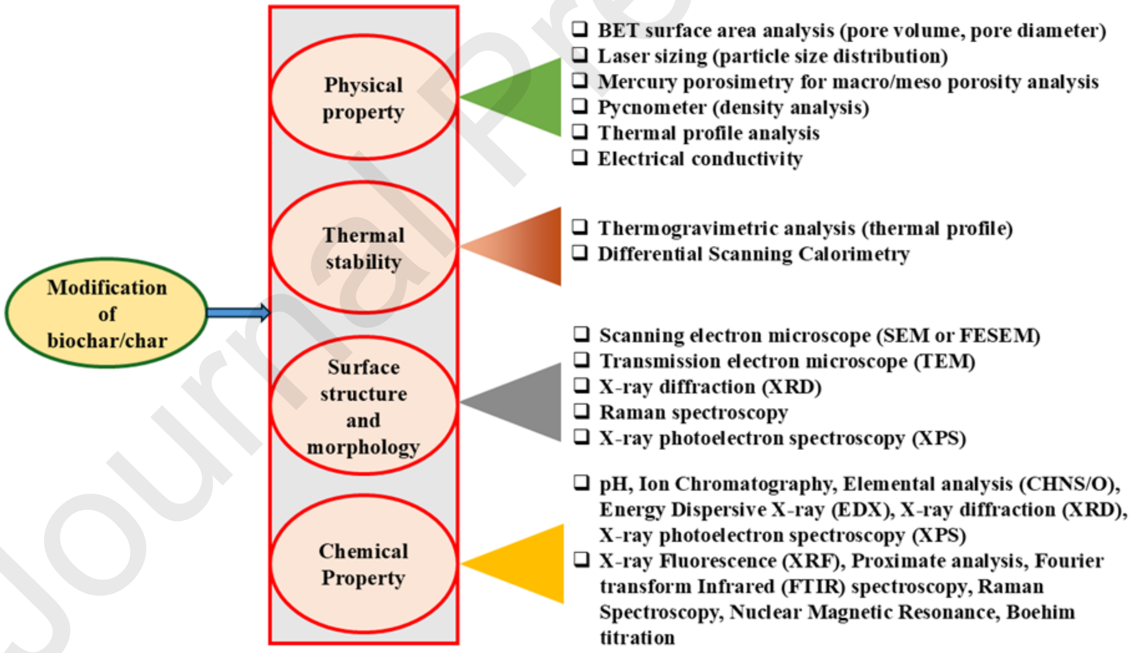


Fig. 5. Classification of characterization techniques versus biochar properties.

2.2.3. Morphology and surface structure

Biochar has critical characteristics that include its surface shape and chemical structure. Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) are effective tools for determining the progression of biochar surface structure, porosity, and pore distribution prior to and following amendment (Vickers, 2017). Raman spectroscopy is thought to be an effective approach for analyzing flaws or graphitization in carbon-based materials. In biochar engineering and development, two bands are vitally pertinent: the D band, which reflects the degree of disorder and defect caused by vacancies, edges, and functional groups, and the G band, which is associated with the crystalline and graphitic structures (Kumar et al., 2022; Yun et al., 2018). The forecast intensity ratio of the D band to the G band (ID/IG) shows the disorder and degree of the faultiness of the biochar **(Table 3).** It is hypothesized that a rise in the I_D/I_G ratio transported by the Fe addition indicates an increase in the number of damaged sites (Rong et al., 2019). Additionally, it has been shown that when pyrolysis temperature increases up to a certain point, more defective sites develop on biochar (Bai et al., 2021). A low I_D/I_G ratio also indicated a significant level of graphitization (Zhang et al., 2021). In general, the ID/IG value rises with higher pyrolysis temperatures, implying that elevated pyrolysis temperatures promote the formation of fault structures in biochar (Yang et al., 2020). The X-ray diffraction (XRD) method is used to determine a solid material's crystal structures and phase composition. It may also define material change, such as metal oxide loading magnetic biochar composite creation, and evaluate the crystalline/amorphous phase ratio (Ma et al., 2021). The method may assess the stability of biochar components following alterations, such as the adjustment of SiO_2 (Zhang et al., 2020). The surface structure and morphology of the biochar are subjected to process parameters such as temperature, heating rates, particle size, etc. (Mishra et al., 2022b). The surface structure and morphology of the biochar altered due to rapid chemical reactions (Mishra et al., 2022b). **Fig. 6** illustrates the irregular form and porous structure of biochar (pore size=1.4-11.2 µm). Because it makes it easier to remove volatile substances involved in pyrolysis, an increase in porosity can have a favourable effect on the process. The temperature at which biochar is produced through pyrolysis plays a critical role in shaping its structure and morphology. Generally, higher pyrolysis temperatures (600-900 ^oC) result in biochar with increased surface area and porosity as volatile organic compounds are expelled, leaving behind a more porous material (Tan et al., 2018). This process also leads to higher carbon content and greater crystallinity, imparting a more graphitic nature to the biochar (Wang et al., 2024). Conversely, lower pyrolysis temperatures tend to preserve more functional groups on the biochar surface, such as hydroxyl, carboxyl, and phenolic groups (Zhang et al., 2024). The elemental composition is influenced by higher temperatures, yielding biochar with a higher carbon-to-nitrogen ratio and reduced concentrations of oxygen-containing functional groups (Zhang et al., 2024). Biochar stability is enhanced at higher temperatures, making it more resistant to microbial decomposition and potentially prolonging its effectiveness as a soil amendment (Zhang et al., 2024). However, the impact on plant growth varies, with different pyrolysis temperatures influencing nutrient availability, water retention, and soil microbial activity in distinct ways (Zhang et al., 2024). Therefore, the selection of the appropriate pyrolysis temperature is crucial and should align with the intended application of the biochar. Additionally, considering the feedstock used for biochar production is essential as it also contributes to the final properties of the biochar (Zhang et al., 2024).

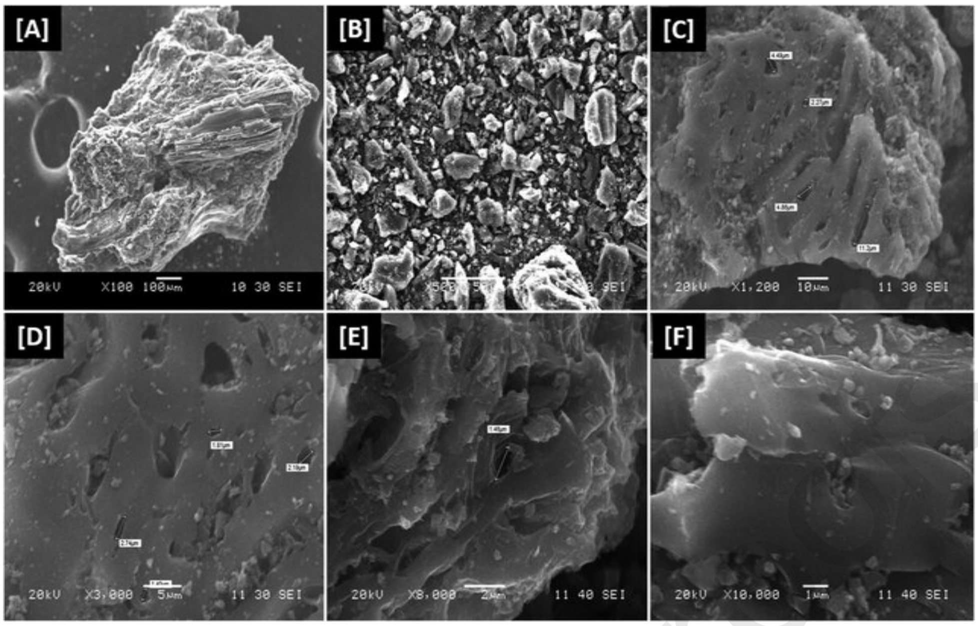


Fig. 6. Shape and surface morphology of bio-char using SEM (adopted from Husain, Zakir, et al. (2020) (Husain et al., 2020).

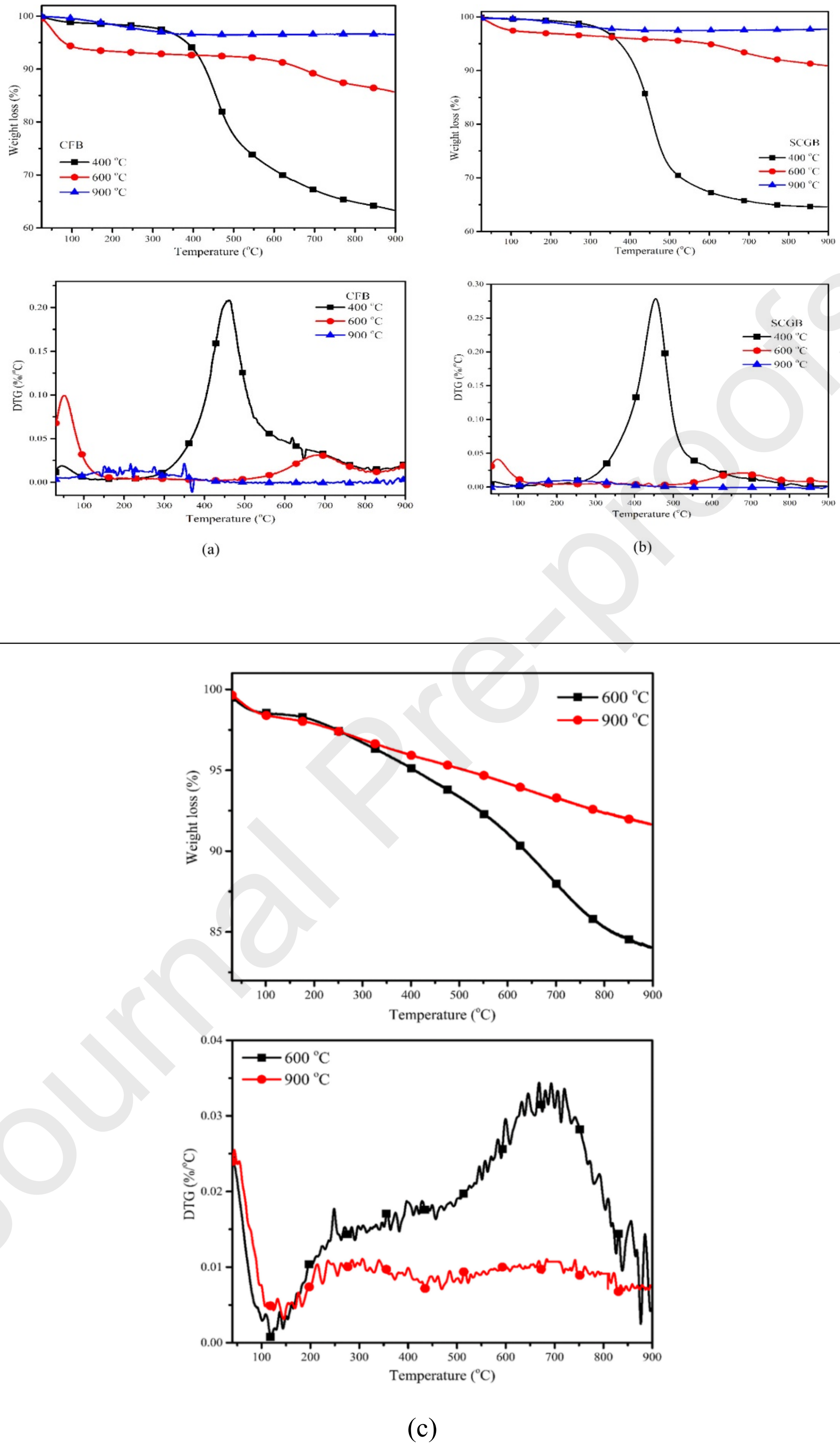
Table 3. The locations of the D and G bands in the Raman spectra of biochar.

Biochar	D band position (cm^{-1})	G band position (cm^{-1})	I_D/I_G	Reference
Sludge-derived biochar	1350	1580	0.84 and 1.06	(Bai et al., 2021)
Magnetic biochar derived from banana peels	1338	1589	0.94 and 0.99	(Rong et al., 2019)
Pyrrolic N-rich biochar	1343	1588	0.79 and 1.07	(Cai et al., 2021)
Multi-porous biochar from lotus biomass	1340	1585	1.67, 1.48, 1.30, and 1.56	(Hou et al., 2021)

Cassava ethanol sludge-derived biochar	1368	1594	0.389 and 0.407	(Zhang et al., 2021)
Graphitic biochar	1310	1590	1.94–2.56	(Sun et al., 2020b)
Nanoscale zero-valent	1309	1561	0.99, 1.04,	(Yang et al., 2020)
Mixed waste oil-derived biochar	1354-1357	1568-1575	0.58-0.85	(Mishra et al., 2022c)
Spent coffee ground and chicken feathers derived biochar	1354-1357	1568-1575	0.85-0.86	(Mishra et al., 2022a)

2.2.4. Biochar stability

Thermogravimetric analysis (TGA) is employed to inspect the thermal stability of biochar (Mishra et al., 2022a) and describe its structure since it offers evidence of the pyrolysis yield, moisture, and numerous structural elements such as hemicellulose, cellulose, and lignin (Sun et al., 2020b). The mass loss in TG analysis can typically be separated into three phases: the first phase reflects the loss caused by water vaporization and decay of bonded hydrated mixtures; in the second phase, the majority of the loss reported is clarified by the thermal decay of polar biomass derived from the majority of cellulose, hemicellulose, and holocellulosic precursors; and lastly, the third phase represents the loss due to the evaporation of lignin (Kim et al., 2020). Finally, it was determined that the last step of mass loss was triggered by the slow and steady thermal deprivation of high molecular weight constituents found in the biomass (Singh et al., 2020). The thermal stability of biochar produced at different temperatures (400, 600, and 900 °C) was investigated by Mishra et al. (2022) in a TGA, and it was shown that biochar produced at 900 °C has greater thermal stability than biochar produced at 600 and 400 °C (**Fig. 7 (a b and c)**) (Mishra et al., 2022a). The biocarbon obtained at temperatures more than 600 °C pyrolyzed completely (removing hydrogen and oxygen), increasing the thermal stability. Nevertheless, the biocarbon obtained at a lower temperature (400 °C) contained some raw impurities that decreased the biocarbon's thermal stability. The biocarbon with the maximum decomposition was found at 400 °C, which was supported by the entire thermal breakdown profile of biocarbon from 900 °C (Mishra et al., 2022a). Since there was less heat and mass transfer during partial pyrolysis, the lower-temperature biocarbon had more raw contaminants (such as hydrocarbons) and decomposed more quickly than the higher-temperature biocarbon. It was believed that because pyrolysis took place in an inert atmosphere, it led to the formation of biocarbon that is particularly resistant at higher temperatures. Since full pyrolysis (maximum heat and mass transfer) occurs at higher temperatures (600 and 900 °C), biocarbon was found to have superior thermal stability (Mishra et al., 2022a).


CFB
400 °C
600 °C
900 °C
Weight loss (%)
DTG (%/°C)
Temperature (°C)
SCGB
400 °C
600 °C
900 °C
Weight loss (%)
DTG (%/°C)
Temperature (°C)
600 °C
900 °C
Weight loss (%)
DTG (%/°C)
Temperature (°C)

(a) (b)

(c)

Fig. 7. TG profile of (a) chicken feather biochar (CFB) and (b) spent coffee ground biochar (SCGB) at 400, 600, and 900 °C (adopted from Mishra et al. (2022)) (Mishra et al., 2022a) (c) mixed waste biochar at 600 and 900 °C (adopted from Mishra et al. (2022)) (Mishra et al., 2022b).

3. Factors impacting the characteristics of biochar

3.1. Type of feedstocks

A complex solid material called biomass is made up of biological, organic, or inorganic components that come from either living or non-living creatures. Woody biomass and non-woody biomass are the two types of biomass (Tripathi et al., 2016). Wood biomass possesses low moisture, minimal voidage, increased density, and a considerable calorific value. Non-woody biomass encompasses animal, solid industrial, and agricultural wastes (Huang et al., 2021). Non-woody biomass is distinguished by high detritus, significant dampness, large voidage, lower density, and poor calorific value. The moisture content of a biomass feedstock has a large influence on the way that biomass develops. Maximum biomass moisture content minimizes char formation, which increases the energy required to attain the pyrolysis temperature (Jafri et al., 2018). When producing biochar, biomass with low moisture content is preferred since it pyrolyzes with less heat energy and takes less time than biomass with high moisture levels, making the process more commercially feasible (Huang et al., 2021).

