

## REVIEW OPEN ACCESS

# Enhanced Surface Properties of Biochar Using Activation Strategies for Sustainable Dye Removal: A Review

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## ABSTRACT

Water pollution due to hazardous dyes is a severe issue that requires investigation through sustainable and cost-effective approaches. In the current scenario, biochar, a carbon-rich material derived from biomass, has found significant importance as an alternative to traditional adsorbents like activated carbon. The wastewater treatment efficacy depends on the structural properties of biochar, such as porosity, surface functional groups, and its mechanism, including physical adsorption, ion exchange, and electrostatic attraction. The current review explores various biochar activation methods, including physical (steam and gasification), chemical (acid, base, oxidant, and salt), and biological (bacterial, fungal, and enzymatic), which are used to increase the adsorption efficiency. However, large-scale production of activated biochar faces many challenges related to quality and sustainability. The application of artificial intelligence (AI) and machine learning (ML) presents new opportunities for optimizing activation parameters and improving predictive modelling. Furthermore, adopting a circular economy approach through biochar reuse in soil remediation, energy recovery, and industrial interdependence can enhance sustainability. Despite promising advancements, research gaps remain in standardizing activation protocols, ensuring long-term stability, and developing policy frameworks for large-scale implementation. Addressing these challenges is critical for advancing biochar as a viable solution for dye removal in wastewater treatment.

## 1 | Introduction

Water pollution caused by industrial dyes is a severe global environmental problem due to the rapid growth of textile, leather, paper, and dye manufacturing industries [1]. About 14% of textile production contributes to 4% of Indian GDP growth, and the country earns about 27% of its total foreign exchange through this sector [2]. Worldwide, up to 10,000 dyes are available, with annual production exceeding  $7 \times 10^5$  metric tons [3]. Notably, about 10%–15% of dye waste is discharged into the environment without being treated. The textile industry is the largest consumer of dyes, accounting for about 50%–60% of the total dye used in leather, paper, plastics, paints and coatings (24%), and printing inks, which are the largest pigment consumers

at around 47%. Globally, fabric dyeing and treatment account for approximately 20% of industrial wastewater. In certain regions, such as Bangladesh, the textile sector uses about 1500 billion liters of water annually, leading to substantial wastewater generation [4]. In India, rivers like the Yamuna, Godavari, and Ganga are severely impacted by untreated effluents from dyeing units. Dye pollution poses significant environmental challenges, affecting aquatic ecosystems and human health. Dyes, such as methylene blue and Congo red, are highly toxic, nonbiodegradable, and persistent in aquatic ecosystems, leading to severe ecological and health hazards [5]. Their release into water bodies causes discoloration, reduces light penetration, and reduces photosynthesis, thereby harming aquatic life. Moreover, many dyes and their degradation byproducts exhibit

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carcinogenic, mutagenic, and cytotoxic effects on human and animal health [6]. Although conventional dye removal techniques such as coagulation, flocculation, and chemical oxidation are widely used, they are often expensive and generate secondary pollutants [7]. Therefore, there is an urgent need for sustainable and cost-effective treatment methods. The adsorption method, particularly using bio-based materials, has gained attention due to its high efficiency, low cost, and eco-friendliness. The use of agricultural and biomass waste for dye removal not only provides an effective solution for wastewater treatment but also promotes circular economy practices. Thus, research on sustainable adsorbents with enhanced adsorption capacity, recyclability, and selectivity remains crucial for mitigating industrial dye pollution and ensuring safe water resources. Biochar, a carbon-rich material produced through the pyrolysis of biomass under limited oxygen conditions, has emerged as an effective adsorbent for wastewater treatment. It possesses a highly porous structure, large surface area, and abundant functional groups, such as hydroxyl ( $-OH$ ) and carboxyl ( $-COOH$ ), which facilitate the adsorption of contaminants, including heavy metals, dyes, and organic pollutants [8]. Compared to conventional adsorbents such as activated carbon, biochar offers several advantages, including lower production costs, enhanced sustainability, and greater potential for large-scale application. Biochar can be derived from various agricultural and biomass wastes, making it a cost-effective and environmentally friendly alternative. Additionally, biochar exhibits better stability under different pH conditions and can be modified to enhance its adsorption capacity. Its ability to remove pollutants via surface interactions, ion exchange, and electrostatic attraction makes it an excellent candidate for wastewater remediation. Activation methods can be broadly classified into physical, chemical, and biological techniques. Physical activation involves thermal treatment under controlled gas flow, such as steam or  $CO_2$ , which increases surface area and pore volume. Chemical activation, using agents such as potassium hydroxide ( $KOH$ ),  $H_3PO_4$ , or zinc chloride ( $ZnCl_2$ ), enhances functional group availability and creates more active adsorption sites [9]. Among these,  $KOH$  activation is particularly effective in developing a well-defined microporous structure, while  $H_3PO_4$  treatment improves surface acidity, enhancing cationic dye adsorption. Biological activation, involving microbial or enzymatic modifications, is a promising eco-friendly approach that enhances surface charge and hydrophobicity [10]. Comparatively, chemical activation yields higher adsorption capacities than physical activation but may involve complex washing steps to remove essential residual chemicals. Although biological activation is environmentally friendly and sustainable, its large-scale applicability is still under research. Overall, selecting an appropriate activation method depends on the target pollutant, economic feasibility, and environmental impact, with hybrid activation approaches (e.g., combining chemical and physical methods) showing promising results for efficient dye removal from wastewater [11]. This review examines recent advancements in physical, chemical, and biological activation methods for biochar to enhance dye adsorption. Key perspectives for large-scale and circular applications are discussed with the goal of practical deployment in real settings.

