



Modified Biochar for Dye Removal from Wastewater: Recent Advances in Functionalization Techniques and Adsorption Mechanisms: A Review

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Abstract:

The presence of synthetic dyes in industrial wastewater presents a serious environmental threat due to their high chemical stability, toxicity, and resistance to biodegradation. This review provides a comprehensive analysis of recent advancements in the use of modified biochar as a sustainable and cost-effective adsorbent for dye removal from wastewater. Various thermal conversion methods, such as pyrolysis, hydrothermal carbonization, gasification, and torrefaction, are discussed, as they affect biochar properties, including porosity, carbon content, and active functional groups. Furthermore, the review systematically examines physical (e.g., heat treatment and grinding), chemical (e.g., modification with acids, bases, and metals), and biological (e.g., using algae or microorganisms) modification methods to enhance the adsorption capacity and selectivity of biochar. Special attention is given to chemical modifications, such as chitosan and metal impregnation, which have been reported to significantly improve dye removal efficiencies, often exceeding 80%. Various adsorption mechanisms were also analyzed, including physical adsorption, ion exchange, and electrostatic interactions. Moreover, the review highlights the role of surface area, porosity, and functional group composition in improving sorption capacities, alongside recent efforts to model and optimize these processes using artificial intelligence and machine learning. Finally, the modified biochar is an environmentally sustainable option for treating industrial wastewater and achieving circular economy goals.

Keywords:

Adsorption; Adsorption mechanisms; Biochar; Biochar modification; Dyes; Sustainability; Wastewater treatment.

Highlights:

- Modified biochar effectively removes persistent dyes from industrial wastewater.
- Chemical modifications (e.g., chitosan, metals) enhance dye removal efficiency >80%.
- Integration with computational models can optimize treatment and reduce costs.
- Modified biochar supports sustainable wastewater treatment and the circular economy.

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1. INTRODUCTION

The efficient management of wastewater has garnered attention in recent decades from the agricultural, industrial, and public health sectors. Owing to humans' use of water in many ways, resulting in the generation of very dangerous effluents, such as dyes, by-products, heavy metals, and others, which render water unsuitable for reuse in agriculture or human consumption [1]. Each year, the output of the global use of dye is around 2 million tons due to its application across several industries, including plastics, food, paper, textiles, cosmetics, inks, and pharmaceuticals. Approximately 15% of dye waste from the dyeing process is discharged into the environment. The presence of dye chemicals in aquatic environments leads to a reduction in dissolved oxygen levels, obstructing sunlight penetration into these water sources. Simultaneously, the bioaccumulation of dyes in the marine ecosystem might subsequently introduce harmful substances into the human food chain. Dyes are very stable chemicals with significant resistance to photolysis, rendering them enduring in natural environments [2]. Traditional methods for treating wastewater containing dyes include chemisorption, ozonation, ion exchange, membrane filtration, anaerobic lagoons, sedimentation, oxidation ponds, coagulation–flocculation, photocatalytic degradation, gamma irradiation, electrochemical methods, and biological treatments such as activated sludge and microbial degradation [3]. While many of these technologies can achieve satisfactory removal efficiencies, they often involve high operational costs, complex procedures, and the generation of secondary pollutants. For example, ozonation and advanced oxidation processes require specialized equipment and significant energy input, whereas membrane filtration is prone to fouling and requires frequent maintenance [4]. Adsorption is a very effective, environmentally friendly, and cost-effective method among these therapies, since other technologies require considerable chemicals and high energy consumption, making them economically inefficient. Chemical dye removal from wastewater typically involves the use of adsorbents with high specific surface area (SSA) in carbonaceous materials. Wastewater may be treated using inexpensive adsorbents, ideally made from natural resources and industrial byproducts, such as silica, fly ash, bentonite, cellulose, activated charcoal, biochar, and aerogels [5]. Because of its

usefulness in removing both organic and inorganic pollutants from wastewater in a synergistic fashion and its low cost, biochar has recently attracted considerable attention as an adsorbent. Biochar may be produced using the traditional pyrolysis method under anaerobic conditions at high temperatures; it has a high carbon content. Producing biochar specifically designed to adsorb organic contaminants is crucial for environmental protection because of its large surface area, numerous functional groups, and porous structure [6]. Among the many benefits of chitosan, a renewable and biodegradable polymer, are its wide range of uses, low cost, high biocompatibility, and biodegradability. Insect and crustacean exoskeletons are composed of chitin, the nitrogenous polymer that ranks second among naturally occurring polysaccharides. Chitosan is made up of linear copolymer chains made up of N-acetyl-D-glucosamine units and 2-amino-2-deoxy- β -D-glucose (deacetylated D-glucosamine). Chitosan primarily functions as an amino acid linker ($-\text{NH}_2$) in D-glucosamine units and as a hydroxyl bonder ($-\text{OH}$) in N-acetyl-D-glucosamine and D-glucosamine units. When these groups achieve a positive charge (NH_3^+ or H_3O^+), they may form a chelating ligand that electrostatically binds with dye anions or metal ions. Consequently, chitosan's efficacy as an adsorbent for removing metal ions or ionic dyes from aqueous solutions has [7]. Adding chitosan or other external materials to biochar is becoming more popular because it takes advantage of the synergistic effects of biochar's high surface area and porosity with chitosan's strong chemical affinity [8]. Table 1 summarizes the previous studies on dye adsorption using modified biochar. In addition, chitosan has the potential to act as an organic adhesive, thereby increasing biochar's capacity to adsorb pollutants by binding them to its surface [9]. The phloridzin adsorption capacity of 28.96 mg/g was almost twice that of 15.93 mg/g for unmodified biochar from apple branches, in contrast to chitosan-coated biochar [10]. The conversion of chicken litter into biochar for color adsorption from aqueous solutions has many advantages. Biochar made from poultry litter is rich in carbon and minerals such as potassium and phosphorus, making it highly porous and having a large specific surface area. This makes it ideal for effectively removing organic and inorganic dyes.