3.2. Temperature

An important factor that influences the properties of biochar is the pyrolysis temperature. The pyrolysis temperature has a considerable impact on the structure and characteristics of biochar (Cao et al., 2014; Mishra et al., 2022a). As the temperature is raised, the surface area, ash content, and biochar pH also upsurge (Kim et al., 2012) while the yield of biochar decreases (Mishra et al., 2022a). Biochar formed at low temperatures has aliphatic and cellulose-like structures, providing it with a more expanded organic character. These might be valuable substrates for bacteria and fungi to mineralize, which in itself is necessary for nutrient cycling and aggregate formation (Koshila Ravi et al., 2019). Biochar generated at higher temperatures (400-700 °C) using organic feed had decreased ion exchange and functional groups as a response to dehydration and decarboxylation but still contained considerable quantities of carbon in poly-condensed aromatic structures (Amalina et al., 2022). At greater pyrolysis temperatures, carbon polycondensed into aromatic rings, maximizing the surface area and pore formation of the biochar. Biochar generated at higher temperatures has large surface areas and microporosity, while biochar produced at lower temperatures has weak adsorption capability (Kołodyńska et al., 2012). As the volatile component in carbon-rich biomasses is eliminated during pyrolysis or carbonization, biochar develops porosity, aromatic structure development, and polymerization. As a result, it is plausible to assume that the temperature at which biochar is formed during pyrolysis, whether from agricultural waste, chicken litter, or other animal manures, has a significant impact on the quantity and quality of the product (**Table 4**) (Amalina et al., 2022).

Table 4. The temperature influences the physicochemical characteristics of biochar during pyrolysis.

Biomass	Temperature (°C)	Yield (wt.%)	Ash (%)	BET surface area (m^2/g)	V_{total} (cm^3/g)	pH	H/C	O/C	References
Alfalfa	350	47.70	7.10	3.50	-	-	0.80	0.20	(Choi & Kan, 2019)
	450	30.70	9.10	4.00	-	-	0.50	0.10	(Choi & Kan, 2019)
	550	28.30	16	183	-	-	0.30	0.10	(Choi & Kan, 2019)
	650	27.50	13.60	405	-	-	0.20	0.10	(Choi & Kan, 2019)
Oange peel	200	61.60	0.30	7.75	0.010	-	1.14	0.45	(Chen & Chen, 2009)
	300	37.20	1.57	32.30	0.031	-	0.78	-	(Chen & Chen, 2009)
	400	30	2.10	34	0.010	-	0.58	0.22	(Chen & Chen, 2009)
	500	26.90	4.27	42.40	0.020	-	0.38	0.21	(Chen & Chen, 2009)
Rice straw	300	38	-	6.77	-	7.90	0.07	0.43	(Shen et al., 2019)

	500	31	-	22.38	-	10.40	0.04	0.22	(Shen et al., 2019)
	700	30	-	115.47	-	10.70	0.03	0.13	(Shen et al., 2019)
Pineal shell	350	36.53	2.46	0.82	0.001	7.10	0.06	0.32	(Mohammed et al., 2018)
	450	33.09	2.75	1.29	0.005	7.80	0.05	0.27	(Mohammed et al., 2018)
	550	29.23	3.323	228.11	0.038	8.70	0.04	0.15	(Mohammed et al., 2018)
Rice straw	300	36.90	13.40	20.20	-	8.20	0.07	0.36	(Fan et al., 2018)
	500	30.10	28.40	50.11	-	9.70	0.04	0.27	(Fan et al., 2018)
	700	16.80	34.20	288.34		10.0	0.03	0.25	(Fan et al., 2018)

3.3. Biomass pre-treatment

The properties of biochar are significantly affected by the pre-treatment methods (Anukam & Berghel, 2020; Zadeh et al., 2020). Two familiar pre-treatment techniques are biomass particle size reduction and immersion of feedstock in a solution. When biomass is reduced in particle size, the production of biochar increases. A somewhat acidic solution was used to pre-treat pine wood, for instance. Pre-treatment processes such as nitrogen and metal doping can sway biochar synthesis, whilst solution pre-treatment techniques such as soaking or steaming can impact the elemental framework and biochar characteristics (Anukam & Berghel, 2020). Baking can diminish oxygen and humidity levels while enhancing carbon content (Zadeh et al., 2020).

3.4. Rate of heating

Heating conditions alter biochar production in addition to bio-oil and syngas products (Akhtar & Saidina Amin, 2012). Increased heating rates and optimal input material treatment temperatures stimulate bio-oil production; meanwhile, relatively low heating rates and optimum temperatures promote biochar synthesis. A reduced heating rate (20 °C s^{-1}) enabled the inherent porosity of the sawdust to be transmitted to the material with no apparent morphological modifications in the instance of biochar formed from pine sawdust. On the other hand, the sawdust cell structure was devolatilized at increased reaction temperatures (500 °C s^{-1}) (Xu & Chen, 2013). Greater overall pyrolysis temperatures, comparatively low heating rates, and prolonged residence time, on the other hand, accelerated biomass transition into gaseous yield. Lower calorific values and lower pyrolysis temperatures unmistakably led to char creation (Yorgun & Yıldız, 2015). Higher heating rates, short vapor residence times, and intermediate final pyrolysis temperatures (500-550 ^{o}C) frequently optimize the formation of liquid products. The portions of the three consistent products (biochar, liquids, and gases) can be changed and managed across a large range by adjusting the pyrolysis settings (Akhtar & Saidina Amin, 2012).

3.5. Size of the particle

Another essential aspect that affects how pyrolysis products disperse is the biomass particle dimensions. It involves the pace of heat and mass transmission as well as the intensity of side reactions within this particle. The particle size of input materials depends significantly on the feed ingredients and the pyrolysis technique. Fine particles are preferred for fast pyrolysis mechanisms owing to their ability to heat up more uniformly, releasing more volatile matter and improving the yields of bio-oil and gas products (Akhtar & Saidina Amin, 2012). The study showed that bigger particles (those with a size greater than 1.8 mm) exhibited higher internal temperature gradients, resulting in core temperatures that were lower than their surface temperatures. It has resulted in increased yields of liquid and char and lower yields of bio-oil and gas products (Aysu & Küçük, 2014). **Fig. 8** demonstrates the pictorial presentation of factors that influenced biochar adsorption ability.

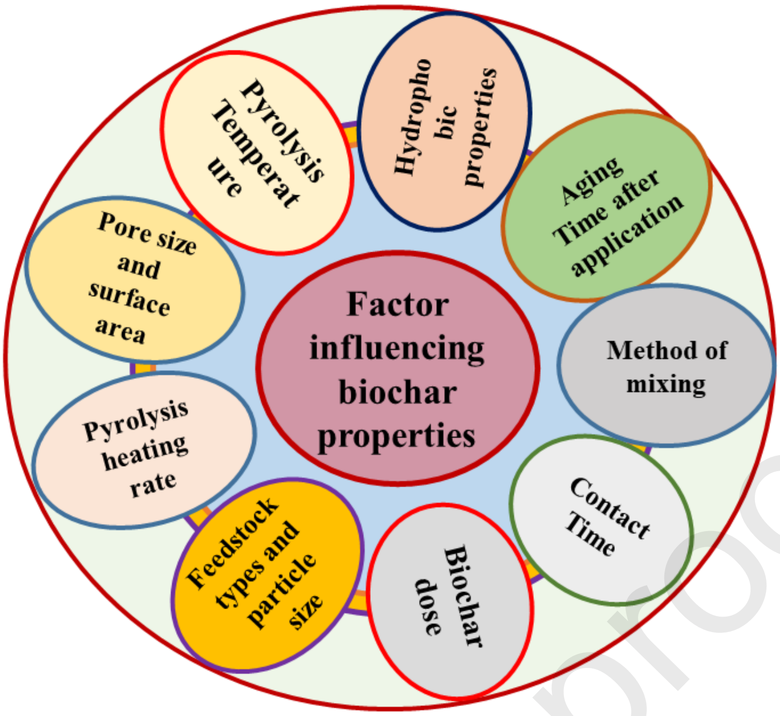


Fig. 8. Schematic presentation of factors that influenced biochar adsorption ability.

4. Factors affecting pollutant removal

The type of the targeted contaminants, the treatment's operating parameters, and the physicochemical properties of the biochar all have a substantial influence on the elimination of impurities and the material's adsorption capability (**Table 1**) (Jellali et al., 2021). With the use of the multivariate optimization technique, several studies have documented the impact of various factors and how they interact with one another on the effectiveness of pollutant removal (Salehi et al., 2020). The parameters that affect how well biochar removes organic contaminants are depicted in **Fig. 9.** The dose of biochar and the initial pH of the solution are the two most frequently addressed factors.

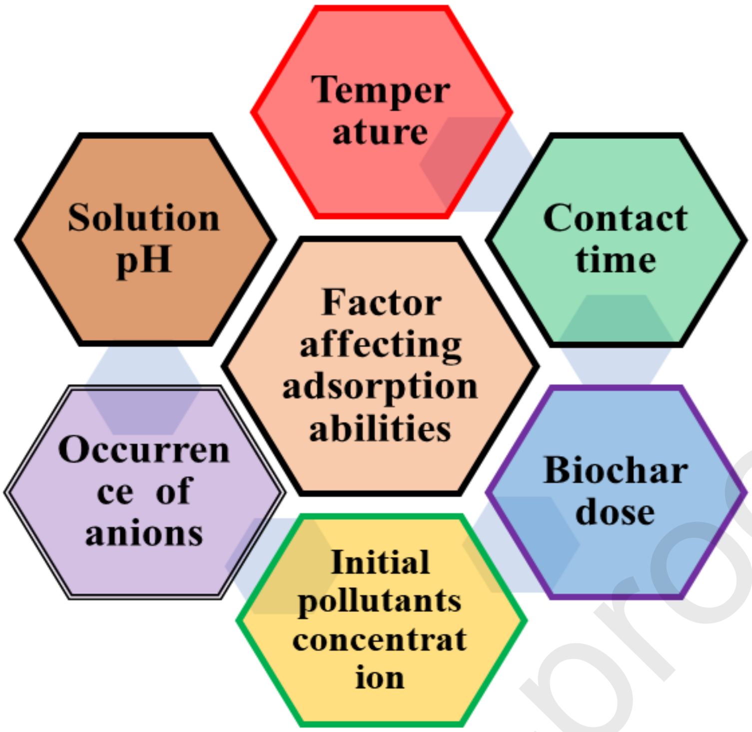


Fig. 9. The primary influencing factor is eliminating organic pollutants through biochar.

4.1. Effect of biochar dose

Adsorption studies frequently include the consequence of biochar quantity on pollutant deletion efficiencies since there is a considerable association between adsorbent dose and adsorption abilities. Despite this, a threshold biochar dose exists over which pollutant elimination does not increase (Singh & Srivastava, 2020). This trend is explained by using active adsorption sites for pollutant adsorption (Du et al., 2020). The drop in adsorption capacity after the ideal point may be caused by inadequate pollutant molecule availability for spare active sites (Wang et al., 2019). Separate research found that increasing the amount of biochar leads to the reaction equilibrium being achieved faster, showing a greater initial adsorption rate and greater accessibility of open reactive sites on the surface of the adsorbent (Vigneshwaran et al., 2021). Although only noticeably at lower doses and marginally more so at higher dosages, the adsorption capability decreases exponentially as biochar is raised (Lawal et al., 2021).

4.2. Effect of initial solution pH

The protonation and deprotonation of oxygen-rich molecules on the biochar surface or composites, along with the pH of the pollutant solution, affect the removal process's effectiveness (El Kassimi et al., 2020). Additionally, pH impacts the level of adsorbate ionization (El Kassimi et al., 2020). The positively charged adsorbent surface promotes anion adsorption at pH values lower than the point of zero charges (PZC). However, cation adsorption is increased when the surface is negatively charged, and the pH is greater than the PZC (Wang et al., 2020a). Chaukura et al. (2017) observed maximum methyl orange adsorption at pH values lower than the PZC of biochar; it was accounted for by a hypothetical electrostatic contact of the dyes to the interface of the biochar, assuming that they were anions at the conditions observed (Chaukura et al., 2017). As the pH of the solution increases, the ability of biochar or nano-metal biochar composites to adsorb organic dyes frequently decreases (Zhao et al., 2021).

4.3. Effect of pollutant concentration

The starting concentration of the adsorbate has a significant impact on the adsorption process's performance. According to studies, the adsorption capacity reduces as the initial concentration of contaminants rises (Zhou et al., 2019). This is explained by the targeted contaminants occupying active spots on the surface of the adsorbent material (Vigneshwaran et al., 2021). The starting concentration of the pollutant and the adsorption potential of biochar are inversely correlated; nevertheless, the pollutant removal yield declines over time (Mu & Ma, 2021). This may be explained by the fact that mass transfer improved substantially by applying a concentration driving force (Chakraborty et al., 2018), which boosted the rate of diffusion and raised the possibility that particles would reach the material surface (Iqbal et al., 2013). Sayin et al. (2021) confirmed that when ciprofloxacin starting concentration increased from 50 to 150 mg L^{-1}, adsorption efficiency decreased. This was attributed to the eventual saturation of a particularly active site for antibiotic molecule adsorption (Sayin et al., 2021). When *Indigo Carmine* (IC) dye was investigated for adsorption using *C. odorata* biochar, the study illustrated that with an increase in dye concentration (10 to 100 mg L^{-1}) with the same amount of biochar, a drop in elimination efficacy was noted (Nnadozie & Ajibade, 2021).

4.4. Effect of anions presence

A wide range of available anions, including NO_3, Cl, SO_4, and PO_4, may combat the contaminant particles during adsorption in an aquatic environment. Owing to the increased competition for the adsorption sites on the biochar interphase, Wang et al. (2021) discovered that the removal efficiency of parsanilic acid decreased when PO_4^3 was present (Wang et al., 2021). The decline in repulsion between adsorbent particles and the subsequent rise in nanomaterial aggregation caused by the increase in NaCl concentration resulted in a decrease in biochar's adsorption abilities (Liu et al., 2019a). Nevertheless, beyond a definite quantity of NaCl, the adsorption ability tends to grow, which was described by an upsurge in ionic strength, which accelerated the activity coefficient of water-insoluble organic constituents, leading to a reduction in solubility (i.e., salting-out effect), and was thus favorable to contaminant adsorption (Li et al., 2017). Other plausible causes include lower solubility of micropollutants in the presence of greater Na^+ concentrations and interface charge neutralization of carbon-rich adsorbents produced by double-layer compression (Shin et al., 2020).

4.5. Effect of contact time

The assessment of the biochar adsorption process must take contact time into account. As per testified reports, the adsorption efficiency increases exponentially at the commencement of the treatment before progressively declining till adsorption equilibrium is attained, at which time the sorption sites are filled (Yu et al., 2021b). The declining trend in the concentrations of the solution's bulk phase and the adsorbent's surface, along with the ultimate adsorption saturation of active biochar sites (Trinh et al., 2020). Numerous studies reported similar outcomes when ciprofloxacin was removed from the body (Li et al., 2018a; Velusamy et al., 2021). In their study on the elimination of ciprofloxacin by H_3PO_4-treated biochar, Sayin et al. (2021) noted that as treatment time increased, the rate at which antibiotic molecules were adsorbed decreased upto equilibrium point (Sayin et al., 2021). In their work, Nguyen et al. (2021) evaluated numerous metal salt-amended biochars generated from diverse agro-wastes for the elimination of Congo red dye. The results indicated the diverse equilibrium durations necessary for the dissimilar biochars used at the same initial dye concentration (Nguyen et al., 2021b).

4.6. Effect of temperature

The adsorption temperature can also influence the ability of biochar to remove impurities. The majority of water treatment studies, however, are accompanied by ambient temperature to mimic the temperature that occurs in the surroundings (25 ^{o}C) (Jung et al., 2018; Xu et al., 2019). The adsorption upsurges with temperature in the region of 15 to 35 ^{o}C, which is indicative of an endothermic reaction (Cheng et al., 2021a). Comparable findings on the endothermicity of p-nitrophenol adsorption by pine sawdust biochar (Liu et al., 2020) and diclofenac by pine wood biochar was observed (Lonappan et al., 2018). The chance of pollutant particles coming into touch with the active sites improved as the temperature rose (Jung et al., 2018). However, in an exothermic process, a rise in temperature within a similar range might cause a reduction in the adsorption capacity (Velusamy et al., 2021). Nonetheless, there exists a proportional relationship between temperature and molecular motion acceleration, which decreases the Gibbs free energy and promotes adsorbent-ion interaction (Zhu et al., 2020). The biochar surface can produce aromatic carbon that has better surface properties for adsorbing a wide variety of contaminants when the temperature is raised (Wang et al., 2016).