## 2 | Activated Biochar

Activated biochar is a specially engineered form of biochar that has been further treated to enhance its surface area, porosity, and chemical functionality, making it far more effective for adsorption and catalytic applications than raw biochar. Biochar itself is a carbon-rich material produced by the pyrolysis of biomass under limited oxygen conditions, but its natural form often has limited surface activity and adsorption capacity [12]. Through activation—achieved by physical methods (such as treatment with steam or  $CO_2$  at high temperatures), chemical methods (using agents like  $KOH$ ,  $H_3PO_4$ , or  $ZnCl_2$ ), or biological/green approaches—the internal pore structure of biochar is enlarged while additional surface functional groups such as hydroxyl ( $-OH$ ), carboxyl ( $-COOH$ ), and carbonyl ( $-C=O$ ) are introduced. These modifications not only increase its specific surface area but also improve its chemical reactivity, ion exchange capacity, and affinity toward pollutants like dyes, heavy metals, and organic contaminants [13]. Typically, activated biochar is composed of a high proportion of carbon along with oxygen, hydrogen, minerals, and sometimes heteroatoms such as nitrogen, sulfur, or phosphorus depending on the feedstock and activation process. Its unique combination of a porous carbon matrix, functionalized surface chemistry, and structural stability makes activated biochar an important material for environmental remediation, energy storage, and other advanced applications.

### 2.1 | Material Structure and Composition

Activated biochar is not just ordinary biochar, which is a carbon-rich residue obtained from biomass pyrolysis, but it is a material that undergoes activation (physical, chemical, or biological) to significantly alter its structure and properties. The activation process develops a highly porous structure composed of micropores, mesopores, and macropores that together create hierarchical porosity, resulting in a large surface area that can range from 1000 to 3000  $m^2/g$  depending on the activation method. These pores are well-tailored to adsorb a variety of molecules such as dyes, metals, and organic pollutants. In addition to porosity, activated biochar contains diverse surface functional groups, including oxygen-containing groups such as  $-OH$ ,  $-COOH$ ,  $-C=O$ , and  $-O-$ , which improve hydrophilicity and ion exchange capacity [14]. This is depending on the feedstock and modification. In biochar, the element nitrogen, sulfur, or phosphorus groups may also be incorporated, enhancing chemical reactivity and adsorption performance. Structurally, activated biochar mainly consists of a carbon matrix that is largely amorphous, interspersed with some graphitic domains and disordered layered structures that provide mechanical strength and stability. The material composition of activated biochar depends strongly on the type of biomass used (such as water hyacinth and coconut shell) as well as the activation method applied. Typically, it consists of 60%–85% carbon, which forms the main framework responsible for adsorption and conductivity. Oxygen accounts for about 10%–30% of the composition, largely contributing functional groups for chemical interactions, while hydrogen is present in smaller proportions (2%–5%). Mineral content,

expressed as ash, can range between 5% and 15% and often contains oxides such as  $\text{SiO}_2$ ,  $\text{CaO}$ ,  $\text{K}_2\text{O}$ , and  $\text{Fe}_2\text{O}_3$  depending on the feedstock [15]. In some cases, heteroatoms such as nitrogen, sulfur, or phosphorus are present, especially when the biomass source is protein- or lignin-rich, or when doping is employed during activation. Altogether, the high carbon content, abundant functional groups, and presence of minerals combine to give activated biochar its strong adsorption capacity and versatility for environmental and industrial applications.

## 2.2 | Dye Interaction Mechanism

Dyes are among the most common pollutants in wastewater originating from industries such as textiles, paper, plastics, and tanneries [16]. Because of their toxic and insistent nature, removing dyes from water is important for environmental protection. So, biochar is a carbonaceous adsorbent governed by different mechanisms, including physical adsorption, ion exchange,  $\pi$ - $\pi$  interactions, and electrostatic attraction; these are influenced by the dye type, biochar surface characteristics, and environmental conditions [17].

As shown by Figure 1a, activated biochar possesses a hierarchical pore structure consisting of micropores, mesopores, and macropores. Micropores (< 2 nm) provide a very high surface area and are particularly effective for capturing small molecules such as heavy metal ions, whereas mesopores (2–50 nm) facilitate diffusion and transport of larger molecules like dyes into the inner pore network. Macropores (> 50 nm) act as channels that allow easy access for the adsorbate to reach the smaller pores inside [18]. In addition to this porous framework, the surface of activated biochar is possible to be enriched with functional groups such as hydroxyl ( $-\text{OH}$ ), carboxyl ( $-\text{COOH}$ ), and carbonyl ( $\text{C}=\text{O}$ ), which play a key role in adsorption mechanisms. These groups enable electrostatic attraction, hydrogen bonding, metal ion complexation, and  $\pi$ - $\pi$  interactions with various contaminants, thereby enhancing adsorption efficiency. Figure 1b illustrates the adsorption process at the adsorbent-adsorbate interface. Pollutant molecules, represented as adsorbate, move randomly in the solution and gradually diffuse toward the biochar surface. Upon reaching the surface, they interact with the pores and functional groups, leading to adsorption through a