Table 1 The Conditions and Outcomes of Previous Studies.

Adsorbent	Adsorbate	Adsorb Dose	Contact Time (min)	Adsorption Capacity (mg/g)	Temp. (°C)	pH	Ref.
Buckthorn Fruits biochar	Congo Red	3 g/L	80	4.95 mg/g	25	5	[11]
Wet-torrefied microalgal biochar	Methylene blue	1 g/L	7200	113.00 mg/g	25	6	[12]
Wet-torrefied microalgal biochar	Congo red	2 g/L	240	164.35 mg/g	25	6–8	[12]
Surfactant Modified Chitosan Beads	Crystal violet	0.36 g	120	97.09 mg/g	50	6	[13]
Surfactant Modified Chitosan Beads	Tartrazine	0.72 g	120	30.09 mg/g	50	3	[13]
Calcium rich biochar from Crab Shell	Malachite green	0.50 g/L	150	12501.98 mg/g	25	7	[14]
Calcium rich biochar from Crab Shell	Congo Red	0.50 g/L	2	20317 mg/g	25	4	[14]
Ziziphus Lotus stones	Basic Yellow 28	0.5 g/L	180	424 mg/g	20	8	[15]
Ziziphus Lotus stones	Basic Red 46	0.5 g/L	180	307 mg/g	20	8	[15]
Date palm petiole derived biochar	Crystal violet	NA	15	209 mg/g	30	7	[16]
Activated wakame biochar material	Methylene blue	0.06 g/50 mL	NA	841.67 mg/g	20	2–12	[17]
Activated wakame biochar material	Rhodamine B	0.06 g/50 mL	NA	533.7 mg/g	20	2–12	[17]
Activated wakame biochar material	Malachite green	0.06 g/50 mL	NA	4066.96 mg/g	20	2–7	[17]
Activated biochar derived from <i>Opuntia ficus-indica</i>	Malachite green	60 mg/100 mL	120	1344.38 mg/g	30	6	[18]
Biochar derived from <i>Caulerpa scalpelliformis</i>	Remazol brilliant blue R	2 g/L	300	120.00 mg/g	30	2	[19]
Biochar derived from <i>Caulerpa scalpelliformis</i>	Remazol brilliant orange 3R	2 g/L	300	139.76 mg/g	30	2	[19]
Biochar derived from <i>Caulerpa scalpelliformis</i>	Remazol brilliant violet 5R	2 g/L	300	139.76 mg/g	30	2	[19]
Biochar derived from <i>Caulerpa scalpelliformis</i>	Remazol black B	2 g/L	300	159.08 mg/g	30	2	[19]

2.PRODUCTION OF BIOCHAR

Combustion, torrefaction, gasification, and slow and rapid pyrolysis are among the technologies used for biomass conversion [20]. The amounts of carbon and char produced by each method are different. Heat rate, feedstock residence time, yield, carbon content, and temperature are only a few of the factors that affect the processes. Charcoal was formerly made by burning woody biomass, which produced low yields and caused serious air pollution. Updates to methods for both endothermic and exothermic processes have allowed for the most effective means of extracting energy from organic materials. In contrast to combustion, gasification involves the thermal decomposition of organic substances in an oxygen-rich atmosphere [21]. Even yet, these methods fall short of meeting energy needs, offering less efficiency and less satisfaction in lowering emissions. Conversely, pyrolysis is the most prevalent, ancient, and efficient method for fulfilling energy demands and minimizing emissions [22]. Biochar (a solid), bio-oil (a liquid), and syngas (a gas) are the three end products of pyrolysis. It is possible to convert garbage into energy as a means of addressing the energy crisis. The pyrolysis process (Fig. 1) may be classified into slow, moderate, and fast categories based on heating rate, temperature, pressure, and residence time [23]. While quick pyrolysis at higher temperatures often yields greater

quantities of gases and liquids, slow pyrolysis should maintain a heating rate of 0.1-1 °C/min to achieve a considerable production of biochar. As the temperature rises, the proportion of pyrolysis solid in the total mass increases. Even though it produces biochar and bio-oil in equal measure, intermediate pyrolysis, which occurs between slow and rapid pyrolysis, is rarely recommended for biochar production [24, 25]. A number of factors, including feedstock type and pyrolysis temperature, affect BC properties. In this manner, several possible approaches to increasing BC production are proposed:

- (i) Minimizing energy waste in continuous feeding paralyzers by switching to batch reactors
- (ii) Using exothermic procedures to improve energy efficiency and biochar output
- (iii) Modifying Biochar characteristics (textural attributes and surface chemistry) by varying operational parameters
- (iv) Enhancing process economics and mitigating pollutant emissions
- (v) investigating novel biomass-derived feedstocks [5, 26].

2.1.Synthesis Methods of Producing Biochar

The high demand for biochar in many industries has prompted the transformation of biomass into biochar [27]. One common production process for biochar is

thermochemical conversion. Thermochemical conversion methods include hydrothermal

carbonization, pyrolysis, gasification, and torrefaction [28, 29].