4.7. Effect of chemical impregnation ratio on the elimination of pollutants

Numerous studies were conducted to determine the impact of the ratio of magnetic to unprocessed material on the efficiency of pollution elimination. It has been discovered that increasing this proportion improves the ability of magnetic biochar adsorption up to a certain point, but increasing it further causes the adsorption capacity to diminish (Wang et al., 2016). Son et al. (2018), on the other hand, demonstrated that copper removal capacities decrease with decreasing biochar/Iron ratio and Fe-recovery efficiency, which is attributed to iron oxide particles choking the exterior pores of the biochar (Son et al., 2018). In addition, Yang et al. (2016) discovered that the development of oxygen-rich functional groups, particularly the C-O group, at the biochar surface augmented the elimination efficacy of mercury as the $FeCl_3$/sawdust impregnation mass ratio increased. However, excessive $FeCl_3$ might result in the following: (i) the accumulation of Fe_3O_4 molecules on the exterior of magnetic biochar and (ii) a change in the textural characteristics, which lowers the yield of mercury removal (Yang et al., 2016).

4.7.1. Post-processing modification of biochar: activation and functionalization

Based on the kind of biomass feedstock, biochars that still include different refractory oxides such as Fe_2O_3, SiO_2, KCl, Al_2O_3, $CaSO_4$, and $CaCO_3$ are produced by the thermal breakdown of biomass in an oxygen-free or significantly oxygen-limited environment (Vijayaraghavan, 2021). Additionally, the majority of pure biochars have negatively charged surfaces due to their many oxygen-containing function groups, which causes them to specifically sorb to cations (such as heavy metal ions) (Yang et al., 2019). However, sorption is restricted to anionic species (oxyanion, anionic dyes, and organics) (Tan et al., 2016). Due to the limited uses of biochar, researchers are compelled to alter biochar for specific purposes by introducing new and extra metal oxides using various techniques (Dai et al., 2021). Furthermore, the physicochemical characteristics of biochar produced from traditional biomass pyrolysis may be subpar, including surface area, pore volume, pore width, and surface oxygenated groups. These characteristics vary greatly and are influenced by the types of feedstock used and the conditions of manufacturing (Li et al., 2018b). However, in the process of treating water, the accessible functional groups carboxyl (-COOH), hydroxyl (-OH), and carbonyl (C=O) are crucial (Liu et al., 2012). The kind of functional groups that are already present on the surface have a significant impact on whether biochar is hydrophilic (measured by the polarity index) or hydrophobic (measured by the aromaticity).

There have been reports of several methods, including chemical and thermal treatments, impregnation, and steam activation, increasing the quantity of this last (Shen et al., 2008). Because of its advantageous physicochemical characteristics, which include a high surface area with a high active site, improved charge separation, greater accessibility of functional groups, a high porous volume, improved catalyzing capacity, stability, and recoverability, biochar can also function as a great photocatalyst when coupled with other catalysts (Ahmaruzzaman, 2021). Nevertheless, photocatalyst-based biochar synthesis has to be improved (Sun et al., 2020a). The adsorption and photocatalytic capabilities of the nanocomposites were both improved when a suitable quantity of ZnO was added to the charcoal (Yu et al., 2021a). The use of Mn- and Fe-loaded biochar for the removal of atrazine in an aqueous solution using heterogeneous catalytic ozonation produced similar results (Tian et al., 2021). Ahmaruzzaman presented many methods for synthesizing biochar-supported photocatalysts, including the Sol-gel method, the Solvothermal process, the Hydrothermal process, the Thermal Polycondensation methodology, and ultrasound-aided synthesis (Ahmaruzzaman, 2021). The various post-modification techniques for biochar can be categorized into four primary groups, as illustrated in **Fig. 10:** 1) modifying the surface area and porosity of the biochar; 2) altering the surface of the biochar to make it positively charged; 3) augmenting the surface oxygen-containing functional groups; and 4) magnetizing the biochar to aid in the recovery of the biochar particles. One treatment may be able to improve two or more properties at once. An example of this would be the H_2SO_4 treatment, which improves the amount of functional groups that contain oxygen while also improving specific surface area. Various categories for these changes have been documented in the literature (Cheng et al., 2021b). These include the categorization based on the physicochemical properties of the biochar that is the subject of the alteration (Li et al., 2018b), and the process type (chemical, physical, or composite) (Benis et al., 2020).

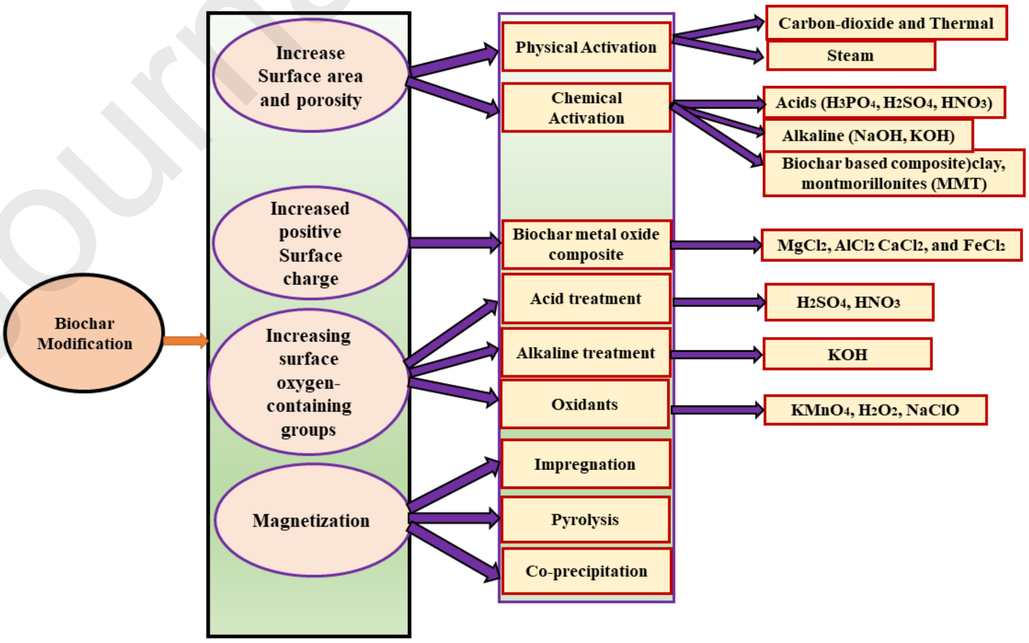


Fig. 10. Typical biochar modifications and their classification.

5. Biochar adsorption mechanism

It is essential to comprehend in what way biochar adsorbs toxins to improve its performance, particularly for the common pollutants present in livestock effluent, as this efficiency varies depending on the kind and character attributes of the contaminants. This study looked at biochar's organic framework, surface functional charge, surface electrical characteristics, and mineral content in the adsorption process.

5.1. Organic structure

Two layers make up the biochar's organic framework: stacked graphene sheets and aromatic structures dotted throughout the graphene (Joint Research et al., 2010). As a result, biochar has the advantage of having many pore structures and specific surface areas. The large SSA and tight pore architectures of biochar increase its physical adsorption effectiveness and make it easier to adsorb organic molecules with similar molecular masses (Tan et al., 2015).

5.2. Surface functional groups

The surface charge on the biochar repairs the metals by complex formation, interface precipitation, and attractive electrostatic forces. Even though the adsorption ability of Pb (II) was poorer at precise surface areas organized in high-temperature situations, surface functional groups on biochar surfaces would be demolished at temperatures of 500 ^{o}C or higher (Zhang et al., 2013b). This indicates that [OH and CH] surface functional groups are essential for HMs. The verified study exhibited that adding HNO_3/NH_3 to the surface of biochar made from chicken dung can provide novel amino functional groups that can improve dimethyl sulfide adsorption (Nguyen & Lee, 2015).

5.3. Surface electrical properties

The contaminant adsorption procedure depends heavily on the surface of the biochar's capacity to draw electrons and protons. A suitable adsorbent for positive ions like NH_3 and HMs is biochar, which typically has a negative surface charge. Anions like phosphate can be assimilated if the biochar is modified so that the exterior energy is polarised. Fang et al. (2014) enhanced corncob biochar by adding magnesium salt, making the surface energy of the positive biochar increase the effectiveness of phosphate adsorption (Fang et al., 2014).

5.4. Mineral ingredients

Mineral components in biochar, often including CO_3^{2-}, PO_3^{2-}, etc., can enhance their potential for adsorption. The surface precipitation was vital in the adsorption of Pb (II) by degraded cattle dung biochar. On the surface of the biochar, Pb (II) responded with CO_3^{2-}, HCO_3^-, and $H_2PO_4^-$ ions to yield $Pb(CO_3)_2(OH)_2$, $PbCO_3$, and $Pb_5(PO_4)_3X$ (where X may be F^-, Cl^-, Br^-, or OH^-) precipitate (Inyang et al., 2012). Without a doubt, several synergistic effects are used to adsorb particular microorganisms. In general, porosity incapacitation and the electrostatic interaction of organic surface charge are the only factors involved in the adsorption of organic carcinogens onto biochar. Electrostatic forces, ion exchange, responses of surface charge to complexation, and mineral component precipitation are the primary mechanisms by which HMs might be adsorbable. The main adsorption methods for nitrogen and phosphorus are electrostatic attraction and mineral composition precipitation.

6. Application of biochar

Biochar has a greater proportion of inert carbon components, oxygen-containing carbon groups, and a large surface area. It also has a pore structure that increases the soil's capacity to sequester carbon, reduce greenhouse gas emissions, improve structure, and increase crop yield (Lu et al., 2020; Yadav et al., 2023). The characteristics and composition of biochar affect the way it is used (Lu et al., 2020). The environment is negatively impacted by the high levels of organic matter, HMs, N_2, P, and other specific contaminants found in livestock waste. Biochar has a remarkable capacity to absorb pathogens while they are liquid. A total of 46% of the applications for the remediation of HMs, 13% for the adsorption of N_2 and P, 39% for the adsorption of organic pollutants (OPs), and the remaining 2% for the assessment of other activities were made utilized biochar in the remediation of contaminates (Tan et al., 2015).

6.1. Removal of organic pollutants

Antibiotics, phenolic compounds, herbicides, and other organic contaminants can be effectively absorbed by biochar (Zeghioud et al., 2022). The connection between the types of toxins taken and the different kinds of OPs in animal effluent has sparked much interest in agricultural properties and the environment. Sulfamethoxazole, fluoroquinolones, and several other antibiotics may all be absorbed by biocarbon in the aqueous phase. The aforementioned medicines are mainly adsorbed through interactions between electron donors and receptors, hydrogen bonds, and cationic bridges. Fluoroquinolone, an antibiotic used to treat diseases of the urinary system, intestine, respiratory system, soft skin tissue, joint, and abdominal cavity, has a maximum adsorption capacity of 19.40 mg g^{-1}. Additionally, a correlation between the amount of volatile substances in the source sludge and the percentage of fluoroquinolones that biochar adsorbs adsorb was shown to be positive. Sulfamethoxazole is an antibiotic used to treat Proteus and Escherichia coli-caused acute and chronic urinary tract infections. Sulfamethoxazole was adsorbed using biochar made from donax (Zheng et al., 2013). Inorganic elements in the raw feed heightened the sulfamethoxazole's ability to adsorb in low-temperature biochar while decreasing it in high-temperature. Phenols, herbicides, high-chroma organic contaminants, and other chemicals in the aqueous medium are significantly adsorbed by biochar (Sun et al., 2013). In addition to the polarity of the OPs and biochar, as well as the aromaticity or the compatibility of various surface charges, its adsorption method is subjected to a range of physical and chemical interactions. The intermolecular gravity and electrostatic force between OPs and biochar significantly influence its physical adsorption. The formation of hydrogen bonds, covalent bonds, and coordination bonds between environmental contaminants and biochar generally accomplishes chemical adsorption. To create biochar, coles, peanuts, and rapeseed straw were pyrolyzed at 350 °C and showed a 123.50-195.40 mg g^{-1} capacity for methyl violet adsorption (Qiu et al., 2009). The best methyl violet adsorption on rapeseed straw biochar occurred at cellar temperature. Methyl violet and charcoal were attracted to one another by an electric field, according to FTIR and zeta potential (ZP) tests. Zheng et al. (2010) produced biochar by pyrolyzing mixed wood waste at 450 ^{o}C for 1 h (Zheng et al., 2010). The maximal adsorption capacities of two herbicides, atrazine and simazine, originated to be 1158 and 1066 mg g^{-1}, respectively, and their adsorption efficiency increased in an acidic environment. **Table 5** shows the elimination of various OPs from an aqueous solution utilizing biochar.

Table 5. Remove organic pollutants from the aqueous solution using biochar.

Biomass	Contaminants	pH	Q_e (mg/g)	Q_m (mg/g)	Removal rate (%)	References
Corn stover	Methylene blue	11.0	201.6	349.7	25.2	(Li et al., 2019)
Eucalyptus bark	Methylene blue	11.3	90.1	104.2	36.8	(Dawood et al., 2016)
Kelp seaweed and spent mushroom substrate	Crystal violet	6.0	562.6	610.1	14.1	(Sewu et al., 2017)
Pine fruit shell	Phenol	6.5	16.0	16.0	31.9	(Mohammed et al., 2018)
Pinewood	Salicylic acid	2.5	10.0	22.7	40.0	(Essandoh et al., 2015)
Food waste	Phenol	3.0	9.8	14.6	65.2	(Lee et al., 2019)
Pine fruit shell	Phenol	6.5	9.9	10.4	19.8	(Mohammed et al., 2018)
Cattle manure	Methylene blue		161.3	242.0	97.5	(Zhu et al., 2018)
Pine fruit shell	Phenol	6.5	26.5	26.7	52.9	(Mohammed et al., 2018)

6.2. Heavy metal pollutants

Heavy metals are substances that have a density of greater than 4-5 g cm^{-3}, and the majority of them are unsafe for living creatures (Duruibe et al., 2007). The most common heavy metals are Pt, Pd, Ni, Hg, Cd, Zn, Pb, As, Ag, Cu, Fe, and Cr (Jaishankar et al., 2014), which can be released into the environment by either anthropogenic activity like mining and industries or by natural resources like volcanoes. The fundamental problem with heavy metals is that they cannot biodegrade, can build up in the environment, and then infiltrate the food chain (Singh et al., 2011). They are toxic and cause various diseases, including cancer, ulcers, osteomalacia, aminoaciduria, proteinuria, central and peripheral neuropathies, etc. (Mamtani et al., 2011). Heavy metals are poisonous and cannot be broken down by nature. Even if there is just a little deposition, health problems will still exist. Heavy metal contaminants in livestock wastewater, particularly Zn, Cd, Cu, and Pb, are present in high concentrations and can seriously pollute the environment (Gholizadeh & Hu, 2021). The electron transfer on its interface, chemical cross-linking of the HMs ions with its functional groups on the surface, and surface accumulation between the ashes are the statistically important aspects in explaining the adsorption of HMs ions on biochar. The results of pyrolyzing sugar beet root at 600 ^{o}C for 2 h yielded biochar at 22 ^{o}C, which had a clearance efficacy of around 97% for Cd (II), Ni (II), Pb (II), and Cu (II) (Inyang et al., 2012). Nevertheless, there was an inhibition of the four different ions' ability to adsorb. Although Cu (II) adsorption selectivity was least effective, Cd (II) adsorption was at its greatest. Sludge was pyrolyzed at temperatures of 300, 500, 700, and 900 ^{o}C to create biochar (Xing et al., 2019). The outcomes showed that biochar has a strong potential to lower soil levels of heavy metals. Liang et al. (2017) employed rice husk-derived biochar to treat the polluted soil from a wetland near Dongting Lake by pyrolyzing it at a temperature of 500 ^{o}C (Liang et al., 2017). The combination of 400 g of soil and 40 g of biochar was incubated for no more than two months. The findings showed that the levels of HMs in the soil decreased. **Table 6** listed the deletion of various HMs using biochar derived from different types of biomass.

Table 6. Biochar or activated carbon is made from biomass for the adsorption of different pollutants.