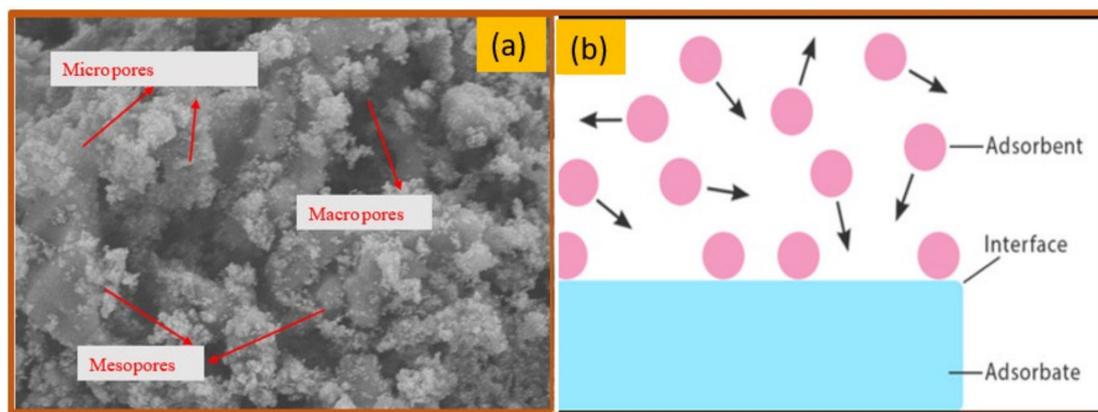
combination of physical forces, such as van der Waals interactions and pore filling, as well as chemical mechanisms, including electrostatic interactions and ion exchange. Over time, a balance is achieved between molecules attaching to and detaching from the surface, establishing adsorption equilibrium [19]. Overall, the adsorption mechanism of activated biochar results from the synergy between its porous carbon matrix, which provides abundant sites for physical adsorption, and its functionalized surface chemistry, which promotes selective and strong chemical interactions with pollutants.

## 2.3 | Factors Influencing Adsorption Efficiency

The dye adsorption onto biochar is affected by several factors, including pH, temperature, initial dye concentration, and the properties of the biochar itself [20]. Optimizing these parameters significantly enhances biochar's performance in wastewater treatment. Proper pH control enables favorable electrostatic interactions; temperature adjustments influence adsorption performance, adjusting initial dye concentration avoids early saturation, and tailoring biochar properties through activation boosts its adsorption capacity [21]. Together, these factors contribute to maximizing the efficiency of biochar-based adsorption systems, making them cost-effective and sustainable for dye removal applications.

### 2.3.1 | pH

pH plays a key role by affecting the surface charge of biochar and the ionization state of dye molecules. Functional groups like  $-\text{COOH}$ ,  $-\text{OH}$ , and  $-\text{C}=\text{O}$  on the biochar surface can gain or lose protons depending on the solution pH [22]. Cationic dyes such as methylene blue and crystal violet are better adsorbed at higher pH levels (typically pH 8–10) due to the negatively charged biochar surface, often resulting in removal efficiencies of 90%–98%. In contrast, anionic dyes like Congo red and methyl orange exhibit better adsorption at low pH (typically pH 3–5) due to the protonated (positively charged) biochar surface, showing 85%–95% efficiency [23]. For example, corn husk biochar demonstrates maximum adsorption of methylene blue (96%) at pH 9 and Congo red (92%) at pH 4.



**FIGURE 1** | (a) The structure of active biochar. (b) The adsorption mechanism of dye on activated biochar.

### 2.3.2 | Temperature

Temperature influences dye adsorption by affecting the adsorption capacity, diffusion rate, and interaction strength between dye molecules and the biochar surface [24]. In endothermic processes, increased temperature enhances adsorption by aiding dye diffusion into pores [25]. For instance, sawdust-derived biochar improved methylene blue removal from 84% at 30°C to 96% at 60°C [25].

### 2.3.3 | Initial Dye Concentration

The starting concentration of dye affects how efficiently biochar adsorbs it. At low concentrations (5–10 mg/L), active sites are abundantly available, enabling near-complete adsorption; conversely, in exothermic processes like Congo red adsorption on walnut shell biochar, higher temperatures led to a decline in efficiency from 91% at 30°C to 77% at 60°C, suggesting a physisorption-driven mechanism [26]. Temperature shifts can also influence desorption and active site exposure, making it a critical parameter for the optimization of cationic dyes like methylene blue, with removal efficiencies often exceeding 95%–98%. However, at higher concentrations (e.g., > 100 mg/L), competition for limited sites results in saturation, reducing adsorption efficiency to 60%–75%. For example, banana peel biochar shows 97% removal at 10 mg/L but only 68% at 120 mg/L. To address this, chemical activation can significantly enhance surface area and functional group density, improving efficiency at higher concentrations to 80%–90% [26].

### 2.3.4 | Biochar Surface Properties

The surface characteristics of biochar, such as porosity, surface area, functional groups, and chemical composition, greatly influence its adsorption performance [26]. Biochar produced at higher pyrolysis temperatures (> 600°C) typically has better microporosity and surface area, favoring the adsorption of small dye molecules, while lower temperatures (300°C–500°C) preserve more oxygen-containing functional groups, which are effective in adsorbing anionic dyes via electrostatic interactions [27]. Functional groups like –OH, –COOH, and –C=O enhance ion exchange and surface binding. Additionally, biochar with graphitic structures, such as coconut shell biochar, promotes  $\pi$ – $\pi$  interactions with aromatic dyes. Biochar from bamboo and lignocellulosic biomass also exhibits strong dye interactions due to their hydrophobic nature and  $\pi$ -electron-rich surfaces.

## 3 | Activation Strategies for Biochar

Dyes are among the most common pollutants in wastewater, primarily originating from industries such as textiles, paper, plastics, and dye manufacturing [28]. Biochar, a carbonaceous adsorbent, has gained attention due to its high surface area, porosity, and abundance of surface functional groups [29]. The adsorption mechanism of dyes includes physical adsorption, ion exchange,  $\pi$ – $\pi$  interactions, and electrostatic attraction. The efficiency of each mechanism depends on factors such as the

nature of the dye, the properties of the biochar surface, and environmental conditions.