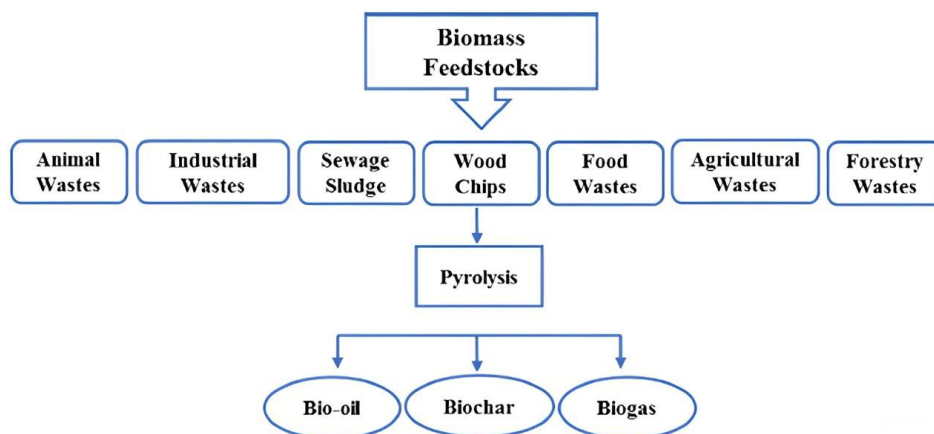


Fig. 1 Schematic Illustration of the Pyrolysis Process for Converting Biomass Feedstocks Into Biochar [30].

2.1.1. Pyrolysis

Pyrolysis is the thermal degradation of organic compounds in an oxygen-free environment, typically between 250–900 °C [31]. It breaks down materials such as lignin, cellulose, hemicellulose, and lipids, releasing non-carbon elements (e.g., oxygen, hydrogen) and thereby increasing carbon content [32]. The process yields syngas (CO, H₂, CO₂, C₁–C₂ hydrocarbons), bio-oil, and char as gaseous, liquid, and solid products, respectively. Figure 2 shows the schematic diagram of the process. Higher pyrolysis temperatures (>500 °C) enhance hydrophobicity, surface area, and microporosity, making biochar more effective for removing organic contaminants [33]. In contrast, lower temperatures (<500 °C) produce biochar with more oxygenated functional groups, favoring inorganic pollutant removal. Rising temperatures also increase ash content and pH [34, 35]. Pyrolysis may be categorized as either rapid or slow based on the heating rate, temperature, residence duration, and pressure.

2.1.1.1. Slow Pyrolysis

Slow pyrolysis, or classic pyrolysis, has been used since the early 1900s to produce methanol, ethanol, acetic acid, and charcoal from wood [36]. It involves gradually heating organic material in an oxygen-free environment to over 400 °C, using low heating rates (5–100 °C/min) and long residence times (5 minutes to several days) at 400–650 °C [37, 38]. This process favors the production of high-quality char with minimal liquid and gas byproducts [39–41]. While slow pyrolysis is a well-established method for biochar production, bio-oil recovery remains experimental [42].

2.1.1.2. Fast Pyrolysis

Fast pyrolysis is a thermochemical process that rapidly converts solid biomass into energy-rich

bio-oil. It involves high heating rates (>100 °C/min), short vapor residence times (0.5–2 s), and moderate temperatures (400–600 °C). To improve bio-oil quality, the vapors must be quickly cooled to minimize thermal degradation [43].

2.1.2. Hydrothermal Carbonization

Transforming wet biomass into biochar at moderate temperatures (180–250 °C) and elevated pressures (2–10 MPa) in the presence of water is known as hydrothermal carbonization (HTC) [45]. In contrast to conventional pyrolysis, hydrothermal carbonization (HTC) eliminates the need for feedstock desiccation, hence enhancing energy efficiency when processing high-moisture biomass, including food waste, algae, and sewage sludge [46]. During HTC, organic material undergoes hydrolysis, dehydration, and decarboxylation, producing hydrochar, a carbon-dense solid that may subsequently be converted into biochar [47]. This biochar has a substantial surface area and porosity, augmenting its capacity to absorb contaminants and enhance soil fertility when used as a soil amendment [48]. HTC biochar has superior stability and carbon retention relative to pyrolysis biochar, making it a tool that effectively offsets the effects of climate change and sequesters carbon [49]. Nonetheless, obstacles such as substantial upfront investment costs and the need for effective wastewater management must be addressed for widespread deployment [50]. Notwithstanding these constraints, HTC remains a viable technique for sustainable waste valorization and biochar synthesis, offering considerable environmental and economic advantages [51]. Figure 3 illustrates the schematic diagram of the hydrothermal carbonization process.