Feeds	Heavy Metal	pH	Temperature (°C)	Adsorption time (min)	Surface area (m^2/g)	Adsorption capacity (mg/g)	Removal efficiency (%)	Reference
Cron Stalk and Polyethylene	Pb(II)	4.5	25	5-720	304.99-581.85	99.95	50.35	(Fan et al., 2020)
Pulp mill sludge and rice straw	cadmium(II),	< 2	22	1440	-	29.5-42.7	30-62	(Islam et al., 2021)
Pulp mill sludge and rice straw	copper(II),	< 2	22	1440	-	18.5-39.4	30-62	(Islam et al., 2021)
Pulp mill sludge and rice straw	nickel(II)	< 2	22	1440	-	40.2-64.1	30-62	(Islam et al., 2021)
Pulp mill sludge and rice straw	lead(II)	< 2	22	1440	-	(109.9-256.4	30-62	(Islam et al., 2021)
Coconut shell	Ni	5	30	-	-	3.97	-	(Landin-Sandoval et al., 2020)

Elm tree	Pb	20	80	60	465-1085	232.56	-	(Kharrazi et al., 2020)
Corn Stalk	As	4	25	60	-	148.5	-	(Yang et al., 2022)
Bamboo, sugarcane and neem	Fe, Ni, Cu, Cr, Cd and Pb	4	35	-	1.04-43.90	-	99.83-99.96	(Singh et al., 2021a)
Corn Stalk	Cd	4	25	60	-	158.5	-	(Yang et al., 2022)
Palmae shells	Cd	8	25	35	-	9.87	93.20	(Egirani et al., 2020)
Tire combined with activated carbon.	Dyes	7	25	180	-	71.43	-	(Belgacem et al., 2022)
Citrus limetta peel	Cr (VI)	8	37	120	76.19	92.19	-	(Singh et al., 2021b)
Citrus limetta peel	Cr (III)	8	37	120	76.19	174.98	-	(Singh et al., 2021b)

6.3. Nitrogen and phosphorus pollutants

The wastewater from animals encompasses a range of nutrients, mainly N_2 and P. Most recent studies on resource recovery and recycling have focused on the exploitation of adsorption and fixing of biochar. In addition to minimizing eutrophication, biochar can also be recycled and returned to the soil, improving soil potency and recovering nutritional reserves. The biochar was produced from the pyrolysis of corncobs and then modified with calcium and magnesium (Fang et al., 2015). The results exhibited that reformed biochar has a significant ability to adsorb phosphate, with an extreme adsorption rate of 319.63 mg g^{-1} (Fang et al., 2015). This suggests that cations of magnesium and calcium may be added to corncob biochar to increase its ability to interact with ions, which in turn increases the efficiency of its phosphate adsorption. The results showed that phosphorus is incorporated in biochar, which may be used as fertilizers. **Table 7** lists the adsorption of various pollutants using biochar.

Table 7. Maximum capacity and mechanism for N and P adsorption on different biochars.

Pollutants	Feeds	Surface area (m^2/g)	pH	Temperature (K)	q_m (mg/g)	References
NO_3^-	Rice husk	179.0	7	298	2.1	(Pratiwi et al., 2016)
	Date palm-prepared at 300K	15.8	2	298	7.26	(Alsewaileh et al., 2019)
	Date palm-prepared at 700K	268.4	2	298	8.37	(Alsewaileh et al., 2019)
	Amine-grafted corn cob	-	6.5	297	49.9	(Kalaruban et al., 2016)
	Amine-grafted coconut copra	-	6.5	297	59.2	(Kalaruban et al., 2016)
	Quaternary Starch	-	6.5	303	205	(Chauhan et al., 2016)
	Chamaecyparis obtusa-prepared at 700 K	482.5	7.5	303	3.29	(Song et al., 2019)

NH_4^+	Rice husk	179.0	7	298	4.7	(Pratiwi et al., 2016)
	Avocado seed-derived	-	5	298	5.4	(Zhu et al., 2016)
	Corncob	-	7	298	12.83	(Nguyen et al., 2019)
	Rice husk (adsorption from slurry solutions)	273.6	7.8	318	59.56	(Kizito et al., 2015)
	Rice husk (adsorption from pure NH_4Cl)	-	7.8	303	71.94	(Kizito et al., 2015)
	Wood (adsorption from slurry solutions	11.0	9.8	318	78.06	(Kizito et al., 2015)
	Wood (adsorption from pure NH_4Cl)	-	9.8	303	133.33	(Kizito et al., 2015)
	SB-AE (Sugarcane bagasse)	-	9.8	298	73.4	(Mao et al., 2016)
	PSBMIHM-AE	-	7	298	100.2	(Mao et al., 2016)
	Corncob	23.3	5.65	297	0.04	(Micháleková-Richveisová et al., 2017)
	Activated Rice Husk Ash	-	6	303	0.74	(Mor et al., 2016)

PO_4^{3-}	Zirconium loaded okara	-	3	298	16.43	(Nguyen et al., 2015)
	Rape	184.0	2	333	19.46	(Zhang et al., 2019b)
	Chinese cabbage	124.0	2	333	19.66	(Zhang et al., 2019b)
	Canola straw	213.7	-	-	48.76	(Jiang et al., 2015)
	Soybean straw	134.9	5.2	298	53.99	(Jiang et al., 2015)
	Peanut straw	99.1	-	-	55.2	(Jiang et al., 2015)
	Eggshell and rice straw	25.8	7	298	204	(Liu et al., 2019b)
	Cow dung	225.0	7	298	345	(Chen et al., 2018)

6.4. Enhance the soil's properties and increase nutrient availability

In agriculture, the structure of soil enhances the application of biochar (Sakhiya et al., 2020), resulting in the improvement of the soil's physiological, chemical, and biological properties (Liang et al., 2017; Tisserant & Cherubini, 2019), which aids the agricultural soil in increasing its absorption capacity of nutrients. Through adsorption, biochar can remove all heavy metals easily compared to other techniques, including the elimination of toxic substances and organic pollutants in soil and plants **(Fig. 11)** (Wang & Wang, 2019). Biochar decomposes organic pollutants such as chlorobenzene, p-Nitrophenol, polychlorinated biphenyls, halo hydrocarbon, polycyclic aromatic hydrocarbons (PAHs), 2-chlorobiphenyl and diethyl phthalate. Using biochar in soil enhances water holding capacity, availability of soil moisture, improved water filtration, and nutrient retention (Ghassemi-Golezani & Farhangi-Abriz, 2022; Yadav & Khare, 2020b). Applying biochar to soil can restore soil fertility and improve its physical, chemical, and biological properties (Yadav & Khare, 2020b). The absorption of soil nutrients and water by roots decreases because of crop reductions that are affected by soil salinity (Ghosh & Maiti, 2022). The addition of biochar to soil can help reduce soil salinity, thereby increasing ion exchange capacity and enhancing essential and minor soil nutrients (Ghosh & Maiti, 2022; Yadav & Khare, 2020b). Once all the sodium in the soil is adsorbed, it results in an increase in exchangeable magnesium and calcium, which in turn replaces sodium in the soil, reducing its alkalinity (Yadav & Khare, 2020b). Biochar is a diverse nutrient source because it contains many of the essential plant nutrients; hence, it can influence nutrient interaction in the soil by making nutrients more available, reducing nutrient mobility, and altering the nutrient cycle and nutrient reactions in the soil (Bolan et al., 2022). It also reduces the soil's leaching loss of nitrogen fertilizer (Yadav & Khare, 2020b). The adsorption of potassium, nitrogen, phosphorous, and organic matter in the soil is high due to its high adsorption capacity (Ghosh & Maiti, 2022). Karimi et al. (2020) demonstrated that the use of biochar (BC200) stimulates the soil's inorganic nitrogen and increases the amount of accessible Fe, Cu, and Zn when applied to calcareous soil (Karimi et al., 2020).

6.5. Soil remediation

Soil contamination resulting from industrial and domestic activities, as well as different chemicals, compounds, or substances, can directly or indirectly impact the activities of non-targeted microorganisms (Ghosh & Maiti, 2022; Yadav & Khare, 2020b). Elimination of soil contaminants is possible through the utilization of biochar (Hale et al., 2015). It can reduce pollutants in the soil as it has a large surface area, superior water-holding capacity, and a porous structure. It is also an affordable and sustainable remedy developed from waste (Akhil et al., 2021). Numerous studies have shown that using biochar as an immobilization strategy effectively remediates soils contaminated with heavy metals and metalloids (Sharma et al., 2020a; Yaashikaa et al., 2019). Wang et al. (2019) found that biochar produced from Carya spp. can significantly adsorb and reduce the leaching of sodium bispyribac and clomazone in soil (Wang & Wang, 2019).

6.6. Induces microbial activity in the soil

The physical and chemical properties of soil after the addition of biochar alters, thereby affecting the ability to work as a carrier to establish microorganisms in the soil (Akhil et al., 2021). Soil microorganisms decompose organic matter, recycle nutrients, and enhance soil fertility, improving nutrient availability and crop production (Matykiewicz, 2020). Biochar in the soil helps increase the activity of microbes, leading to microbial growth by providing a medium for the microbes (Lehmann & Joseph, 2024; Lyu et al., 2020). Biochar improves soil quality and health by benefiting mycorrhizal fungi and soil organisms (Kannan et al., 2020). Further, Yang et al. (2021) documented that hat biogas-derived biochar positively affects microbiota by reducing arsenic and ferric ion suppression (Yang et al., 2021).

6.7. Climate change mitigation

Global warming caused by increasing greenhouse gas (GHG) is considered one of the significant environmental issues in the 21st century, and the carbon cycle plays a crucial role in both its cause and mitigation (Ahmad et al., 2023; Bolan et al., 2022). Biochar possesses exceptional physical and chemical properties, making it valuable for various applications aimed at enhancing environmental quality. It can act as a catalyst for contaminant degradation by accumulating transition metals **(Fig. 11)** (Lyu et al., 2020). Proper management of organic waste can indirectly reduce methane emissions from landfills, industrial energy usage, and other greenhouse gas emissions, thus helping mitigate climate change (Lehmann & Joseph, 2024). Montanarella & Lugato (2013), removing 0.49 GtC per year from the atmosphere through biochar application would require converting approximately 2.2 GtC of feedstock into biochar annually (Montanarella & Lugato, 2013). The pyrolysis of animal manures or the use of biochar can help reduce the leaching of phosphates and nitrates from soil, potentially mitigating nutrient runoff from agricultural watersheds **(Fig. 12)** (Lehmann & Joseph, 2024).

Biochar management is considered a system rather than just a distinct component, as it has the potential to reduce greenhouse gas emissions. Mineralization is less in biochar when compared to the raw material it is created from, which helps mitigate climate change by lowering the system's CO_2 emissions (Lehmann & Joseph, 2024; Lyu et al., 2020). Since biochar is tightly bound to soil particles, it results in decreased CO_2 emissions (Sharma et al., 2020b). The role of biochar has been investigated in two critical areas of climate change mitigation, i.e., carbon sequestration and GHG reduction.

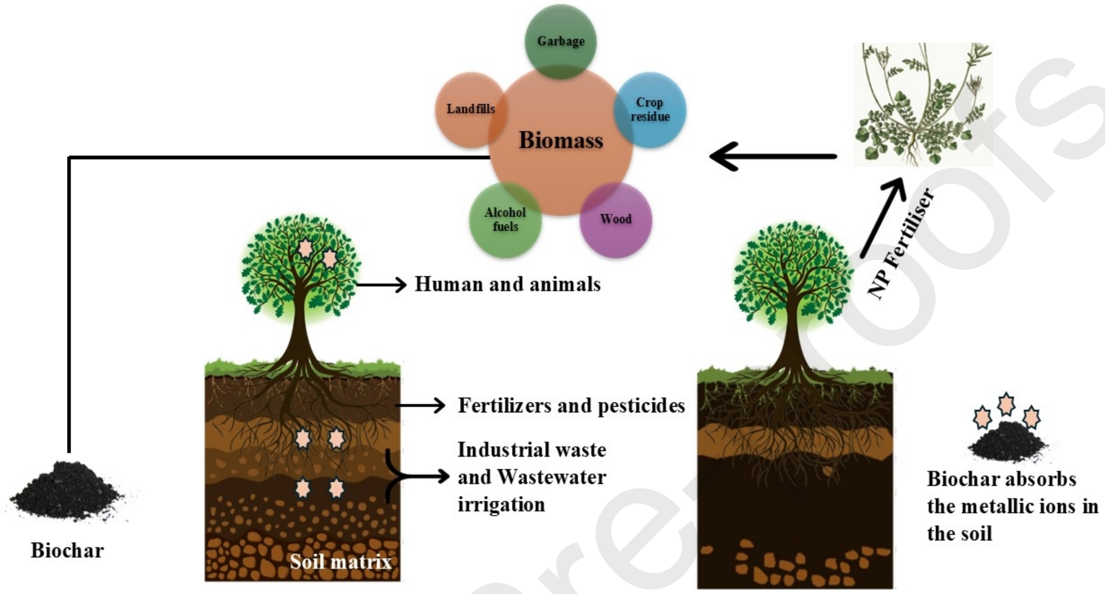


Fig. 11. Metal contamination remediation with biochar implication is depicted schematically by adsorbing the metallic impurities (Modified from Refs. (Shakya & Agarwal, 2020; Sharma et al., 2020b; Yadav & Khare, 2020b) (Shakya & Agarwal, 2020; Sharma et al., 2020b; Yadav & Khare, 2020a)).

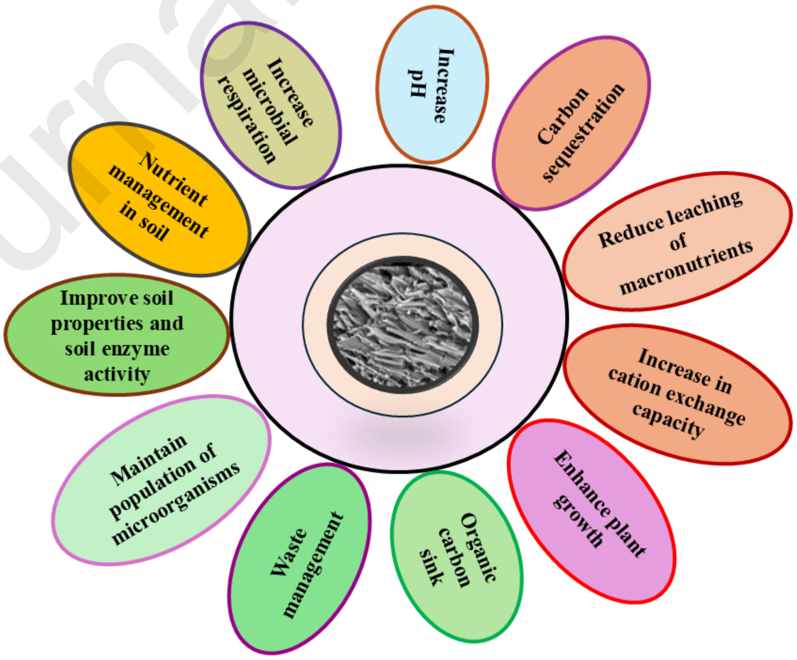


Fig. 12: Benefits of incorporating biochar into the soil with low physicochemical properties (Modified with Refs. Pankaj (2020); Panwar et al. (2019) (Pankaj, 2020; Panwar et al., 2019)).

6.8. Carbon sequestration

Biochar was initially proposed as a soil amendment to enhance carbon sequestration by storing stable carbon in the soil (Bolan et al., 2022). Biochar, a stable form of carbon, has the potential to serve as a long-term carbon store and significantly reduce greenhouse gas emissions. By using biomass in waste management strategies, organic carbon that would otherwise be burned or composted can be preserved as minerals over time. This makes biochar a promising alternative to current waste disposal systems. Additionally, certain biochar-based composites may enhance biochar's stability and carbon retention compared to virgin biochar (Wang et al., 2022). Creating biochar from leftover biomass from the agriculture and food processing industries can aid in long-term carbon sequestration and positively affect soils and environmental quality.

6.9. Mitigate greenhouse gas emissions

The usage of biochar on a global scale is estimated to reduce greenhouse gas emissions by 12% (Wang et al., 2022). Biochar alone can cut global GHG emissions, but a recent study suggests that applying biochar composite in the soil in place of virgin biochar can help improve climate change in 2 ways (Lehmann & Joseph, 2024; Wang et al., 2022). First, it is hypothesized that combining biochar with compost will enhance decomposition by adding stable carbon and creating a valuable biochar-compost mix, which could offset the drawbacks of pyrolysis biochar, such as low macronutrient content and methane emissions. Second, biochar has been associated with increased soil organic matter and reduced emissions of potent greenhouse gases like CH_4 and N_2O (Wang et al., 2022). In reality, increased plant growth or reduced soil greenhouse gas emissions may be needed for a biochar system to achieve a better emission balance compared to using biochar as charcoal fuel (Lehmann & Joseph, 2024). Biochar significantly reduces methane emissions from rice fields by promoting methanotroph communities (methane-consuming bacteria) and decreasing the diversity of methanogens (methane-producing bacteria) (Singh et al., 2017).