## 3.1 | Physical Activation

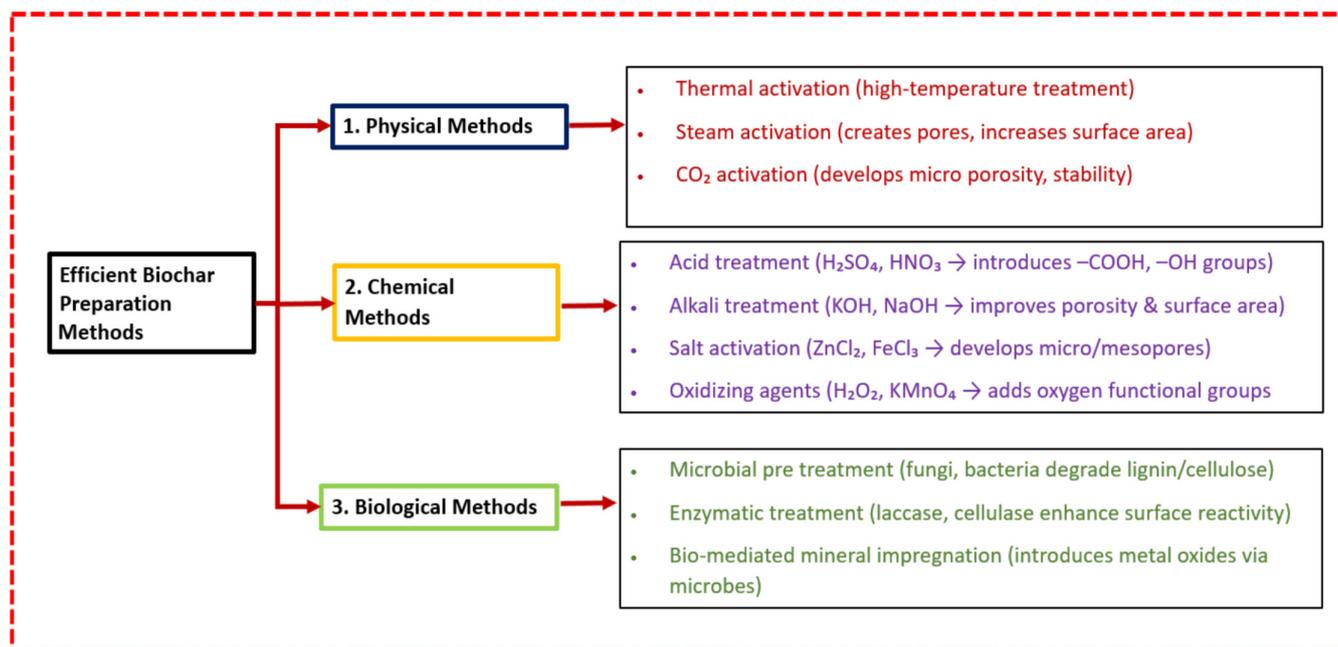
Physical activation is a widely used method for improving the porosity and surface area of bioadsorbents derived from agricultural or plant-based biomass. Two special techniques under this category are steam activation and gasification. Steam activation involves exposing carbonized biomass to high-temperature steam, typically between 700°C and 900°C, in the absence of oxygen [30]. This process endorses the development of microspores and mesopores by oxidizing the volatile matter and enhancing the internal surface area. It is particularly advantageous because it does not introduce chemical contaminants, making the resulting activated carbon environmentally friendly and suitable for water and air purification. However, steam activation requires significant energy input and controlled conditions of pressure and temperature, making it more expensive [31]. Figure 2 shows the summary of different ways of activating biomass and their advantages. Examples include steam-activated rice husk or coconut shell biochar used effectively for dye adsorption such as methylene blue and heavy metal removal. On the other hand, gasification is a thermochemical process that converts organic materials into a combustible gas mixture (syngas) and a solid char residue at high temperatures (typically > 800°C) in a limited oxygen environment [32]. The remaining char or biochar is often rich in carbon and has increased surface area and porosity due to devolatilization and pore development. Although gasification consumes more energy and can produce gas emissions, the resulting biochar can be highly effective in removing pollutants such as dyes and heavy metals. Gasified biochars from feedstocks like coconut shells, bamboo, and corncob have shown good adsorption capacities in environmental applications [33].

### 3.1.1 | Thermal Activation (High-Temperature Treatment)

This method, biochar is subjected to high temperatures (600°C–900°C) in an inert or controlled atmosphere. The heat treatment removes volatile organic compounds and decomposes unstable components, leaving behind a more carbon-rich and stable structure [34]. This process increases the degree of graphitization, improves the mechanical stability of the biochar, and partially opens up the pore structure. Although thermal activation alone does not create as many pores as chemical or steam activation, it significantly improves the stability, carbon content, and durability of biochar, making it suitable for adsorption and catalytic applications [35].

### 3.1.2 | Steam Activation (Creates Pores and Increases Surface Area)

Steam activation involves exposing biochar to superheated steam (700°C–900°C). The steam reacts with carbon in the biochar through the water–gas reaction ( $C + H_2O \rightarrow CO + H_2$ ), which etches away carbon atoms from the matrix. This controlled gasification process opens blocked pores and creates new



**FIGURE 2** | Different methods of activation of biomass.

micropores and mesopores, thereby increasing the surface area and pore volume. Steam activation is particularly effective for generating hierarchical porosity that enhances the adsorption capacity of activated biochar, making it ideal for removing organic dyes, heavy metals, and other pollutants from water and air [13].

### 3.1.3 | CO<sub>2</sub> Activation (Develops Microporosity and Stability)

In CO<sub>2</sub> activation, biochar is treated at 800°C–1000°C under a flow of carbon dioxide gas. Similar to steam activation, CO<sub>2</sub> reacts with carbon ( $C + CO_2 \rightarrow 2CO$ ) in a controlled gasification process. However, this reaction proceeds more slowly than steam activation, allowing better control over pore development. As a result, CO<sub>2</sub> activation is highly effective in generating micropores (pores <2 nm) while preserving the structural integrity and stability of biochar. The biochar produced is highly porous, thermally stable, and particularly suited for applications that require adsorption of small molecules or gases, such as CO<sub>2</sub> capture or removal of heavy metal ions [36].