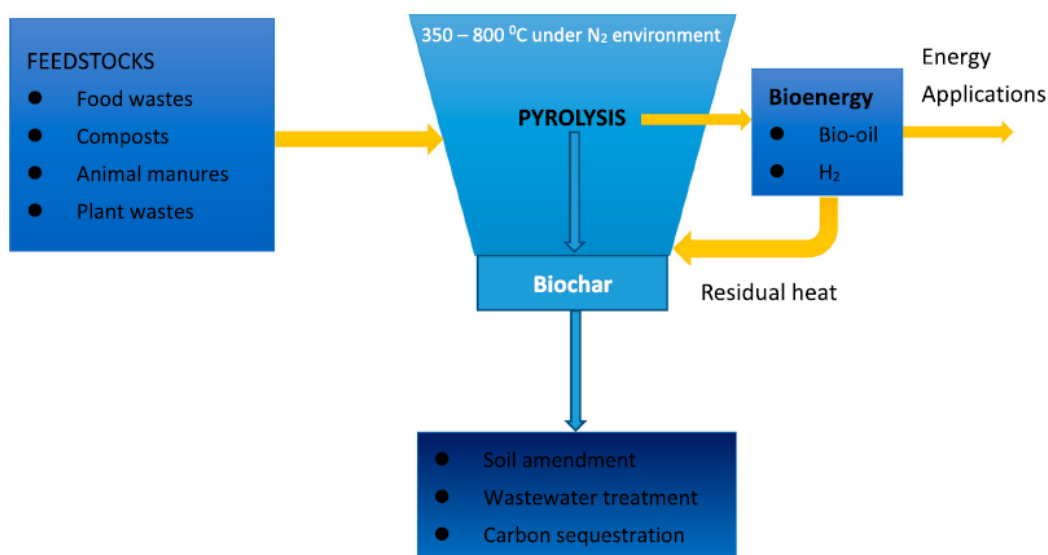


Fig. 2 Schematics of Biochar and Bioenergy Production Process During Pyrolysis [44].

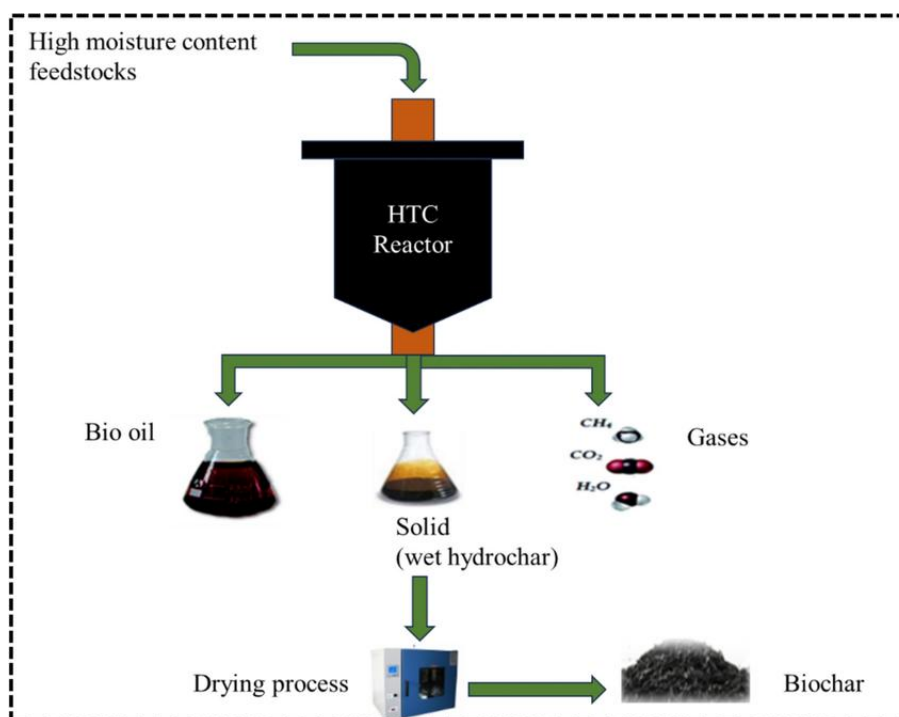


Fig. 3 Schematic Illustration of the Hydrothermal Carbonization (HTC) Process for Converting High-Moisture Biomass into Biochar [52].

2.1.3. Gasification

Using gasification agents like steam, oxygen, or carbon dioxide, carbonaceous materials undergo a thermochemical transformation to produce syngas, a gaseous mixture of carbon, carbon dioxide, methane, and other minor hydrocarbons [53]. The main factor determining syngas production is reaction temperature. Carbon monoxide and hydrogen synthesis increased with increasing temperature, but methane, carbon dioxide, and hydrocarbon levels declined [54]. The process primarily yields syngas as an immediate byproduct, whereas char is formed in relatively lower amounts [55]. A diagram illustrating the gasification process is provided in Fig. 4. The process can be divided into the following steps:

2.1.3.1. Drying

This process eliminates the moisture content of biomass entirely without any energy recovery. Since moisture levels vary across different biomass types, a separate drying step is typically required during gasification, especially when the biomass has a high moisture content [56].

2.1.3.2. Oxidation/Combustion

The gasification process relies on the oxidation and combustion of gasification agents as its primary energy sources. By reacting with the combustible elements in a gasifier, gasification agents create carbon dioxide (CO₂) and water [57].