7. Water treatment by biochar at pilot scale

Water treatment by biochar at a pilot scale is gaining global attention as a sustainable and innovative approach to address water quality challenges. Across the world, various research initiatives and pilot projects are exploring the application of biochar in treating water from diverse sources. The process involves the production of biochar through biomass pyrolysis, followed by meticulous characterization of its physical and chemical properties. These pilot-scale systems, implemented in different regions, aim to assess the efficacy of biochar in adsorbing contaminants such as heavy metals and organic pollutants. The success of these endeavours relies on optimizing operational parameters based on local water conditions and contaminant profiles. As the results of these pilot projects become available, they contribute valuable insights into the feasibility and efficiency of biochar-based water treatment methods on a larger scale, providing a potential environmentally friendly solution to water quality management challenges worldwide. Given the volume of wastewater produced worldwide daily, it is critical to create pilot or industrial plant reactors based on biochar for the treatment of polluted water (Kakade et al., 2021). Very little research has been done on the removal of organic and inorganic contaminants from pilot-scale biochar reactors. A pilot-scale woodchip bioreactor modified with biochar was able to remove nitrate metal and trace organic pollutants from urban stormwater runoff. The bioreactor is made up of nine parallel columns, each measuring 10 cm in diameter and 50 cm in length, with the same adsorbent (woodchips, woodchips+biochar, and woodchips+straw) filled in every third column. The results indicated a limited adsorption ability for organic pollutants but a strong capacity to remove nitrate and four of the five metals examined (Cd, Cu, Ni, and Pb, but not Zn) (Ashoori et al., 2019). Last but not least, scientific developments regarding result extrapolation provide a serious issue that necessitates further research being done within the context of reusability throughout several cycles.

8. Conclusions and future research

This study examines various biochar production techniques, traits, and applications. The quantity and quality of biochar, which may be tailored to fit specific demands, are impacted by multiple pyrolysis conditions and feedstock components. An essential source of removing dangerous pollutants might be biochar. The occurrence of functional groups on the biochar surface, such as hydroxyl and carboxyl groups, is primarily responsible for releasing pollutants by biochar. It has been suggested that biochar is a viable adsorbent substance for the removal of organic pollutants from wastewater. A less expensive method and the potential for many cycles of biochar make biochar-based adsorbent manufacture feasible, according to certain estimates of production costs. However, further study from a variety of angles is required to guarantee the effectiveness and affordability of biochar and scale it up for enormous scale use in different areas. Several biochar sorbents that have been communicated to, including paper trash, pandanus leaves, coir pith, and coconut coir dust, have shown poor efficiency and limited ability to remove organic contaminants. Surface alterations are anticipated to contribute to their capacity growth. It is crucial to investigate the connections between a few key elements of the manufacturing process, activation, functionalization, and treatment to get the best possible environmental remediation potential for biochars in an environmentally responsible manner. It is essential to bear in mind that a bio-based sorbent with great potential for effective industrial application must possess economic appeal and have readily accessible raw materials in vast numbers found in the environment or as bio-residues. Utilizing these sorbents for multiple uses of regeneration and reuse on an industrial scale can save manufacturing costs and energy usage while providing a sustainable product. Because of their high adsorption capacity, affordability, and greater suitability for eliminating phenolic substances and anionic dyes, combined modified clay/biochar composites demonstrated significant benefits over single-modified clays.

The literature has very few investigations on the large-scale or pilot use of biochar for the elimination of organic contaminants. Research on magnetic biochar with catalytic degrading activity for the removal of organic pollutants from aqueous medium is making significant progress and is set to become a new area of attention. It is important to carefully analyze studies on the hazardous components created during the manufacture of magnetic biochar. It is essential to put into practice an environmentally sound management plan for pollutant-loaded sewage-derived biochars, or SDBs. The idea of the circular economy should guide this strategy, which would allow for i) the environmentally friendly and inexpensive regeneration and reuse of these SDBs in future adsorption cycles, ii) the recovery of the adsorbed chemicals and their reprocessing as resources in an industry; and iii) the protection of the environment against additional pollution. To create functional and affordable altered biochars for the effective removal of organic substances from wastewater, two strategy approaches should be investigated: i) The first involves employing a range of environmentally friendly chemicals to optimize the biochar physicochemical activation process. ii) The second alternative involves impregnating nanocomposites with generated biochar by taking advantage of its high specific surface areas.

A strong and creative tool in the trial's design and analysis stage is the employment of expertise plan software to optimize the influencing parameter. A branch of artificial intelligence (AI) called machine learning (ML) seeks to eliminate explicit computer programming through prediction and experience. Machine learning-based predictive models can minimize the amount of effort and expense needed and the time needed to remediate effluents. For instance, ML may be used to create prediction models for pyrolysis process optimization and forecast biochar yield and C-char based on pyrolysis parameters and biomass properties. Creating biochar substrates with a high ability to remove organic pollutants through science-based design can be a useful tool for developing sustainable wastewater treatment facilities. The generated models provided precise estimates of the adsorption capacity of the materials under consideration. The models were based on data from sophisticated microscopic and spectroscopic methods (biochar surface functionality and porous structure).

Real-scale applications need the development of more compact reactors that can hold catalysts supported by iochar. The use of biochar-based catalysts in pilot-scale reactors that may be utilized at the industrial level requires further investigation. Optimizing the characteristics of biochar and the activation procedures and parameters is crucial to achieving the greatest efficiency in eliminating organic pollutants, minimizing post-treatment byproducts, and reducing energy consumption. Coordinated efforts are currently underway to develop guidelines or best practices regarding the supply of biomass, the production of biochar, and the applications of biochar, which are primarily restricted to organic farming and agriculture under the auspices of the European Biochar Certificate (EBC) in Europe and the International Biochar Institute (IBI) on a global scale. Remember that the EBC has prioritized health and safety protection in the process of creating and utilizing biochar in an environmentally friendly manner. Although there is not yet a set of standards for the physicochemical characteristics of the substates that ensure adequate adsorption efficiencies, biochar-based substrates for environmental applications are a promising replacement for substrates currently used for wastewater treatment and the removal of organic pollutants. These well-coordinated efforts still take the form of literature reviews, which aim to make inferences and provide recommendations and guidelines for researchers who need to expand on the scattered but current body of knowledge regarding the possible uses of biochar and biochar composites in environmental applications.

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Availability of data and materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declaration of Competing Interest

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Author contributions

Deepraj Sarkar, Tanushka Florence Panicker: conceptualization, data curation, investigation, writing-original draft, and visualization; **Ranjeet Kumar Mishra:** conceptualization, data curation, methodology, investigation, visualization, original draft correction, and supervision. **M Srinivas Kini:** Administrator, investigation, visualization, and supervision

References

Abas, F.Z., Ani, F.N. 2014. Comparing characteristics of oil palm biochar using conventional and microwave heating. *Jurnal Teknologi*, **68**(3).

Ahmad, S., Jia, H., Ashraf, A., Yin, D., Chen, Z., Xu, C., Chenyang, W., Jia, Q., Xiaoyue, Z., Israr, M., Ahmed, R. 2023. Water resources and their management in Pakistan: A critical analysis on challenges and implications. *Water-Energy Nexus*, **6**, 137-150.

Ahmaruzzaman, M. 2021. Biochar based nanocomposites for photocatalytic degradation of emerging organic pollutants from water and wastewater. *Materials Research Bulletin*, **140**, 111262.

Akhil, D., Lakshmi, D., Kartik, A., Vo, D.-V.N., Arun, J., Gopinath, K.P. 2021. Production, characterization, activation and environmental applications of engineered biochar: a review. *Environmental Chemistry Letters*, **19**, 2261-2297.

Akhtar, J., Saidina Amin, N. 2012. A review on operating parameters for optimum liquid oil yield in biomass pyrolysis. *Renewable and Sustainable Energy Reviews*, **16**(7), 5101-5109.

Alsewaileh, A.S., Usman, A.R., Al-Wabel, M.I. 2019. Effects of pyrolysis temperature on nitrate-nitrogen (NO3−-N) and bromate (BrO3−) adsorption onto date palm biochar. *Journal of environmental management*, **237**, 289-296.

Amalina, F., Razak, A.S.A., Krishnan, S., Zularisam, A.W., Nasrullah, M. 2022. A comprehensive assessment of the method for producing biochar, its characterization, stability, and potential applications in regenerative economic sustainability – A review. *Cleaner Materials*, **3**, 100045.

Anukam, A., Berghel, J. 2020. *Biomass pretreatment and characterization: A review*. IntechOpen London, UK.

Ashoori, N., Teixido, M., Spahr, S., LeFevre, G.H., Sedlak, D.L., Luthy, R.G. 2019. Evaluation of pilot-scale biochar-amended woodchip bioreactors to remove nitrate, metals, and trace organic contaminants from urban stormwater runoff. *Water research*, **154**, 1-11.

Aysu, T., Küçük, M.M. 2014. Biomass pyrolysis in a fixed-bed reactor: Effects of pyrolysis parameters on product yields and characterization of products. *Energy*, **64**, 1002-1025.

Bai, X., Zhang, Y., Shi, J., Xu, L., Wang, Y., Jin, P. 2021. A new application pattern for sludge-derived biochar adsorbent: Ideal persulfate activator for the high-efficiency mineralization of pollutants. *Journal of Hazardous Materials*, **419**, 126343.

Bakraoui, M., Karouach, F., Ouhammou, B., Aggour, M., Essamri, A., El Bari, H. 2020. Biogas production from recycled paper mill wastewater by UASB digester: Optimal and mesophilic conditions. *Biotechnology Reports*, **25**, e00402.

Belgacem, A., Ould Brahim, I., Belmedani, M., Hadoun, H. 2022. Removal of methyl green dye from aqueous solutions using activated carbon derived from cryogenic crushed waste tires. *Iran. J. Chem. Chem. Eng. Research Article Vol*, **41**(1).

Benis, K.Z., Damuchali, A.M., Soltan, J., McPhedran, K.N. 2020. Treatment of aqueous arsenic–A review of biochar modification methods. *Science of The Total Environment*, **739**, 139750.

Bolan, N., Hoang, S.A., Beiyuan, J., Gupta, S., Hou, D., Karakoti, A., Joseph, S., Jung, S., Kim, K.-H., Kirkham, M. 2022. Multifunctional applications of biochar beyond carbon storage. *International Materials Reviews*, **67**(2), 150-200.

Cai, S., Zhang, Q., Wang, Z., Hua, S., Ding, D., Cai, T., Zhang, R. 2021. Pyrrolic N-rich biochar without exogenous nitrogen doping as a functional material for bisphenol A removal: Performance and mechanism. *Applied Catalysis B: Environmental*, **291**, 120093.

Cao, H., Xin, Y., Wang, D., Yuan, Q. 2014. Pyrolysis characteristics of cattle manures using a discrete distributed activation energy model. *Bioresource Technology*, **172**, 219-225.

Chakraborty, P., Show, S., Banerjee, S., Halder, G. 2018. Mechanistic insight into sorptive elimination of ibuprofen employing bi-directional activated biochar from sugarcane bagasse: Performance evaluation and cost estimation. *Journal of Environmental Chemical Engineering*, **6**(4), 5287-5300.

Chauhan, K., Kaur, J., Singh, P., Sharma, P., Sharma, P., Chauhan, G.S. 2016. An efficient and regenerable quaternary starch for removal of nitrate from aqueous solutions. *Industrial & Engineering Chemistry Research*, **55**(9), 2507-2519.

Chaukura, N., Murimba, E.C., Gwenzi, W. 2017. Synthesis, characterisation and methyl orange adsorption capacity of ferric oxide–biochar nano-composites derived from pulp and paper sludge. *Applied Water Science*, **7**(5), 2175-2186.

Chen, B., Chen, Z. 2009. Sorption of naphthalene and 1-naphthol by biochars of orange peels with different pyrolytic temperatures. *Chemosphere*, **76**(1), 127-133.

Chen, B., Zhou, D., Zhu, L. 2008. Transitional adsorption and partition of nonpolar and polar aromatic contaminants by biochars of pine needles with different pyrolytic temperatures. *Environmental science & technology*, **42**(14), 5137-5143.

Chen, Q., Qin, J., Sun, P., Cheng, Z., Shen, G. 2018. Cow dung-derived engineered biochar for reclaiming phosphate from aqueous solution and its validation as slow-release fertilizer in soil-crop system. *Journal of cleaner production*, **172**, 2009-2018.

Cheng, F., Li, X. 2018. Preparation and application of biochar-based catalysts for biofuel production. *Catalysts*, **8**(9), 346.

Cheng, H., Liu, Y., Li, X. 2021a. Adsorption performance and mechanism of iron-loaded biochar to methyl orange in the presence of Cr6+ from dye wastewater. *Journal of Hazardous Materials*, **415**, 125749.

Cheng, N., Wang, B., Wu, P., Lee, X., Xing, Y., Chen, M., Gao, B. 2021b. Adsorption of emerging contaminants from water and wastewater by modified biochar: A review. *Environmental Pollution*, **273**, 116448.

Choi, Y.-K., Kan, E. 2019. Effects of pyrolysis temperature on the physicochemical properties of alfalfa-derived biochar for the adsorption of bisphenol A and sulfamethoxazole in water. *Chemosphere*, **218**, 741-748.

Creamer, A.E., Gao, B. 2016. Carbon-Based Adsorbents for Postcombustion CO2 Capture: A Critical Review. *Environmental Science & Technology*, **50**(14), 7276-7289.

Dai, L., Lu, Q., Zhou, H., Shen, F., Liu, Z., Zhu, W., Huang, H. 2021. Tuning oxygenated functional groups on biochar for water pollution control: A critical review. *Journal of Hazardous Materials*, **420**, 126547.

Dai, Y., Wang, W., Lu, L., Yan, L., Yu, D. 2020. Utilization of biochar for the removal of nitrogen and phosphorus. *Journal of Cleaner Production*, **257**, 120573.

Dawood, S., Sen, T.K., Phan, C. 2016. Adsorption removal of Methylene Blue (MB) dye from aqueous solution by bio-char prepared from Eucalyptus sheathiana bark: kinetic, equilibrium, mechanism, thermodynamic and process design. *Desalination and water treatment*, **57**(59), 28964-28980.

Deng, Y., Zhang, T., Wang, Q. 2017. Biochar adsorption treatment for typical pollutants removal in livestock wastewater: a review. *Engineering applications of biochar*, **5**, 72-79.

Dey, S., Veerendra, G.T.N., Phani Manoj, A.V., Babu Padavala, S.S.A. 2024. Removal of chlorides and hardness from contaminated water by using various biosorbents: A comprehensive review. *Water-Energy Nexus*, **7**, 39-76.

Ding, J., Xu, W., Liu, S., Liu, Y., Tan, X., Li, X., Li, Z., Zhang, P., Du, L., Li, M. 2021. Activation of persulfate by nanoscale zero-valent iron loaded porous graphitized biochar for the removal of 17β-estradiol: Synthesis, performance and mechanism. *Journal of Colloid and Interface Science*, **588**, 776-786.

Dong, C., Fang, W., Yi, Q., Zhang, J. 2022. A comprehensive review on reactive oxygen species (ROS) in advanced oxidation processes (AOPs). *Chemosphere*, **308**, 136205.

Du, L., Xu, W., Liu, S., Li, X., Huang, D., Tan, X., Liu, Y. 2020. Activation of persulfate by graphitized biochar for sulfamethoxazole removal: The roles of graphitic carbon structure and carbonyl group. *Journal of Colloid and Interface Science*, **577**, 419-430.

Duruibe, J.O., Ogwuegbu, M., Egwurugwu, J. 2007. Heavy metal pollution and human biotoxic effects. *International Journal of physical sciences*, **2**(5), 112-118.

Egirani, D., Poyi, N., Shehata, N. 2020. Preparation and characterization of powdered and granular activated carbon from Palmae biomass for cadmium removal. *International Journal of Environmental Science and Technology*, **17**(4), 2443-2454.

EIA. 2021. Bioenergy has a critical role to play in getting on track with the Net Zero Scenario.

El Kassimi, A., Boutouil, A., El Himri, M., Laamari, M.R., El Haddad, M. 2020. Selective and competitive removal of three basic dyes from single, binary and ternary systems in aqueous solutions: A combined experimental and theoretical study. *Journal of Saudi Chemical Society*, **24**(7), 527-544.

Elkhalifa, S., Al-Ansari, T., Mackey, H.R., McKay, G. 2019. Food waste to biochars through pyrolysis: A review. *Resources, Conservation and Recycling*, **144**, 310-320.

Essandoh, M., Kunwar, B., Pittman Jr, C.U., Mohan, D., Mlsna, T. 2015. Sorptive removal of salicylic acid and ibuprofen from aqueous solutions using pine wood fast pyrolysis biochar. *Chemical Engineering Journal*, **265**, 219-227.