## 3.2 | Chemical Activation

Activation plays an important role in modifying biochar's surface chemistry, porosity, and functional groups, making it highly efficient for dye adsorption, heavy metal removal, and organic pollutant degradation [37]. Acid activation enhances functional groups for ion exchange, base activation improves porosity and surface charge, oxidant activation creates highly reactive sites, and salt activation modifies pore structure and functional composition. By selecting the appropriate activation method, biochar's adsorption capacity can be optimized for specific applications, making it a versatile and sustainable material for environmental remediation. Chemical activation is

an efficient method used to enhance the surface properties, porosity, and adsorption capacity of biochar [38]. This process involves treating biochar with various chemicals, which modify its pore structure, surface charge, and functional groups, making it more effective for applications such as dye removal, heavy metal adsorption, and wastewater treatment [39]. Chemical activation can be classified into acid activation, base activation, oxidant activation, and salt activation, each of which plays a distinct role in tailoring biochar properties for specific adsorption mechanisms.

### 3.2.1 | Acid Activation (H<sub>2</sub>SO<sub>4</sub>, HCl, and HNO<sub>3</sub>)

Acid activation involves treating biochar with strong acids like sulfuric acid (H<sub>2</sub>SO<sub>4</sub>), hydrochloric acid (HCl), and nitric acid (HNO<sub>3</sub>), which significantly alter its surface chemistry and functional group composition [40]. Acid treatment removes inorganic impurities, ash content, and loosely bound carbon, leading to an increased presence of functional groups that contain oxygen as (–COOH, –OH, and –C=O) on the surface. These functional groups enhance the biochar's ability to adsorb cationic pollutants, such as methylene blue and heavy metals (Pb<sup>2+</sup>, Cd<sup>2+</sup>, and Cu<sup>2+</sup>), by electrostatic attraction and ion exchange mechanisms [41]. For example, HNO<sub>3</sub>-treated biochar has been found to increase nitrate functional groups (–NO<sub>2</sub>), improving adsorption capacity for positively charged pollutants. However, it is important to note that overly aggressive acid treatment can compromise the structural integrity of biochar by degrading its carbon matrix, thereby reducing its mechanical stability and reusability [42].

### 3.2.2 | Base Activation (NaOH and KOH)—Pore Development and Surface Charge Alteration

Base activation using alkali salts such as sodium hydroxide (NaOH) and potassium hydroxide (KOH) is a widely adopted

**TABLE 1** | Comparison of different treatment methods for bioadsorbent preparation.

<b>Treatment method</b>			
<b>Physical</b>	<b>Advantages</b>	<b>Disadvantages</b>	<b>Examples/case studies</b>
Steam activation	<ul style="list-style-type: none"> <li>- Produces highly porous bioadsorbent</li> <li>- No chemical residue left</li> </ul>	<ul style="list-style-type: none"> <li>- Requires high temperature and pressure</li> <li>- Expensive process</li> </ul>	<ul style="list-style-type: none"> <li>- Steam-activated rice husk biochar for methylene blue adsorption</li> <li>- Steam-activated sugarcane bagasse for lead (II) removal [48]</li> <li>- Steam-activated palm shell biochar for Cr (VI) adsorption</li> </ul>
Gasification	<ul style="list-style-type: none"> <li>- Increases carbon content</li> <li>- Enhances microporosity</li> </ul>	<ul style="list-style-type: none"> <li>- High energy consumption</li> <li>- Produces gas emissions</li> </ul>	<ul style="list-style-type: none"> <li>- Gasified coconut shell biochar for dye removal</li> <li>- Gasified corn cob biochar for heavy metal removal [49]</li> <li>- Gasified bamboo biochar for phenol adsorption</li> </ul>
<b>Chemical</b>			
Acid treatment	<ul style="list-style-type: none"> <li>- Improves surface functional groups</li> <li>- Removes impurities</li> </ul>	<ul style="list-style-type: none"> <li>- Can degrade material at high acid concentrations</li> <li>- Acid disposal concerns</li> </ul>	<ul style="list-style-type: none"> <li>- H<sub>2</sub>SO<sub>4</sub>-treated water hyacinth for Congo red removal</li> <li>- HCl-modified coconut husk for lead removal [50]</li> <li>- HNO<sub>3</sub>-treated walnut shell for dye adsorption</li> </ul>
Base treatment	<ul style="list-style-type: none"> <li>- Enhances porosity</li> <li>- Increases negative surface charge for cationic dye removal</li> </ul>	<ul style="list-style-type: none"> <li>- Can alter structural integrity</li> <li>- High base concentrations may damage material</li> </ul>	<ul style="list-style-type: none"> <li>- NaOH-treated banana peel for methylene blue</li> <li>- KOH-treated rice husk for chromium adsorption</li> <li>- NaOH-activated bagasse for phenol removal [51]</li> </ul>
Oxidant treatment	<ul style="list-style-type: none"> <li>- Introduces oxygen-containing functional groups</li> <li>- Improves adsorption capacity</li> </ul>	<ul style="list-style-type: none"> <li>- Can lead to excessive oxidation and degradation</li> </ul>	<ul style="list-style-type: none"> <li>- H<sub>2</sub>O<sub>2</sub>-treated sawdust for dye removal</li> <li>- KMnO<sub>4</sub>-modified coconut shell for heavy metal removal [52]</li> <li>- Oxidized activated carbon for dye adsorption</li> </ul>
Salt treatment	<ul style="list-style-type: none"> <li>- Modifies surface charge</li> <li>- Cost-effective</li> </ul>	<ul style="list-style-type: none"> <li>- May cause unwanted salt accumulation</li> </ul>	<ul style="list-style-type: none"> <li>- CaCl<sub>2</sub>-treated algae for anionic dye removal</li> <li>- ZnCl<sub>2</sub>-treated palm kernel shell for heavy metal adsorption</li> <li>- MgCl<sub>2</sub>-treated orange peel for nitrate removal [53]</li> </ul>
<b>Biological</b>			
Bacterial treatment	<ul style="list-style-type: none"> <li>- Eco-friendly and sustainable</li> <li>- Functionalized bionanoparticles</li> </ul>	<ul style="list-style-type: none"> <li>- Time-consuming</li> <li>- Requires specific bacterial strains</li> </ul>	<ul style="list-style-type: none"> <li>- <i>Bacillus subtilis</i>-modified bioadsorbent for methylene blue</li> <li>- <i>Pseudomonas putida</i>-treated coconut shell for lead removal</li> <li>- <i>Bacillus cereus</i>-based treatment of textile effluent [54]</li> </ul>
Fungal treatment	<ul style="list-style-type: none"> <li>- Biofilms enhance adsorption</li> <li>- Natural enzyme production</li> </ul>	<ul style="list-style-type: none"> <li>- Limited scalability</li> <li>- Requires controlled conditions</li> </ul>	<ul style="list-style-type: none"> <li>- <i>Aspergillus niger</i>-bioadsorbent for dye removal</li> <li>- <i>Trametes versicolor</i>-based fungal biomass for phenol adsorption</li> <li>- <i>Phanerochaete chrysosporium</i> for reactive dye removal [55]</li> </ul>