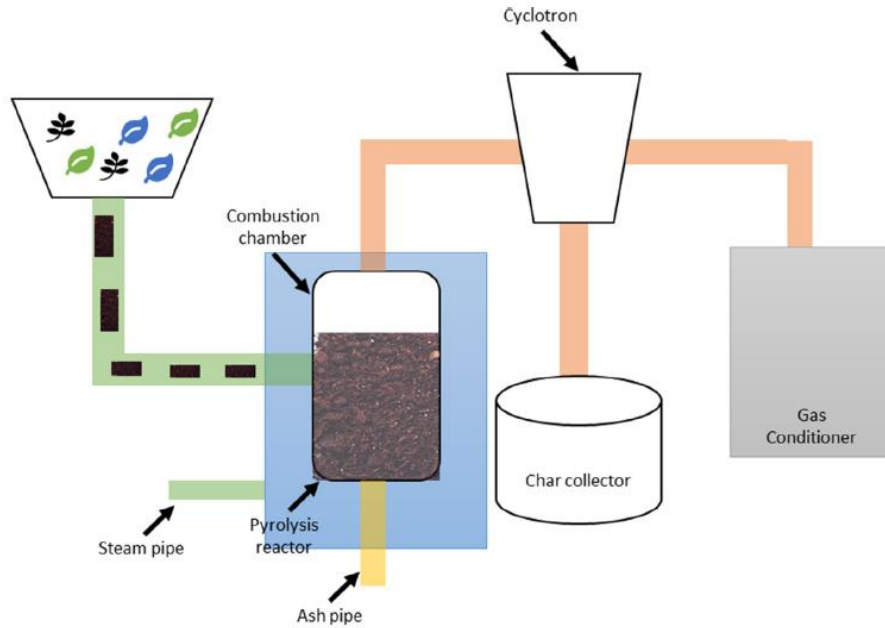


Fig. 4 Schematic Diagram of the Biomass Gasification Process Showing the Pyrolysis Reactor, Combustion Chamber, Gas Cleaning System, and Char Collection [30].

2.1.4. Torrefaction

Torrefaction is a mild thermal treatment of biomass, often called mild pyrolysis, carried out at 200–300 °C under limited oxygen [58]. While biochar for water treatment is typically produced via pyrolysis, torrefaction is primarily used for biofuel production. However, torrefaction-char, due to its higher oxygen-containing functional groups and simpler production process, shows promise as an adsorbent [59]. Li et al. [60] found that torrefaction-char outperformed pyrolyzed biochar in removing U(VI) and methylene blue,

with significantly higher adsorption capacities (192.7 mg/g vs. 56.2 mg/g). Similarly, torrefied barley straw at 220 °C for 20 minutes showed improved dye uptake. Its high yield, lower energy input, and enhanced adsorption potential make torrefaction-char a promising material for water purification [61]. Figure 5 illustrates the schematic diagram of the steps involved in the torrefaction process, and Table 2 shows the advantages and disadvantages of the biochar preparation methods.

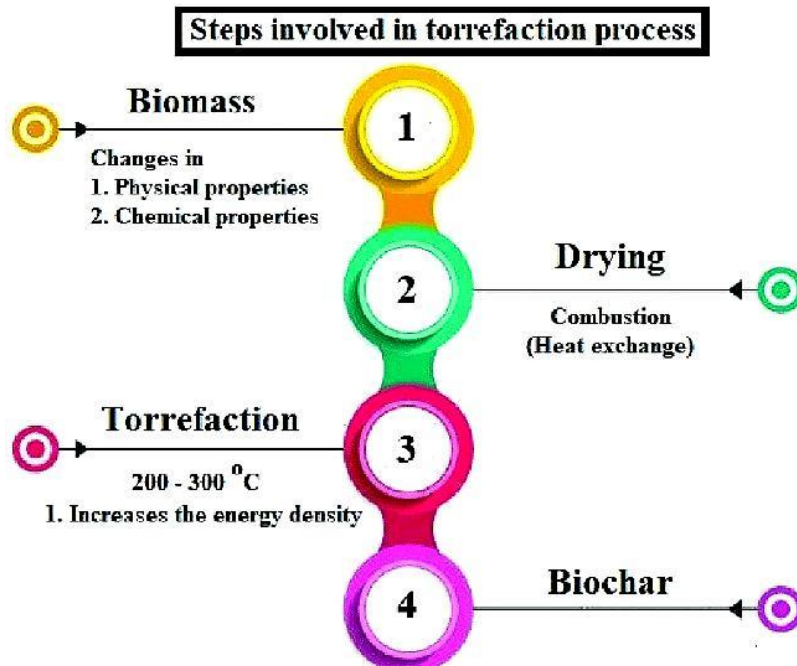


Fig. 5 Steps Involved in the Torrefaction Process [62].

Table 2 A Synopsis of the Benefits and Drawbacks of Biochar Preparation Processes.

The Preparation Methods	Advantages	Disadvantages
Pyrolysis	Minimal size requirements for raw materials, increased yields, and decreased manufacturing costs [63].	Long response time [64].
Hydrothermal carbonization	Eliminates the need for pre-drying, achieves high carbon content with a plethora of functional groups, and lowers energy usage [65].	There is a lack of chemical stability in prepared biochar when exposed to acidic, alkaline, or hot environments. [66].
Gasification	Fast reaction time [67].	The yield is inferior than that of other preparation procedures [68].
Torrefaction	Improves the chemical stability of biochar, reduces moisture, and improves combustion properties [69].	Low biochar productivity compared to other methods [70].

3. MODIFICATIONS OF BIOCHAR

Biochar often requires modification to be utilized more effectively in applications such as water purification, heavy metal removal, and soil fertility enhancement. Raw biochar typically has limitations, including restricted porosity, a lack of active functional groups, and reduced absorption capacity. To address these issues, various modification techniques have been developed, which can be categorized into physical, chemical, and biological methods. The choice of modification technique depends on the specific application and desired properties of the biochar.

3.1. Physical Modifications

Biochar's inherent properties can be significantly improved through physical modification techniques. Unlike chemical treatments, these methods focus solely on altering structural and morphological characteristics without introducing external reactive agents. Physical enhancement serves as a foundational step in biochar optimization, tailoring its porosity, surface area, and particle dynamics to meet specific application requirements [71].