Fan, S., Sun, Y., Yang, T., Chen, Y., Yan, B., Li, R., Chen, G. 2020. Biochar derived from corn stalk and polyethylene co-pyrolysis: characterization and Pb (ii) removal potential. *RSC advances*, **10**(11), 6362-6376.

Fan, S., Wang, Y., Li, Y., Wang, Z., Xie, Z., Tang, J. 2018. Removal of tetracycline from aqueous solution by biochar derived from rice straw. *Environmental Science and Pollution Research*, **25**, 29529-29540.

Fang, C., Zhang, T., Li, P., Jiang, R., Wu, S., Nie, H., Wang, Y. 2015. Phosphorus recovery from biogas fermentation liquid by Ca-Mg loaded biochar. *J Environ Sci (China)*, **29**, 106-14.

Fang, C., Zhang, T., Li, P., Jiang, R.F., Wang, Y.C. 2014. Application of magnesium modified corn biochar for phosphorus removal and recovery from swine wastewater. *Int J Environ Res Public Health*, **11**(9), 9217-37.

Fang, J., Zhan, L., Ok, Y.S., Gao, B. 2018. Minireview of potential applications of hydrochar derived from hydrothermal carbonization of biomass. *Journal of Industrial and Engineering Chemistry*, **57**, 15-21.

Flesch, F., Berger, P., Robles-Vargas, D., Santos-Medrano, G.E., Rico-Martínez, R. 2019. Characterization and determination of the toxicological risk of biochar using invertebrate toxicity tests in the state of Aguascalientes, México. *Applied Sciences*, **9**(8), 1706.

Ghassemi-Golezani, K., Farhangi-Abriz, S. 2022. Improving plant available water holding capacity of soil by solid and chemically modified biochars. *Rhizosphere*, **21**, 100469.

Gholizadeh, M., Hu, X. 2021. Removal of heavy metals from soil with biochar composite: A critical review of the mechanism. *Journal of Environmental Chemical Engineering*, **9**(5), 105830.

Ghosh, D., Maiti, S.K. 2022. Mechanism of removal of contaminants by modified biochar. *BioChar: Applications for Bioremediation of Contaminated Systems*, 277.

Gupta, S., Kua, H.W., Koh, H.J. 2018. Application of biochar from food and wood waste as green admixture for cement mortar. *Science of the total environment*, **619**, 419-435.

Hale, L., Luth, M., Crowley, D. 2015. Biochar characteristics relate to its utility as an alternative soil inoculum carrier to peat and vermiculite. *Soil Biology and Biochemistry*, **81**, 228-235.

Hou, Y., Liang, Y., Hu, H., Tao, Y., Zhou, J., Cai, J. 2021. Facile preparation of multi-porous biochar from lotus biomass for methyl orange removal: Kinetics, isotherms, and regeneration studies. *Bioresource Technology*, **329**, 124877.

Hu, B., Tang, Y., Wang, X., Wu, L., Nong, J., Yang, X., Guo, J. 2021. Cobalt-gadolinium modified biochar as an adsorbent for antibiotics in single and binary systems. *Microchemical Journal*, **166**, 106235.

Huang, H., Reddy, N.G., Huang, X., Chen, P., Wang, P., Zhang, Y., Huang, Y., Lin, P., Garg, A. 2021. Effects of pyrolysis temperature, feedstock type and compaction on water retention of biochar amended soil. *Scientific Reports*, **11**(1), 7419.

Husain, Z., Ansari, K.B., Chatake, V.S., Urunkar, Y., Pandit, A.B., Joshi, J.B. 2020. Valorisation of biomass pellets to renewable fuel and chemicals using pyrolysis: characterisation of pyrolysis products and its application. *Indian Chemical Engineer*, **62**(1), 78-91.

IEA. 2021. Bioenergy 2021.

Inyang, M., Gao, B., Yao, Y., Xue, Y., Zimmerman, A.R., Pullammanappallil, P., Cao, X. 2012. Removal of heavy metals from aqueous solution by biochars derived from anaerobically digested biomass. *Bioresour Technol*, **110**, 50-6.

Iqbal, M.J., Farhan, C., Khalil, A., Munawar, I., Mushtaq, M., Naeem, M., Bokhari, T. 2013. Kinetic study of Cr (III) and Cr (VI) biosorption using Rosa damascena phytomass: a rose waste biomass. *Asian Journal of Chemistry*, **25**(4), 2099-2103.

Islam, M.S., Kwak, J.-H., Nzediegwu, C., Wang, S., Palansuriya, K., Kwon, E.E., Naeth, M.A., El-Din, M.G., Ok, Y.S., Chang, S.X. 2021. Biochar heavy metal removal in aqueous solution depends on feedstock type and pyrolysis purging gas. *Environmental Pollution*, **281**, 117094.

Jafri, N., Wong, W.Y., Doshi, V., Yoon, L.W., Cheah, K.H. 2018. A review on production and characterization of biochars for application in direct carbon fuel cells. *Process Safety and Environmental Protection*, **118**, 152-166.

Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B.B., Beeregowda, K.N. 2014. Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary toxicology*, **7**(2), 60.

Jellali, S., Khiari, B., Usman, M., Hamdi, H., Charabi, Y., Jeguirim, M. 2021. Sludge-derived biochars: A review on the influence of synthesis conditions on pollutants removal efficiency from wastewaters. *Renewable and Sustainable Energy Reviews*, **144**, 111068.

Jiang, J., Yuan, M., Xu, R., Bish, D.L. 2015. Mobilization of phosphate in variable-charge soils amended with biochars derived from crop straws. *Soil and Tillage Research*, **146**, 139-147.

Joint Research, C., Institute for, E., Sustainability, Bastos, A., Verheijen, F., Jeffery, S. 2010. *Biochar application to soils : a critical scientific review of effects on soil properties, processes and functions*. Publications Office.

Jung, K.-W., Lee, S.Y., Lee, Y.J. 2018. Hydrothermal synthesis of hierarchically structured birnessite-type MnO2/biochar composites for the adsorptive removal of Cu (II) from aqueous media. *Bioresource technology*, **260**, 204-212.

Kakade, A., Salama, E.-S., Han, H., Zheng, Y., Kulshrestha, S., Jalalah, M., Harraz, F.A., Alsareii, S.A., Li, X. 2021. World eutrophic pollution of lake and river: Biotreatment potential and future perspectives. *Environmental Technology & Innovation*, **23**, 101604.

Kalaruban, M., Loganathan, P., Shim, W., Kandasamy, J., Ngo, H., Vigneswaran, S. 2016. Enhanced removal of nitrate from water using amine-grafted agricultural wastes. *Science of the Total Environment*, **565**, 503-510.

Kambo, H.S., Dutta, A. 2015. A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications. *Renewable and Sustainable Energy Reviews*, **45**, 359-378.

Kang, Z., Jia, X., Zhang, Y., Kang, X., Ge, M., Liu, D., Wang, C., He, Z. 2022. A review on application of biochar in the removal of pharmaceutical pollutants through adsorption and persulfate-based AOPs. *Sustainability*, **14**(16), 10128.

Kannan, P., Krishnaveni, D., Ponmani, S. 2020. Biochars and its implications on soil health and crop productivity in semi-arid environment. *Biochar Applications in Agriculture and Environment Management*, 99-122.

Karimi, A., Moezzi, A., Chorom, M., Enayatizamir, N. 2020. Application of biochar changed the status of nutrients and biological activity in a calcareous soil. *Journal of Soil Science and Plant Nutrition*, **20**, 450-459.

Kharrazi, S.M., Mirghaffari, N., Dastgerdi, M.M., Soleimani, M. 2020. A novel post-modification of powdered activated carbon prepared from lignocellulosic waste through thermal tension treatment to enhance the porosity and heavy metals adsorption. *Powder Technology*, **366**, 358-368.

Kim, J.E., Bhatia, S.K., Song, H.J., Yoo, E., Jeon, H.J., Yoon, J.-Y., Yang, Y., Gurav, R., Yang, Y.-H., Kim, H.J. 2020. Adsorptive removal of tetracycline from aqueous solution by maple leaf-derived biochar. *Bioresource Technology*, **306**, 123092.

Kim, K.H., Kim, J.Y., Cho, T.S., Choi, J.W. 2012. Influence of pyrolysis temperature on physicochemical properties of biochar obtained from the fast pyrolysis of pitch pine (Pinus rigida). *Bioresour Technol*, **118**, 158-62.

Kizito, S., Wu, S., Kirui, W.K., Lei, M., Lu, Q., Bah, H., Dong, R. 2015. Evaluation of slow pyrolyzed wood and rice husks biochar for adsorption of ammonium nitrogen from piggery manure anaerobic digestate slurry. *Science of the Total Environment*, **505**, 102-112.

Kołodyńska, D., Wnętrzak, R., Leahy, J.J., Hayes, M.H.B., Kwapiński, W., Hubicki, Z. 2012. Kinetic and adsorptive characterization of biochar in metal ions removal. *Chemical Engineering Journal*, **197**, 295-305.

Koshila Ravi, R., Anusuya, S., Balachandar, M., Muthukumar, T. 2019. Microbial interactions in soil formation and nutrient cycling. in: *Mycorrhizosphere and pedogenesis*, Springer, pp. 363-382.

Kumar, A., Monika, Mishra, R.K., jaglan, S. 2022. Pyrolysis of low-value waste miscanthus grass: Physicochemical characterization, pyrolysis kinetics, and characterization of pyrolytic end products. *Process Safety and Environmental Protection*, **163**, 68-81.

Lam, S.S., Chase, H.A. 2012. A review on waste to energy processes using microwave pyrolysis. *Energies*, **5**(10), 4209-4232.

Landin-Sandoval, V., Mendoza-Castillo, D., Bonilla-Petriciolet, A., Aguayo-Villarreal, I., Reynel-Avila, H., Gonzalez-Ponce, H. 2020. Valorization of agri-food industry wastes to prepare adsorbents for heavy metal removal from water. *Journal of Environmental Chemical Engineering*, **8**(5), 104067.

Lawal, A.A., Hassan, M.A., Farid, M.A.A., Yasim-Anuar, T.A.T., Samsudin, M.H., Yusoff, M.Z.M., Zakaria, M.R., Mokhtar, M.N., Shirai, Y. 2021. Adsorption mechanism and effectiveness of phenol and tannic acid removal by biochar produced from oil palm frond using steam pyrolysis. *Environmental Pollution*, **269**, 116197.

Lee, C.-G., Hong, S.-H., Hong, S.-G., Choi, J.-W., Park, S.-J. 2019. Production of biochar from food waste and its application for phenol removal from aqueous solution. *Water, Air, & Soil Pollution*, **230**(3), 1-13.

Lee, J., Lee, K., Sohn, D., Kim, Y.M., Park, K.Y. 2018. Hydrothermal carbonization of lipid extracted algae for hydrochar production and feasibility of using hydrochar as a solid fuel. *Energy*, **153**, 913-920.

Lehmann, J., Joseph, S. 2024. *Biochar for environmental management: science, technology and implementation*. Taylor & Francis.

Leng, L., Huang, H., Li, H., Li, J., Zhou, W. 2019. Biochar stability assessment methods: a review. *Science of the total environment*, **647**, 210-222.

Li, J., Yu, G., Pan, L., Li, C., You, F., Xie, S., Wang, Y., Ma, J., Shang, X. 2018a. Study of ciprofloxacin removal by biochar obtained from used tea leaves. *Journal of Environmental Sciences*, **73**, 20-30.

Li, L., Yang, M., Lu, Q., Zhu, W., Ma, H., Dai, L. 2019. Oxygen-rich biochar from torrefaction: A versatile adsorbent for water pollution control. *Bioresource technology*, **294**, 122142.

Li, M.-f., Liu, Y.-g., Zeng, G.-m., Liu, S.-b., Hu, X.-j., Shu, D., Jiang, L.-h., Tan, X.-f., Cai, X.-x., Yan, Z.-l. 2017. Tetracycline absorbed onto nitrilotriacetic acid-functionalized magnetic graphene oxide: influencing factors and uptake mechanism. *Journal of Colloid and Interface Science*, **485**, 269-279.

Li, R., Wang, J.J., Gaston, L.A., Zhou, B., Li, M., Xiao, R., Wang, Q., Zhang, Z., Huang, H., Liang, W. 2018b. An overview of carbothermal synthesis of metal–biochar composites for the removal of oxyanion contaminants from aqueous solution. *Carbon*, **129**, 674-687.

Liang, J., Yang, Z., Tang, L., Zeng, G., Yu, M., Li, X., Wu, H., Qian, Y., Li, X., Luo, Y. 2017. Changes in heavy metal mobility and availability from contaminated wetland soil remediated with combined biochar-compost. *Chemosphere*, **181**, 281-288.

Liu, J., Yang, H., Gosling, S.N., Kummu, M., Flörke, M., Pfister, S., Hanasaki, N., Wada, Y., Zhang, X., Zheng, C., Alcamo, J., Oki, T. 2017. Water scarcity assessments in the past, present, and future. *Earth's Future*, **5**(6), 545-559.

Liu, L., Deng, G., Shi, X. 2020. Adsorption characteristics and mechanism of p-nitrophenol by pine sawdust biochar samples produced at different pyrolysis temperatures. *Scientific reports*, **10**(1), 1-11.

Liu, P., Liu, W.-J., Jiang, H., Chen, J.-J., Li, W.-W., Yu, H.-Q. 2012. Modification of bio-char derived from fast pyrolysis of biomass and its application in removal of tetracycline from aqueous solution. *Bioresource technology*, **121**, 235-240.

Liu, S., Li, M., Liu, Y., Liu, N., Tan, X., Jiang, L., Wen, J., Hu, X., Yin, Z. 2019a. Removal of 17β-estradiol from aqueous solution by graphene oxide supported activated magnetic biochar: adsorption behavior and mechanism. *Journal of the Taiwan Institute of Chemical Engineers*, **102**, 330-339.

Liu, X., Shen, F., Qi, X. 2019b. Adsorption recovery of phosphate from aqueous solution by CaO-biochar composites prepared from eggshell and rice straw. *Science of the total environment*, **666**, 694-702.

Liu, Y., Li, F., Deng, J., Wu, Z., Lei, T., Tan, M., Wu, Z., Qin, X., Li, H. 2021. Mechanism of sulfamic acid modified biochar for highly efficient removal of tetracycline. *Journal of Analytical and Applied Pyrolysis*, **158**, 105247.

Lonappan, L., Rouissi, T., Brar, S.K., Verma, M., Surampalli, R.Y. 2018. An insight into the adsorption of diclofenac on different biochars: mechanisms, surface chemistry, and thermodynamics. *Bioresource technology*, **249**, 386-394.

Lu, L., Yu, W., Wang, Y., Zhang, K., Zhu, X., Zhang, Y., Wu, Y., Ullah, H., Xiao, X., Chen, B. 2020. Application of biochar-based materials in environmental remediation: from multi-level structures to specific devices. *Biochar*, **2**, 1-31.

Luo, J., Ma, R., Lin, J., Sun, S., Gong, G., Sun, J., Chen, Y., Ma, N. 2023. Review of microwave pyrolysis of sludge to produce high quality biogas: Multi-perspectives process optimization and critical issues proposal. *Renewable and Sustainable Energy Reviews*, **173**, 113107.

Lyu, H., Zhang, Q., Shen, B. 2020. Application of biochar and its composites in catalysis. *Chemosphere*, **240**, 124842.

Ma, X., Zhou, B., Budai, A., Jeng, A., Hao, X., Wei, D., Zhang, Y., Rasse, D. 2016. Study of biochar properties by scanning electron microscope–energy dispersive X-ray spectroscopy (SEM-EDX). *Communications in Soil Science and Plant Analysis*, **47**(5), 593-601.

Ma, Y., Wu, L., Li, P., Yang, L., He, L., Chen, S., Yang, Y., Gao, F., Qi, X., Zhang, Z. 2021. A novel, efficient and sustainable magnetic sludge biochar modified by graphene oxide for environmental concentration imidacloprid removal. *Journal of Hazardous Materials*, **407**, 124777.

Mamtani, R., Stern, P., Dawood, I., Cheema, S. 2011. Metals and disease: A global primary health care perspective. *Journal of toxicology*, **2011**.

Mao, Y., Zhang, M., Yu, D., Wang, W., Song, Z., Zhao, X., Yue, Q. 2016. Improving the properties of an anion exchanger based on sugarcane bagasse by applying pretreatment methods. *Desalination and Water Treatment*, **57**(38), 17944-17954.

Matykiewicz, D. 2020. Biochar as an effective filler of carbon fiber reinforced bio-epoxy composites. *Processes*, **8**(6), 724.