(Continues)

TABLE 1 | (Continued)

Treatment method			
Physical	Advantages	Disadvantages	Examples/case studies
Enzyme Treatment	<ul style="list-style-type: none"> <li>- Enhances biodegradation</li> <li>- Specific catalytic activity</li> </ul>	<ul style="list-style-type: none"> <li>- Costly enzymes</li> <li>- Requires optimum pH/temperature</li> </ul>	<ul style="list-style-type: none"> <li>- Laccase-modified biochar for dye removal</li> <li>- Peroxidase-treated sawdust for phenol degradation [56]</li> <li>- Cellulase-modified jute fiber for dye biosorption</li> </ul>

strategy to enhance the pore structure and surface properties of biochar. Alkaline activation promotes the development of a highly porous structure by etching carbonaceous material, increasing microspore and mesoporous volumes, and enhancing surface area (up to 2000 m<sup>2</sup>/g in some cases) [43]. KOH activation is particularly effective in producing hierarchical porosity, which is useful for the adsorption of large dye molecules containing more negatively charged groups, which improves the adsorption of cationic pollutants through electrostatic attraction. However, base activation requires thorough washing to remove residual alkaline substances, which could otherwise interfere with adsorption efficiency [44].

### 3.2.3 | Oxidant Activation (H<sub>2</sub>O<sub>2</sub> and KMnO<sub>4</sub>)—Enhancement of Reactive Sites

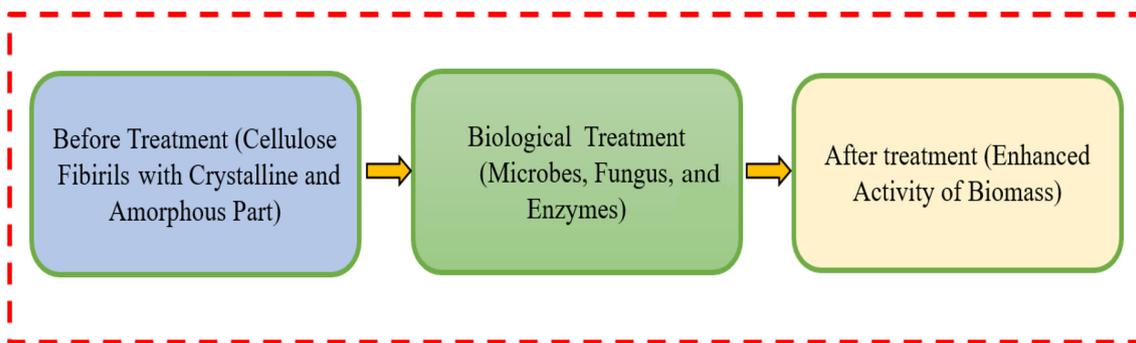
Oxidant activation involves treating biochar with strong oxidizing agents such as hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) and potassium permanganate (KMnO<sub>4</sub>), which introduce oxygen functional groups and create highly reactive adsorption sites. H<sub>2</sub>O<sub>2</sub> activation generates (–OH) and (–C=O) functional groups, improving biochar's hydrophobicity and enhancing chemical interactions with pollutants [45]. This method is particularly useful for removing organic contaminants like phenols and anionic dyes through hydrogen bonding and  $\pi$ – $\pi$  interactions [46]. KMnO<sub>4</sub> activation not only introduces oxygen-containing groups but also creates redox-active sites that facilitate the adsorption and transformation of both organic pollutants and heavy metals [47]. Studies have shown that KMnO<sub>4</sub>-treated biochar exhibits enhanced adsorption of arsenic (As<sup>3+</sup> and As<sup>5+</sup>) and lead (Pb<sup>2+</sup>) ions due to surface oxidation and precipitation mechanisms. Table 1 shows the emerging activation methods for biochar.