The process relies on mechanical and thermal interventions that restructure the carbon matrix while preserving biochar's core composition. By adjusting particle size distribution, pore network connectivity, and surface roughness, these modifications unlock greater potential in adsorption, catalytic activity, and environmental interaction. The non-chemical nature of these techniques makes them particularly attractive for applications demanding purity and ecological safety [72]. Essential technology encompasses:

3.1.1. Thermal Activation

This method relies on reheating biochar at high temperatures ($>700\text{ }^{\circ}\text{C}$) under different atmospheres (gas or oxygen-free), thereby enhancing micropore formation and improving absorption efficiency. A recent study showed that thermal activation of biochar derived from agricultural waste increased its effectiveness in removing cadmium and lead, among other heavy metals, from industrial wastewater by 50% compared to unmodified biochar [73].

3.1.2. Microwave Treatment

This method is used to increase the number and size of pores in biochar via indirect heating,

thereby enhancing its absorption capacity. A study demonstrated that microwave treatment improved the ability of biochar to remove organic contaminants such as antibiotics by up to 70% [74].

3.1.3. Mechanical Grinding (Ball Milling)

This technology is used to reduce the size of biochar particles, which increases their interaction with pollutants. This modification is particularly used in applications related to energy storage and electrode manufacturing [75].

3.2. Chemical Modifications

Chemical modifications involve introducing functional groups to the biochar surface to enhance its reactivity with organic molecules and heavy metals. Here are some of the most popular methods:

3.2.1. Acid Modification

The addition of carboxyl and hydroxyl functional groups to biochar using acids such as HNO_3 and H_2SO_4 improves its ion-exchange capacity. In a recent study, nitric acid-modified biochar showed an 80% improvement in lead (Pb^{2+}) removal from contaminated water compared to raw biochar [76].

3.2.2. Alkali Treatment

Modifying biochar with alkaline materials such as sodium hydroxide (NaOH) and potassium hydroxide (KOH) is an effective method for enhancing its adsorption capacity and removing pollutants from water [77]. This change improves the removal of phosphate and nitrate ions by increasing the effective surface area and creating more adsorption active sites [75]. Studies have shown that alkaline modification of biochar derived from agricultural waste can improve its efficiency in removing phosphate by up to 65% compared to unmodified biochar [78].

3.2.3. Mineral Doping

Impregnating biochar with metal ions such as Fe_3O_4 and MnO_2 makes it more efficient in catalytic processes and allows the magnetic biochar to be easily separated after use. In a recent study, impregnating biochar with Fe_3O_4 particles increased its efficiency for removing organic dyes by 90% within 10 min [79].

3.3. Biological Modifications

In the context of biochar, biomodifications focus on enhancing its functionalities using

microbes or biological materials. This approach is particularly relevant for agricultural applications and the remediation of organic pollution.

3.3.1. Biochar Modification with Bacteria

Biochar's ability to absorb and remove contaminants from water is enhanced by incorporating bacteria into its composition. As an example, a recent study showed that the removal of industrial dyes and organic compounds from contaminated water could be enhanced by treating biochar with cultures of the bacterium *Trichoderma longibrachiatum* [80].

3.3.2. Biochar Modification with Algae and Marine Biological Materials

Algae are used in biochar modification to enhance its ability to absorb heavy metals and organic compounds. A recent study found that introducing algae extracts to biochar increased its effectiveness in removing nitrates and phosphates from water, making it a sustainable solution for treating polluted agricultural water [81].

3.3.3. Biopolymer Modification

Compounds such as chitosan have been used to enhance the adsorption capacity of biochar for organic pollutants and heavy metals. In a recent study, chitosan-coated biochar showed an 80% improvement in the removal of copper (Cu^{2+}) from industrial wastewater [82].

4. PROPERTIES AND APPLICATIONS OF THE BIOCHAR

4.1. Properties of Biochar

4.1.1. Functional Groups

How well biochar adsorbs pollutants is enhanced by the presence of carboxylic (COOH), hydroxyl (OH), amine, amide, and lactonic groups on its surface [26]. The surface functional groups of biochar are mostly influenced by the kind of biomass and the temperature [83]. Furthermore, if attributes such as pH, surface area, and porosity are enhanced, the functional groups in biochar may diminish. The characteristics of biochar may be influenced by pre-treatments of the feedstock and post-treatments of the biochar [53].

4.1.2. Surface Area and Porosity

Biochar will exhibit greater sorption capacity due to its high porosity and large surface area. The pyrolysis process, which creates the porous structure of biochar, is characterized by an increase in water loss during dehydration [84]. The International Union of Pure and Applied Chemistry classifies perovskite holes in biochar as micropores (<2 nm), mesopores (2-50 nm), and macropores (>50 nm) [85]. A biochar with smaller pores will not be able to absorb any pesticide molecule, regardless of its magnetic or charged properties [86]. Similarly, biochar tests conducted at high temperatures may overemphasize pore properties due to increased pore size. Additionally, biochar forms more

favorable aromatic structures at higher pyrolysis temperatures, which likely increases the crystallinity of the mineral components [87]. The surface area of biochar is a direct indicator of its sorption and ion exchange capabilities, making this metric crucial [88]. The function of mass in lowering pollution levels is significant in both aquatic and terrestrial environments [89]. Both the internal and external surface areas may be used to measure the exposed surface area, depending on the size and accessibility of the pores. The external surface area consists of any visible fissures or protrusions in addition to mesopores and macropores. Compared to the external surface area, the internal surface area is entirely composed of micropore walls and other deeper, less obvious imperfections [90]. When it comes to adsorption capacity, the internal surface area of biochar is much more important than mesopores and macropores, which mainly act as pathways for adsorbates to reach micropores. After pyrolysis, biochar substitutes show a substantial improvement in BET surface area compared to raw samples.