Micháleková-Richveisová, B., Frišták, V., Pipíška, M., Ďuriška, L., Moreno-Jimenez, E., Soja, G. 2017. Iron-impregnated biochars as effective phosphate sorption materials. *Environmental Science and Pollution Research*, **24**(1), 463-475.

Mishra, R.K., Mentha, S.S., Misra, Y., Dwivedi, N. 2023. Emerging pollutants of severe environmental concern in water and wastewater: A comprehensive review on current developments and future research. *Water-Energy Nexus*, **6**, 74-95.

Mishra, R.K., Misra, M., Mohanty, A.K. 2022a. Value-Added Bio-carbon Production through the Slow Pyrolysis of Waste Bio-oil: Fundamental Studies on Their Structure–Property–Processing Co-relation. *ACS Omega*, **7**(2), 1612-1627.

Mishra, R.K., Misra, M., Mohanty, A.K. 2022b. Value-added biocarbon production through slow pyrolysis of mixed bio-oil wastes: studies on their physicochemical characteristics and structure–property–processing co-relation. *Biomass Conversion and Biorefinery*.

Mishra, R.K., Misra, M., Mohanty, A.K. 2022c. Value-added biocarbon production through slow pyrolysis of mixed bio-oil wastes: studies on their physicochemical characteristics and structure–property–processing co-relation. *Biomass Conversion and Biorefinery*, 1-15.

Mohamed Noor, N., Shariff, A., Abdullah, N. 2012. Slow pyrolysis of cassava wastes for biochar production and characterization. *Iranica Journal of Energy & Environment*, **3**(5).

Mohammed, N.A., Abu-Zurayk, R.A., Hamadneh, I., Al-Dujaili, A.H. 2018. Phenol adsorption on biochar prepared from the pine fruit shells: Equilibrium, kinetic and thermodynamics studies. *Journal of environmental management*, **226**, 377-385.

Mohan, D., Pittman Jr, C.U., Steele, P.H. 2006. Pyrolysis of wood/biomass for bio-oil: a critical review. *Energy & fuels*, **20**(3), 848-889.

Montanarella, L., Lugato, E. 2013. The application of biochar in the EU: challenges and opportunities. *Agronomy*, **3**(2), 462-473.

Mor, S., Chhoden, K., Ravindra, K. 2016. Application of agro-waste rice husk ash for the removal of phosphate from the wastewater. *Journal of Cleaner Production*, **129**, 673-680.

Mu, Y., Ma, H. 2021. NaOH-modified mesoporous biochar derived from tea residue for methylene Blue and Orange II removal. *Chemical Engineering Research and Design*, **167**, 129-140.

Nguyen, D.L.T., Binh, Q.A., Nguyen, X.C., Huyen Nguyen, T.T., Vo, Q.N., Nguyen, T.D., Phuong Tran, T.C., Hang Nguyen, T.A., Kim, S.Y., Nguyen, T.P., Bae, J., Kim, I.T., Van Le, Q. 2021a. Metal salt-modified biochars derived from agro-waste for effective congo red dye removal. *Environmental Research*, **200**, 111492.

Nguyen, D.L.T., Binh, Q.A., Nguyen, X.C., Nguyen, T.T.H., Vo, Q.N., Nguyen, T.D., Tran, T.C.P., Nguyen, T.A.H., Kim, S.Y., Nguyen, T.P. 2021b. Metal salt-modified biochars derived from agro-waste for effective congo red dye removal. *Environmental Research*, **200**, 111492.

Nguyen, M.-V., Lee, B.-K. 2015. Removal of Dimethyl Sulfide from Aqueous Solution Using Cost-Effective Modified Chicken Manure Biochar Produced from Slow Pyrolysis. *Sustainability*, **7**(11), 15057-15072.

Nguyen, T., Ngo, H., Guo, W., Pham, T., Li, F., Nguyen, T., Bui, X. 2015. Adsorption of phosphate from aqueous solutions and sewage using zirconium loaded okara (ZLO): fixed-bed column study. *Science of the Total Environment*, **523**, 40-49.

Nguyen, X.C., Chang, S.W., Tran, T.C.P., Nguyen, T.T.N., Hoang, T.Q., Banu, J.R., Ala'a, H., La, D.D., Guo, W., Ngo, H.H. 2019. Comparative study about the performance of three types of modified natural treatment systems for rice noodle wastewater. *Bioresource technology*, **282**, 163-170.

Nnadozie, E.C., Ajibade, P.A. 2021. Isotherm, kinetics, thermodynamics studies and effects of carbonization temperature on adsorption of Indigo Carmine (IC) dye using C. odorata biochar. *Chemical Data Collections*, **33**, 100673.

Ok, Y.S., Uchimiya, S.M., Chang, S.X., Bolan, N. 2015. *Biochar: Production, characterization, and applications*. CRC press.

Pankaj, U. 2020. Multifarious Benefits of Biochar Application in Different Soil Types. in: *Biochar Applications in Agriculture and Environment Management*, (Eds.) J.S. Singh, C. Singh, Springer International Publishing. Cham, pp. 259-272.

Panwar, N.L., Pawar, A., Salvi, B.L. 2019. Comprehensive review on production and utilization of biochar. *SN Applied Sciences*, **1**(2), 168.

Park, J.-H., Ok, Y.S., Kim, S.-H., Cho, J.-S., Heo, J.-S., Delaune, R.D., Seo, D.-C. 2016. Competitive adsorption of heavy metals onto sesame straw biochar in aqueous solutions. *Chemosphere*, **142**, 77-83.

Parmar, A., Nema, P.K., Agarwal, T. 2014. Biochar production from agro-food industry residues: a sustainable approach for soil and environmental management. *Current Science*, **107**(10), 1673-1682.

Patel, M., Kumar, R., Pittman Jr, C.U., Mohan, D. 2021. Ciprofloxacin and acetaminophen sorption onto banana peel biochars: environmental and process parameter influences. *Environmental Research*, **201**, 111218.

Patel, S., Kundu, S., Halder, P., Ratnnayake, N., Marzbali, M.H., Aktar, S., Selezneva, E., Paz-Ferreiro, J., Surapaneni, A., de Figueiredo, C.C. 2020. A critical literature review on biosolids to biochar: an alternative biosolids management option. *Reviews in Environmental Science and Bio/Technology*, **19**(4), 807-841.

Pratiwi, E.P.A., Pratiwi, E.P.A., Hillary, A.K., Fukuda, T., Shinogi, Y. 2016. The effects of rice husk char on ammonium, nitrate and phosphate retention and leaching in loamy soil. *Geoderma*, **277**, 61-68.

Praveen, S., Jegan, J., Bhagavathi Pushpa, T., Gokulan, R., Bulgariu, L. 2022. Biochar for removal of dyes in contaminated water: an overview. *Biochar*, **4**(1), 10.

Regmi, P., Garcia Moscoso, J.L., Kumar, S., Cao, X., Mao, J., Schafran, G. 2012. Removal of copper and cadmium from aqueous solution using switchgrass biochar produced via hydrothermal carbonization process. *J Environ Manage*, **109**, 61-9.

Rong, X., Xie, M., Kong, L., Natarajan, V., Ma, L., Zhan, J. 2019. The magnetic biochar derived from banana peels as a persulfate activator for organic contaminants degradation. *Chemical Engineering Journal*, **372**, 294-303.

Safaei Khorram, M., Zhang, Q., Lin, D., Zheng, Y., Fang, H., Yu, Y. 2016. Biochar: A review of its impact on pesticide behavior in soil environments and its potential applications. *Journal of Environmental Sciences*, **44**, 269-279.

Sakhiya, A.K., Anand, A., Kaushal, P. 2020. Production, activation, and applications of biochar in recent times. *Biochar*, **2**, 253-285.

Salehi, E., Askari, M., Velashjerdi, M., Arab, B. 2020. Phosphoric acid-treated spent tea residue biochar for wastewater decoloring: batch adsorption study and process intensification using multivariate data-based optimization. *Chemical Engineering and Processing-Process Intensification*, **158**, 108170.

Sayin, F., Akar, S.T., Akar, T. 2021. From green biowaste to water treatment applications: Utilization of modified new biochar for the efficient removal of ciprofloxacin. *Sustainable Chemistry and Pharmacy*, **24**, 100522.

Sewu, D.D., Boakye, P., Jung, H., Woo, S.H. 2017. Synergistic dye adsorption by biochar from co-pyrolysis of spent mushroom substrate and Saccharina japonica. *Bioresource technology*, **244**, 1142-1149.

Shakya, A., Agarwal, T. 2020. Potential of Biochar for the Remediation of Heavy Metal Contaminated Soil. in: *Biochar Applications in Agriculture and Environment Management*, (Eds.) J.S. Singh, C. Singh, Springer International Publishing. Cham, pp. 77-98.

Sharma, A., Jindal, J., Mittal, A., Kumari, K., Maken, S., Kumar, N. 2021. Carbon materials as CO2 adsorbents: a review. *Environmental Chemistry Letters*, **19**(2), 875-910.

Sharma, G.K., Jena, R.K., Hota, S., Kumar, A., Ray, P., Fagodiya, R.K., Malav, L.C., Yadav, K.K., Gupta, D.K., Khan, S.A. 2020a. Recent development in bioremediation of soil pollutants through biochar for environmental sustainability. *Biochar applications in agriculture and environment management*, 123-140.

Sharma, G.K., Jena, R.K., Hota, S., Kumar, A., Ray, P., Fagodiya, R.K., Malav, L.C., Yadav, K.K., Gupta, D.K., Khan, S.A., Ray, S.K. 2020b. Recent Development in Bioremediation of Soil Pollutants Through Biochar for Environmental Sustainability. in: *Biochar Applications in Agriculture and Environment Management*, (Eds.) J.S. Singh, C. Singh, Springer International Publishing. Cham, pp. 123-140.

Shen, Q., Wang, Z., Yu, Q., Cheng, Y., Liu, Z., Zhang, T., Zhou, S. 2020. Removal of tetracycline from an aqueous solution using manganese dioxide modified biochar derived from Chinese herbal medicine residues. *Environmental research*, **183**, 109195.

Shen, W., Li, Z., Liu, Y. 2008. Surface chemical functional groups modification of porous carbon. *Recent Patents on Chemical Engineering*, **1**(1), 27-40.

Shen, Z., Hou, D., Jin, F., Shi, J., Fan, X., Tsang, D.C., Alessi, D.S. 2019. Effect of production temperature on lead removal mechanisms by rice straw biochars. *Science of the Total Environment*, **655**, 751-758.

Shin, J., Lee, Y.-G., Lee, S.-H., Kim, S., Ochir, D., Park, Y., Kim, J., Chon, K. 2020. Single and competitive adsorptions of micropollutants using pristine and alkali-modified biochars from spent coffee grounds. *Journal of Hazardous Materials*, **400**, 123102.

Singh, C., Tiwari, S., Boudh, S., Singh, J.S. 2017. Biochar Application in Management of Paddy Crop Production and Methane Mitigation. in: *Agro-Environmental Sustainability: Volume 2: Managing Environmental Pollution*, (Eds.) J.S. Singh, G. Seneviratne, Springer International Publishing. Cham, pp. 123-145.

Singh, E., Kumar, A., Mishra, R., You, S., Singh, L., Kumar, S., Kumar, R. 2021a. Pyrolysis of waste biomass and plastics for production of biochar and its use for removal of heavy metals from aqueous solution. *Bioresource Technology*, **320**, 124278.

Singh, R., Gautam, N., Mishra, A., Gupta, R. 2011. Heavy metals and living systems: An overview. *Indian journal of pharmacology*, **43**(3), 246.

Singh, R., Naik, D.V., Dutta, R.K., Kanaujia, P.K. 2020. Biochars for the removal of naphthenic acids from water: a prospective approach towards remediation of petroleum refinery wastewater. *Journal of Cleaner Production*, **266**, 121986.

Singh, V., Singh, J., Mishra, V. 2021b. Sorption kinetics of an eco-friendly and sustainable Cr (VI) ion scavenger in a batch reactor. *Journal of Environmental Chemical Engineering*, **9**(2), 105125.

Singh, V., Srivastava, V.C. 2020. Self-engineered iron oxide nanoparticle incorporated on mesoporous biochar derived from textile mill sludge for the removal of an emerging pharmaceutical pollutant. *Environmental Pollution*, **259**, 113822.

Son, E.-B., Poo, K.-M., Chang, J.-S., Chae, K.-J. 2018. Heavy metal removal from aqueous solutions using engineered magnetic biochars derived from waste marine macro-algal biomass. *Science of the Total Environment*, **615**, 161-168.

Song, B., Sun, R., Liang, H., Hu, Y., Peng, P., She, D. 2019. Effects of lignin and biochar addition on soil nitrogen and phosphorus nutrients and water loss. *J. Soil Water Conserv*, **33**, 227-232.

Spokas, K.A. 2010. Review of the stability of biochar in soils: predictability of O: C molar ratios. *Carbon management*, **1**(2), 289-303.

Statistics, G.B. 2020. World bioenergy association.

Sun, J., Lin, X., Xie, J., Zhang, Y., Wang, Q., Ying, Z. 2020a. Facile synthesis of novel ternary g-C3N4/ferrite/biochar hybrid photocatalyst for efficient degradation of methylene blue under visible-light irradiation. *Colloids and Surfaces a: Physicochemical and Engineering Aspects*, **606**, 125556.

Sun, L., Wan, S., Luo, W. 2013. Biochars prepared from anaerobic digestion residue, palm bark, and eucalyptus for adsorption of cationic methylene blue dye: characterization, equilibrium, and kinetic studies. *Bioresour Technol*, **140**, 406-13.

Sun, Y., Iris, K., Tsang, D.C., Fan, J., Clark, J.H., Luo, G., Zhang, S., Khan, E., Graham, N.J. 2020b. Tailored design of graphitic biochar for high-efficiency and chemical-free microwave-assisted removal of refractory organic contaminants. *Chemical Engineering Journal*, **398**, 125505.

Sun, Y., Zhou, S., Chiang, P.-C., Shah, K.J. 2019. Evaluation and optimization of enhanced coagulation process: Water and energy nexus. *Water-Energy Nexus*, **2**(1), 25-36.

Tan, X.-f., Liu, Y.-g., Gu, Y.-l., Xu, Y., Zeng, G.-m., Hu, X.-j., Liu, S.-b., Wang, X., Liu, S.-m., Li, J. 2016. Biochar-based nano-composites for the decontamination of wastewater: a review. *Bioresource technology*, **212**, 318-333.

Tan, X., Liu, Y., Zeng, G., Wang, X., Hu, X., Gu, Y., Yang, Z. 2015. Application of biochar for the removal of pollutants from aqueous solutions. *Chemosphere*, **125**, 70-85.

Tan, Z., Zou, J., Zhang, L., Huang, Q. 2018. Morphology, pore size distribution, and nutrient characteristics in biochars under different pyrolysis temperatures and atmospheres. *Journal of Material Cycles and Waste Management*, **20**, 1036-1049.

Tian, S.-Q., Qi, J.-Y., Wang, Y.-P., Liu, Y.-L., Wang, L., Ma, J. 2021. Heterogeneous catalytic ozonation of atrazine with Mn-loaded and Fe-loaded biochar. *Water Research*, **193**, 116860.

Tisserant, A., Cherubini, F. 2019. Potentials, limitations, co-benefits, and trade-offs of biochar applications to soils for climate change mitigation. *Land*, **8**(12), 179.

Tomczyk, A., Sokołowska, Z., Boguta, P. 2020. Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. *Reviews in Environmental Science and Bio/Technology*, **19**(1), 191-215.

Trinh, V.T., Nguyen, T.M.P., Van, H.T., Hoang, L.P., Nguyen, T.V., Ha, L., Vu, X.H., Pham, T., Nguyen, T.N., Quang, N. 2020. Phosphate adsorption by silver nanoparticles-loaded activated carbon derived from tea residue. *Scientific reports*, **10**(1), 1-13.

Tripathi, M., Sahu, J.N., Ganesan, P. 2016. Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renewable and Sustainable Energy Reviews*, **55**, 467-481.

Unicef. 2017. World Water Day: one in four children will live with water scarcity by 2040. *The Guardian*.

Velusamy, K., Periyasamy, S., Kumar, P.S., Jayaraj, T., Krishnasamy, R., Sindhu, J., Sneka, D., Subhashini, B., Vo, D.-V.N. 2021. Analysis on the removal of emerging contaminant from aqueous solution using biochar derived from soap nut seeds. *Environmental Pollution*, **287**, 117632.

Vickers, N.J. 2017. Animal communication: when i'm calling you, will you answer too? *Current biology*, **27**(14), R713-R715.