### 3.3 | Biological Activation

Cellulose is composed of crystalline regions, which are highly ordered and resistant to enzymatic attack due to strong hydrogen bonding, and amorphous regions, which are loosely packed and more accessible [47]. The treatment process involves biological agents such as bacteria, fungi-like *Trichoderma reesei*, and enzymes including endoglucanases, exoglucanases, and  $\beta$ -glucosidases, which primarily act on the amorphous regions

to break down cellulose chains into smaller units like glucose. This targeted degradation enhances the porosity and reactivity of the cellulose, resulting in partially broken-down fibrils with improved crystallinity [57]. The processed cellulose is then more suitable for eco-friendly applications such as bioethanol production, nanocellulose isolation, and advanced material development. Biological activation is a considering and eco-friendly strategy aimed at increasing the dye adsorption capacity of biochar through microbial and enzymatic processes. Unlike physical or chemical methods, biological activation employs bacteria, fungi, and their metabolic by-products to sustainably modify the surface chemistry, porosity, and functional groups of biochar [28]. This approach significantly improves the adsorption of textile dyes by introducing biologically active binding sites, increasing surface hydrophobicity, and enhancing ion exchange capacity. In microbial activation, the surface of biochar is colonized by bacteria and fungi, which release enzymes, organic acids, and biosurfactants that alter the surface structure and chemistry of the biochar matrix. These agents generate new functional groups such as carbonyl (–CO), hydroxyl (–OH), and amine (–NH<sub>2</sub>), thereby increasing the biochar's affinity for dye molecules [58]. Enzymes like laccase and peroxidase, secreted by fungi such as *Trametes versicolor*, are especially effective in degrading aromatic dye compounds and oxidizing the biochar surface, enhancing interactions with dye molecules through  $\pi$ – $\pi$  stacking and hydrogen bonding. For example, enzyme-treated biochar has shown superior adsorption performance for dyes like methylene blue and Reactive Red 120, attributed to these enhanced surface interactions [59]. Figure 3 shows the steps involved in surface modification of biomass by biological treatment.

Further, microorganisms such as *Pseudomonas*, *Bacillus*, and *Rhizobium* secrete organic acids (e.g., citric acid and oxalic acid), polysaccharides, and biosurfactants, which improve surface charge distribution and create additional dye-binding sites. Similarly, filamentous fungi like *Aspergillus* and *Penicillium* can introduce oxygen-rich functional groups such as carboxyl (–COOH), hydroxyl (–OH), and phenolic (–C–OH) moieties that increase the dye adsorption capacity of biochar [60]. These modifications facilitate electrostatic attraction, surface complexation, and ligand exchange mechanisms that are crucial in adsorbing both anionic and cationic dyes. Biologically activated biochar not only shows improved dye adsorption efficiency but also exhibits enhanced environmental stability, making it suitable for



**FIGURE 3** | Surface modification of biomass by biological treatment.

long-term application in wastewater treatment systems [61]. By leveraging microbial and enzymatic activity, biochar becomes more reactive and compatible with various dye pollutants, offering a sustainable and green alternative for the remediation of dye-contaminated effluents.

#### 4 | Performance of Various Biomass-Based Adsorbents for Removal of Different Dyes

The dye removal strategy involves selecting an efficient adsorbent, activating it through physical or chemical methods, and optimizing various process parameters. The activation method enhances the surface properties and increases adsorption capacity [62]. The adsorption efficiency is significantly affected by pH, as it affects the ionization of both the dye molecules and the adsorbent surface. Here, it is also important to note that temperature plays a crucial role in determining whether the adsorption process is endothermic or exothermic. The initial dye concentration (ppm) and the specific dye type (e.g., methylene blue and Congo red) impact the adsorption kinetics and equilibrium [63]. The adsorbent dosage (mg/L) must be optimized to balance maximum dye removal and cost-effectiveness. The contact time (min) is a key factor, ensuring sufficient interaction between the dye and the adsorbent. Adsorption kinetics, typically modelled using pseudo-first-order or pseudo-second-order equations, help understand the adsorption mechanism. Isotherm models, such as Langmuir or Freundlich, describe the adsorption equilibrium and provide insights into the adsorption capacity and surface interactions [64]. Table 2 shows the application of optimum activation methods and adsorption parameters for various biomass-based adsorbents.

#### 5 | Future Perspectives

Biochar has shown significant potential in dye removal from wastewater; however, its industrial application requires overcoming several key challenges [84]. Future research must focus on bridging the gap between lab-scale and large-scale processes by optimizing activation techniques, evaluating environmental sustainability through life cycle assessments (LCAs), integrating advanced digital tools like artificial intelligence (AI), and promoting a circular economy approach. These efforts are essential to make

biochar a scalable, efficient, and sustainable alternative to conventional adsorbents in wastewater treatment.

#### 5.1 | Optimization Strategies for Large-Scale Biochar Activation

Future efforts should concentrate on developing energy-efficient activation techniques such as low-temperature thermal treatment and microwave-assisted activation to reduce overall energy consumption and operational costs while maintaining high performance [85]. Hybrid activation strategies that combine chemical and physical treatments offer a promising approach for enhancing porosity and functional groups without causing excessive degradation of the biochar structure [86]. Moreover, transitioning to industrial-scale production requires the design and validation of continuous-flow reactors and pilot-scale systems to replace traditional batch operations [87]. Economic sustainability can be improved by utilizing inexpensive and renewable feed stocks, such as agricultural residues, invasive species like water hyacinth, and municipal biowaste, to produce cost-effective and high-performance biochar [88]. Additionally, the development of predictive models that accurately correlate activation parameters such as temperature, activation time, and chemical dosage—with adsorption efficiency is critical. This would reduce the need for time-consuming experimental trials and support efficient process design using data-driven approaches [89].