Biochar produced during pyrolysis contained newly formed micropores, in contrast to the original biomass, which had none. When the power level increased from 2100 to 2400 W, a rapid residual-unstable discharge and enhanced micropore formation at higher heating rates were observed. The porosity outcomes for both biomass kinds, including the BET surface area and micropore region, increased [91]. The presence of volatile components gives biochar low density and substantial porosity, with variable pore architectures. Treated and untreated natural resources may have different surface areas. The available surface area of activated biochar for purchase is higher. Biochar has a low porosity and small surface area when not activated [30]. Activation is a step in the biochar synthesis process that increases the material's surface area and porosity. Chemical and physical activation techniques are also viable options [26].

4.2. Applications of Biochar for Dye Removal

The improved performance of biochar may be attributed to surface functional groups that incorporate oxygen and other inorganic components, which contribute significantly to dye adsorption beyond mere surface area and porosity. During the adsorption process, the inorganic components of biochar act as catalysts, increasing the material's hydrophilicity towards dyes [92]. However, adsorption capacity might be influenced by surface area, surface alkalinity, and BC activation. Dye removal from wastewater using adsorption techniques is shown in Fig. 6. The five adsorption processes include surface complexation, ion exchange, electrostatic

interactions, precipitation, and physical adsorption [93]. However, there are usually several mechanisms that work together throughout the pollution clearance process.

4.2.1. Physisorption

Physical interactions, including pore filling, π -stacking, and hydrogen bonding, are the main mechanisms by which the dye adsorbs onto the biochar surface. However, biochar's aromaticity, surface area, and porosity all affect physical adsorption. The greater surface area and pore capacity make it easier for contaminants to spread [94]. Hydrogen bonding and π -stacking interactions with pollutants are facilitated by Biochar's aromatic structure [95]. Improvements in pore filling, interactions, and hydrogen bonding between Biochar and the dye may be achieved through post-modification processes. One manifestation of physical adsorption, pore filling, may be caused by the dispersed pores of Biochar [96]. It is possible that π - π interactions are enhanced when cationic dyes include

electron-deficient functional groups, such as hydroxyl and amine groups, on their surfaces [18]. Cationic dyes, for instance, allowed sulfur-doped tapioca peel waste charcoal to form free hydroxyl groups via hydrogen bonding between oxygen and nitrogen centers [97]. Hydrogen bonding was produced by the alkali fusion of fly ash and biochar made from agricultural waste with surface groups that included oxygen [98]. Adsorption occurs when the acid orange 7 dye and the adsorbent form hydrogen bonds [99]. Siddiqui et al. state that when the -OH groups of methylene blue and the acceptor sites of MnO_2/BC interact, a hydrogen-bonding process occurs [100]. Like electrostatic interactions, non-covalent interactions affect the system when molecules bearing positive charges come into contact with surfaces bearing negative charges [26]. Figure 6 illustrates the Dye removal from wastewater using an adsorption technique and mechanism.

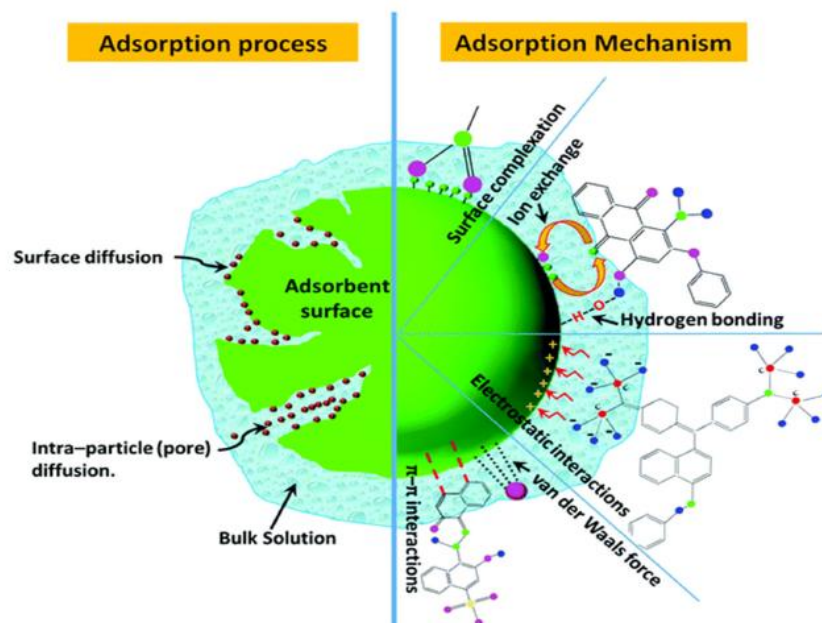


Fig. 6 Dye Removal from Wastewater Using an Adsorption Technique and Mechanism [91].

4.2.2. Ion Exchange

Metal ion or mineral element exchange, or functional group substitution on Biochar surfaces, is how dye adsorption occurs [94]. The ion exchange procedure also comprises a solid phase (adsorbent) exchanging ions with a liquid phase (dye solution). According to Pirbazari et al., the process of obtaining methylene blue dye from wheat straw treated with ferric oxide and NaOH may be facilitated by two main mechanisms: the formation of surface complexes and ion exchange between the dye molecules and the adsorption surfaces [101]. Anionic dyes, such as methyl orange and Congo red, are able to be adsorbed onto graphene oxide-NiFe layered double hydroxide, according to Zheng et al., by ion exchange and electrostatic attraction [102, 103].