Vigneshwaran, S., Sirajudheen, P., Nikitha, M., Ramkumar, K., Meenakshi, S. 2021. Facile synthesis of sulfur-doped chitosan/biochar derived from tapioca peel for the removal of organic dyes: Isotherm, kinetics and mechanisms. *Journal of Molecular Liquids*, **326**, 115303.

Vijayaraghavan, K. 2021. The importance of mineral ingredients in biochar production, properties and applications. *Critical Reviews in Environmental Science and Technology*, **51**(2), 113-139.

Wang, B., Lian, G., Lee, X., Gao, B., Li, L., Liu, T., Zhang, X., Zheng, Y. 2020a. Phosphogypsum as a novel modifier for distillers grains biochar removal of phosphate from water. *Chemosphere*, **238**, 124684.

Wang, C., Wang, H., Cao, Y. 2019. Waste printed circuit boards as novel potential engineered catalyst for catalytic degradation of orange II. *Journal of Cleaner Production*, **221**, 234-241.

Wang, J., Wang, S. 2019. Preparation, modification and environmental application of biochar: A review. *Journal of Cleaner Production*, **227**, 1002-1022.

Wang, L., Ok, Y.S., Tsang, D.C., Alessi, D.S., Rinklebe, J., Mašek, O., Bolan, N.S., Hou, D. 2022. Biochar composites: Emerging trends, field successes and sustainability implications. *Soil Use and Management*, **38**(1), 14-38.

Wang, S., Xia, X., Du, C., Zhang, X., Xiang, Q., Guo, S., Chen, Z. 2024. Effect of terminal temperature on the morphology and heavy metal concentrations of typical rural domestic biochar and its potential use in ammonia nitrogen adsorption. *Environmental Technology & Innovation*, **33**, 103528.

Wang, X., Guo, Z., Hu, Z., Zhang, J. 2020b. Recent advances in biochar application for water and wastewater treatment: a review. *PeerJ*, **8**, e9164.

Wang, Y., Jiang, B., Wang, L., Feng, Z., Fan, H., Sun, T. 2021. Hierarchically structured two-dimensional magnetic microporous biochar derived from hazelnut shell toward effective removal of p-arsanilic acid. *Applied Surface Science*, **540**, 148372.

Wang, Z., Han, L., Sun, K., Jin, J., Ro, K.S., Libra, J.A., Liu, X., Xing, B. 2016. Sorption of four hydrophobic organic contaminants by biochars derived from maize straw, wood dust and swine manure at different pyrolytic temperatures. *Chemosphere*, **144**, 285-291.

Wei, J., Tu, C., Yuan, G., Liu, Y., Bi, D., Xiao, L., Lu, J., Theng, B.K.G., Wang, H., Zhang, L., Zhang, X. 2019. Assessing the effect of pyrolysis temperature on the molecular properties and copper sorption capacity of a halophyte biochar. *Environmental Pollution*, **251**, 56-65.

Wiedner, K., Naisse, C., Rumpel, C., Pozzi, A., Wieczorek, P., Glaser, B. 2013. Chemical modification of biomass residues during hydrothermal carbonization–What makes the difference, temperature or feedstock? *Organic Geochemistry*, **54**, 91-100.

Xiang, L., Liu, S., Ye, S., Yang, H., Song, B., Qin, F., Shen, M., Tan, C., Zeng, G., Tan, X. 2021. Potential hazards of biochar: The negative environmental impacts of biochar applications. *Journal of Hazardous Materials*, **420**, 126611.

Xiang, W., Zhang, X., Chen, J., Zou, W., He, F., Hu, X., Tsang, D.C., Ok, Y.S., Gao, B. 2020. Biochar technology in wastewater treatment: A critical review. *Chemosphere*, **252**, 126539.

Xing, J., Li, L., Li, G., Xu, G. 2019. Feasibility of sludge-based biochar for soil remediation: Characteristics and safety performance of heavy metals influenced by pyrolysis temperatures. *Ecotoxicology and Environmental Safety*, **180**, 457-465.

Xiong, S., Deng, Y., Tang, R., Zhang, C., Zheng, J., Zhang, Y., Su, L., Yang, L., Liao, C., Gong, D. 2020. Factors study for the removal of epoxiconazole in water by common biochars. *Biochemical Engineering Journal*, **161**, 107690.

Xu, K., Zhang, C., Dou, X., Ma, W., Wang, C. 2019. Optimizing the modification of wood waste biochar via metal oxides to remove and recover phosphate from human urine. *Environmental geochemistry and health*, **41**(4), 1767-1776.

Xu, Y., Chen, B. 2013. Investigation of thermodynamic parameters in the pyrolysis conversion of biomass and manure to biochars using thermogravimetric analysis. *Bioresour Technol*, **146**, 485-493.

Yaashikaa, P., Kumar, P.S., Varjani, S.J., Saravanan, A. 2019. Advances in production and application of biochar from lignocellulosic feedstocks for remediation of environmental pollutants. *Bioresource technology*, **292**, 122030.

Yaashikaa, P.R., Kumar, P.S., Varjani, S., Saravanan, A. 2020. A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. *Biotechnology Reports*, **28**, e00570.

Yadav, S.P.S., Bhandari, S., Bhatta, D., Poudel, A., Bhattarai, S., Yadav, P., Ghimire, N., Paudel, P., Paudel, P., Shrestha, J. 2023. Biochar application: A sustainable approach to improve soil health. *Journal of Agriculture and Food Research*, **11**, 100498.

Yadav, V., Khare, P. 2020a. Impact of Pyrolysis Techniques on Biochar Characteristics: Application to Soil. in: *Biochar Applications in Agriculture and Environment Management*, (Eds.) J.S. Singh, C. Singh, Springer International Publishing. Cham, pp. 33-52.

Yadav, V., Khare, P. 2020b. Impact of pyrolysis techniques on biochar characteristics: Application to soil. *Biochar Applications in Agriculture and Environment Management*, 33-52.

Yang, D., Zhang, J., Yang, S., Wang, Y., Tang, X., Xu, J., Liu, X. 2022. Biochar-supported nanoscale zero-valent iron can simultaneously decrease cadmium and arsenic uptake by rice grains in co-contaminated soil. *Science of The Total Environment*, **814**, 152798.

Yang, J., Zhao, Y., Ma, S., Zhu, B., Zhang, J., Zheng, C. 2016. Mercury removal by magnetic biochar derived from simultaneous activation and magnetization of sawdust. *Environmental Science & Technology*, **50**(21), 12040-12047.

Yang, L., Chen, Y., Ouyang, D., Yan, J., Qian, L., Han, L., Chen, M., Li, J., Gu, M. 2020. Mechanistic insights into adsorptive and oxidative removal of monochlorobenzene in biochar-supported nanoscale zero-valent iron/persulfate system. *Chemical Engineering Journal*, **400**, 125811.

Yang, X., Wan, Y., Zheng, Y., He, F., Yu, Z., Huang, J., Wang, H., Ok, Y.S., Jiang, Y., Gao, B. 2019. Surface functional groups of carbon-based adsorbents and their roles in the removal of heavy metals from aqueous solutions: a critical review. *Chemical Engineering Journal*, **366**, 608-621.

Yang, Y., Ye, S., Zhang, C., Zeng, G., Tan, X., Song, B., Zhang, P., Yang, H., Li, M., Chen, Q. 2021. Application of biochar for the remediation of polluted sediments. *Journal of Hazardous Materials*, **404**, 124052.

Yorgun, S., Yıldız, D. 2015. Slow pyrolysis of paulownia wood: Effects of pyrolysis parameters on product yields and bio-oil characterization. *Journal of Analytical and Applied Pyrolysis*, **114**, 68-78.

Yu, F., Tian, F., Zou, H., Ye, Z., Peng, C., Huang, J., Zheng, Y., Zhang, Y., Yang, Y., Wei, X. 2021a. ZnO/biochar nanocomposites via solvent free ball milling for enhanced adsorption and photocatalytic degradation of methylene blue. *Journal of Hazardous Materials*, **415**, 125511.

Yu, K.L., Lau, B.F., Show, P.L., Ong, H.C., Ling, T.C., Chen, W.-H., Ng, E.P., Chang, J.-S. 2017. Recent developments on algal biochar production and characterization. *Bioresource technology*, **246**, 2-11.

Yu, K.L., Lee, X.J., Ong, H.C., Chen, W.-H., Chang, J.-S., Lin, C.-S., Show, P.L., Ling, T.C. 2021b. Adsorptive removal of cationic methylene blue and anionic Congo red dyes using wet-torrefied microalgal biochar: Equilibrium, kinetic and mechanism modeling. *Environmental pollution*, **272**, 115986.

Yun, E.-T., Lee, J.H., Kim, J., Park, H.-D., Lee, J. 2018. Identifying the nonradical mechanism in the peroxymonosulfate activation process: singlet oxygenation versus mediated electron transfer. *Environmental science & technology*, **52**(12), 7032-7042.

Zadeh, Z.E., Abdulkhani, A., Aboelazayem, O., Saha, B. 2020. Recent Insights into Lignocellulosic Biomass Pyrolysis: A Critical Review on Pretreatment, Characterization, and Products Upgrading. *Processes*, **8**(7), 799.

Zeghioud, H., Fryda, L., Djelal, H., Assadi, A., Kane, A. 2022. A comprehensive review of biochar in removal of organic pollutants from wastewater: characterization, toxicity, activation/functionalization and influencing treatment factors. *Journal of Water Process Engineering*, **47**, 102801.

Zhang, B., Zhang, L., Zhang, X. 2019a. Bioremediation of petroleum hydrocarbon-contaminated soil by petroleum-degrading bacteria immobilized on biochar. *RSC advances*, **9**(60), 35304-35311.

Zhang, J., Xia, X., Li, K., Shen, Y., Xue, Y. 2024. New insights into temperature-induced mechanisms of copper adsorption enhancement on hydroxyapatite-in situ self-doped fluffy bread-like biochar. *Chemical Engineering Journal*, **479**, 147657.

Zhang, K., Chang, J., Guan, Y., Chen, H., Yang, Y., Jiang, J. 2013a. Lignocellulosic biomass gasification technology in China. *Renewable Energy*, **49**, 175-184.

Zhang, P., O'Connor, D., Wang, Y., Jiang, L., Xia, T., Wang, L., Tsang, D.C., Ok, Y.S., Hou, D. 2020. A green biochar/iron oxide composite for methylene blue removal. *Journal of hazardous materials*, **384**, 121286.

Zhang, Q., Li, Q., Zhang, L., Yu, Z., Jing, X., Wang, Z., Fang, Y., Huang, W. 2017. Experimental study on co-pyrolysis and gasification of biomass with deoiled asphalt. *Energy*, **134**, 301-310.

Zhang, W., Mao, S., Chen, H., Huang, L., Qiu, R. 2013b. Pb(II) and Cr(VI) sorption by biochars pyrolyzed from the municipal wastewater sludge under different heating conditions. *Bioresour Technol*, **147**, 545-552.

Zhang, Z.-b., Cao, X.-h., Liang, P., Liu, Y.-h. 2013c. Adsorption of uranium from aqueous solution using biochar produced by hydrothermal carbonization. *Journal of Radioanalytical and Nuclear Chemistry*, **295**(2), 1201-1208.

Zhang, Z., Li, Y., Ding, L., Yu, J., Zhou, Q., Kong, Y., Ma, J. 2021. Novel sodium bicarbonate activation of cassava ethanol sludge derived biochar for removing tetracycline from aqueous solution: Performance assessment and mechanism insight. *Bioresource Technology*, **330**, 124949.

Zhang, Z., Yan, L., Yu, H., Yan, T., Li, X. 2019b. Adsorption of phosphate from aqueous solution by vegetable biochar/layered double oxides: fast removal and mechanistic studies. *Bioresource Technology*, **284**, 65-71.

Zhang, Z., Zhu, Z., Shen, B., Liu, L. 2019c. Insights into biochar and hydrochar production and applications: a review. *Energy*, **171**, 581-598.

Zhao, C., Wang, B., Theng, B.K., Wu, P., Liu, F., Wang, S., Lee, X., Chen, M., Li, L., Zhang, X. 2021. Formation and mechanisms of nano-metal oxide-biochar composites for pollutants removal: A review. *Science of The Total Environment*, **767**, 145305.

Zheng, H., Wang, Z., Zhao, J., Herbert, S., Xing, B. 2013. Sorption of antibiotic sulfamethoxazole varies with biochars produced at different temperatures. *Environ Pollut*, **181**, 60-7.

Zheng, W., Guo, M., Chow, T., Bennett, D.N., Rajagopalan, N. 2010. Sorption properties of greenwaste biochar for two triazine pesticides. *J Hazard Mater*, **181**(1-3), 121-6.

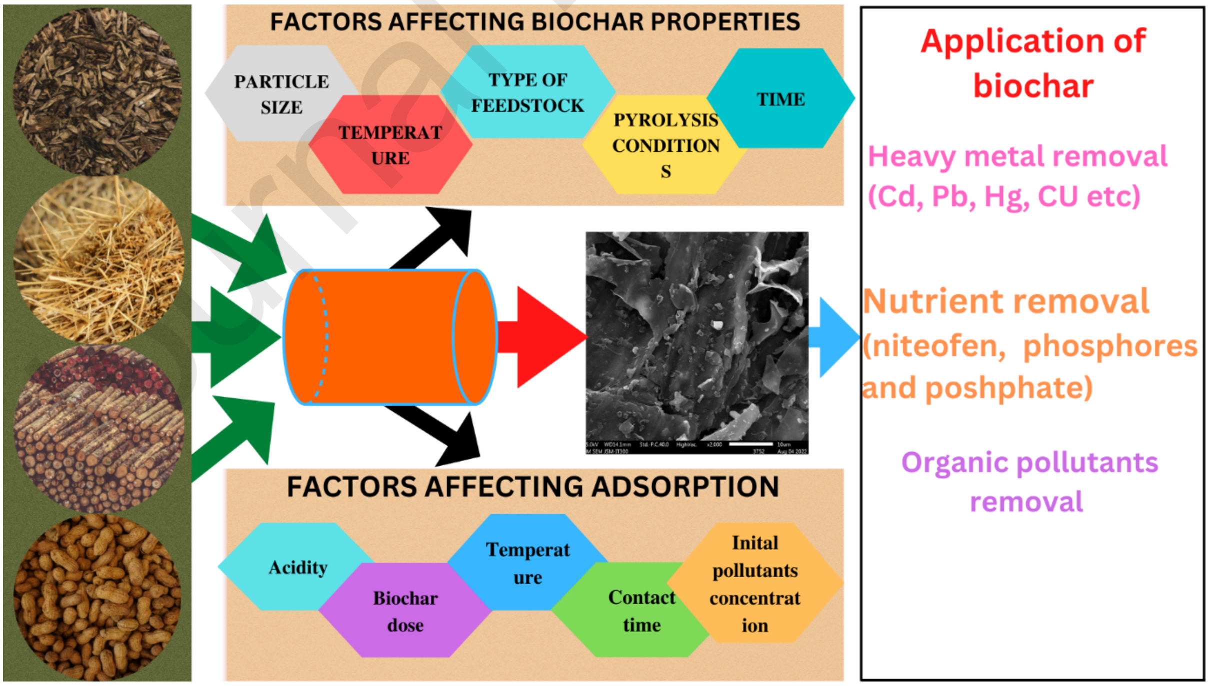
Zhou, Y., Lu, J., Zhou, Y., Liu, Y. 2019. Recent advances for dyes removal using novel adsorbents: a review. *Environmental pollution*, **252**, 352-365.

Zhu, Y., Dai, W., Deng, K., Pan, T., Guan, Z. 2020. Efficient removal of Cr (VI) from aqueous solution by Fe-Mn oxide-modified biochar. *Water, Air, & Soil Pollution*, **231**(2), 1-17.

Zhu, Y., Kolar, P., Shah, S.B., Cheng, J.J., Lim, P. 2016. Avocado seed-derived activated carbon for mitigation of aqueous ammonium. *Industrial Crops and Products*, **92**, 34-41.

Zhu, Y., Zheng, C., Wu, S., Song, Y., Hu, B. 2018. Interaction of Eu (III) on magnetic biochar investigated by batch, spectroscopic and modeling techniques. *Journal of Radioanalytical and Nuclear Chemistry*, **316**(3), 1337-1346.

Graphical Abstract



Highlights

- The pyrolysis of lignocellulosic biomass to produce biochar has been described.
- Process parameters influencing biochar production and its properties are reviewed.
- The conditions for pyrolysis and the factors that influence them have been discussed.
- Applications of biochar were investigated regarding its physicochemical properties.
- Biochar applications for pollutant removal are also inspected.

Declaration of Competing Interest

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