4.2.3. Electrostatic Attraction

Synthetic dyes are primarily categorized into two types: cationic and anionic dyes. Examples of cationic dyes include Rhodamine B, methylene blue, and malachite green, while anionic dyes include tartrazine, orange G, Congo red, and sunset yellow. Understanding dye classification is crucial for selecting the appropriate adsorbent, as electrostatic interactions enable a positively charged adsorbent to effectively remove negatively charged dyes [104]. An electrostatic attraction occurs between the dye and the Biochar surface when the surface charges are opposite [105]. One of the main ways that synthetic colors adsorb onto Biochar is by electrostatic interactions, which may impact the adsorption rate. Evaluated litchi peel biochar's adsorption

capabilities for anionic and cationic dyes. Both the adsorption and additional capacities were 404.4 mg/g and 2468 mg/g, respectively. The adsorption of the dye was primarily driven by electrostatic interactions between the dye's divalent ions and the positively charged BC, but other adsorption mechanisms also contributed [106]. Electrostatic interactions and chemisorption were proposed as mechanisms

for the buildup of cationic and anionic dyes onto different BCs using Elovich or pseudo-second-order kinetic models. Electrostatic and intermolecular interactions control the adsorption of rhodamine dye onto adsorbent surfaces [107]. Table 3 summarizes the isotherm studies on dye adsorption using various biochar-based adsorbents.

Table 3 Comparative Analysis of Adsorption Isotherms for different Dyes on Biochar Adsorbents [108].

Adsorbent	Adsorbate	Applicable Isotherm Models	Adsorption Capacity (mg/g)
Mg-Al-layered hydroxide intercalated date-palm biochar composites.	Methylene blue	Langmuir, Freundlich	302.75
Rice husk biochar	Congo red	Langmuir, Freundlich	15.8
Cow dung biochar	Congo red	Langmuir, Freundlich	12.32
Magnetic chicken bone biochar	Rhodamine B	Freundlich	113.31
Chitin derived biochar	Methyl violet	Freundlich, Langmuir	1005
Switchgrass biochar	Methylene blue	Langmuir, Freundlich	37.6
Switchgrass biochar	Orange G	Langmuir, Freundlich	8.2
Switchgrass biochar	Congo red	Langmuir, Freundlich	8
Banana peel extract and FeSO ₄	Methylene blue	Langmuir, Freundlich, Dubinin-Radushkevich	862
Chemically modified lychee seed biochar	Methylene blue	Langmuir, Freundlich, Temkin, Dubinin-Radushkevich	128
Bamboo shoot shell biochar	Rhodamine B	Langmuir, Freundlich	85.8
Cetyl trimethyl ammonium bromide modified magnetic biochar from pine nut shells	Acid chrome blue K	Langmuir, Freundlich	92
Bovine bone biochar	Basic Red 9	Langmuir, Freundlich	49.5
Fish scale biochar	Basic Red 9	Langmuir, Freundlich	52.3

5. CONCLUSIONS

The main conclusions of the present review could be summarized as follows:

- Biochar, especially in its modified variants, offers a viable and sustainable approach to eliminating dyes from wastewater. Its large surface area, porous composition, and functional groups make it an effective adsorbent for a wide range of contaminants.
- Functionalization strategies such as chitosan coating, chemical activation, and metal impregnation significantly enhance its adsorption capacity, selectivity, and kinetics. Nonetheless, issues about production cost, regeneration, and ecological consequences must be resolved to facilitate large-scale application.
- Future investigations should focus on enhancing biochar synthesis, exploring innovative modification techniques, and integrating biochar with advanced technologies, such as machine learning, to optimize processes, improve process efficiency, and predict adsorption mechanisms.
- By surmounting these obstacles, biochar may significantly contribute to sustainable wastewater treatment, aiding in environmental preservation and circular economy objectives.

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LIST OF ABBREVIATIONS AND DEFINITIONS

SSA	Specific Surface Area
BC	Biochar
CO ₂	Carbon Dioxide
HTC	Hydrothermal Carbonization
U(VI)	Uranium (VI)
HNO ₃	Nitric Acid
Pb ²⁺	Lead ion
KOH	Potassium Hydroxide
NaOH	Sodium Hydroxide
Fe ₃ O ₄	Magnetite
Cu ²⁺	Copper ion
FeSO ₄	Ferrous Sulfate
SF-BC	Biochar modified by FeSO ₄
MnO ₂	Manganese Dioxide
Cd ²⁺	Cadmium ion
AlCl ₃	Aluminum Chloride
NO ₃ ⁻	Nitrate ion
PO ₄ ³⁻	Phosphate ion
H ₃ PO ₄	Phosphoric Acid
TC	Tetracycline
SC	swine manure biochar
CTAB	Cetyltrimethylammonium Bromide
AAD	Auricularia auricular dreg
Cr(VI)	Chromium
MgCl ₂	Magnesium Chloride
SMX	Sulfamethoxazole
BET	Brunauer–Emmett–Teller Method
Na ₂ S	Sodium Sulfide
Hg(II)	Mercury ion
BK	Biochar modified Chemically with KOH
BS	Biochar modified with Na ₂ s
CSB	Coconut shell Biochar
MCSB	Modified Coconut shell Biochar
HCl	Hydrochloric Acid
MnO ₂ /BC	Manganese Dioxide-loaded Biochar
BCM	Biochar modified with MgCl ₂
H ₂ SO ₄	Sulfuric Acid

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