#### 5.2 | Need for LCA and Sustainability Analysis

Despite the green image of biochar-based dye removal, a comprehensive LCA is essential to truly evaluate its sustainability. Future research must systematically assess environmental impacts related to energy use, chemical inputs, and greenhouse gas emissions across various activation techniques such as pyrolysis and hydrothermal carbonization [90]. Equally important is addressing the fate of spent biochar, with studies needed on its regeneration, reuse, and environmentally safe disposal to avoid secondary pollution and ensure long-term sustainability [91]. Integrating techno-economic analysis with LCA is also crucial to determine whether biochar-based adsorption systems

**TABLE 2** | Application of optimum activation methods and adsorption parameters for various biomass-based adsorbents.

Adsorbent	Activation method	pH	Temp. (°C)	Dye conc. (ppm) & dye name	Adsorbent dose (mg/L)	Contact time (min)	Kinetics model	Isotherm model	Optimum dye removal efficiency (%)	Ref.
Water hyacinth Stem		7-9	40-60	4-14 (Methylene Blue)	20-30	50-70	Pseudo-second order	Temkin	85-94	[65]
Banana peel	Thermal (600°C)	4-6	25-45	10-50 (Congo Red)	10-50	30-90	Pseudo-second order	Langmuir	80-92	[66]
Coconut shell	Chemical (KOH, NaOH)	6-8	40-60	5-20 (Crystal Violet)	5-30	60-120	Pseudo-second order	Langmuir	88-96	[67]
Rice husk	Thermal + Chemical (H <sub>3</sub> PO <sub>4</sub> )	5-8	30-55	5-30 (Methylene Blue)	20-40	60-120	Pseudo-second order	Langmuir	82-94	[68]
Sugarcane bagasse	Thermal (450°C-600°C)	5-7	25-50	10-40 (Reactive Red 120)	10-50	30-90	Pseudo-second order	Langmuir	85-90	[69]
Corn cob	Chemical (KOH, ZnCl <sub>2</sub> )	6-8	40-60	5-25 (Methyl Orange)	10-30	30-90	Pseudo-second order	Freundlich	83-93	[70]
Pine sawdust	Thermal (450°C-600°C)	6-9	30-60	5-15 (Congo Red)	10-30	60-120	Pseudo-second order	Langmuir	85-97	[71]
Peanut shells	Chemical (H <sub>2</sub> SO <sub>4</sub> , KOH)	5-8	30-50	5-20 (Methylene Blue)	5-25	60-120	Pseudo-second order	Freundlich	80-92	[72]
Date palm fiber	Thermal (500°C-700°C)	5-8	30-60	5-15 (Basic Violet 10)	10-30	60-120	Pseudo-second order	Langmuir	87-95	[73]
Tea waste	Chemical (H <sub>3</sub> PO <sub>4</sub> , ZnCl <sub>2</sub> )	4-7	25-50	10-40 (Eosin Yellow)	20-50	60-90	Pseudo-second order	Langmuir	80-91	[74]
Orange peel	Thermal + Chemical (HCl, H <sub>3</sub> PO <sub>4</sub> )	3-7	25-50	5-20 (Acid Blue 25)	10-40	30-90	Pseudo-second order	Freundlich	82-94	[75]
Jackfruit peel	Thermal (500°C)	4-8	30-55	5-15 (Malachite Green)	10-30	30-90	Pseudo-second order	Langmuir	84-93	[76]
Neem leaves	Chemical (KOH, NaOH)	6-9	30-60	5-20 (Methylene Blue)	10-30	60-120	Pseudo-second order	Langmuir	85-92	[77]
Coir pith	Thermal (600°C)	5-7	30-50	10-30 (Rhodamine B)	20-50	60-120	Pseudo-second order	Langmuir	85-96	[78]

(Continues)

TABLE 2 | (Continued)

Adsorbent	Activation method	pH	Temp. (°C)	Dye conc. (ppm) & dye name	Adsorbent dose (mg/L)	Contact time (min)	Kinetics model	Isotherm model	Optimum dye removal efficiency (%)	Ref.
Palm kernel shell	Thermal (600°C–800°C)	5–8	35–55	5–20 (Methyl Orange)	10–30	60–120	Pseudo-second order	Freundlich	87–94	[79]
Sawdust (hardwood & softwood)	Chemical (H <sub>2</sub> SO <sub>4</sub> , ZnCl <sub>2</sub> )	5–9	30–55	5–15 (Congo Red)	10–30	60–120	Pseudo-second order	Langmuir	85–97	[80]
Wheat straw	Thermal (500°C)	4–8	30–50	5–20 (Reactive Black 5)	10–30	30–90	Pseudo-second order	Langmuir	83–92	[81]
Jatropha seed husk	Chemical (KOH, H <sub>2</sub> SO <sub>4</sub> )	6–9	30–55	5–20 (Acid Red 88)	10–30	60–120	Pseudo-second order	Freundlich	84–93	[82]
Soybean hulls	Thermal (500°C–700°C)	5–8	30–60	5–15 (Direct Blue 1)	10–30	60–120	Pseudo-second order	Langmuir	85–94	[83]

are cost-competitive compared to traditional technologies [92]. In addition, future studies should explore circular economy models by repurposing spent biochar for other uses like soil remediation, building materials, or energy recovery. The development of standardized sustainability metrics through multicriteria decision analysis (MCDA) frameworks is necessary to assess the environmental, economic, and social impacts of biochar applications and establish guidelines for sustainable practices [93].

### 5.3 | Integration of AI and Machine Learning (ML) for Process Optimization

AI and ML offer transformative potential for optimizing biochar-based dye removal. Future research should advance AI-based predictive models capable of accurately forecasting adsorption capacity by incorporating parameters such as pH, temperature, dye type, and specific biochar properties [94]. Furthermore, AI-driven optimization algorithms, including genetic algorithms and neural networks, can identify ideal activation conditions while minimizing the experimental workload and resource consumption [95]. Building centralized databases that compile results from adsorption studies will help train robust ML models, enhance prediction accuracy, and facilitate cross-comparability among different biochar types and dyes [96]. The integration of real-time AI-powered monitoring systems into wastewater treatment facilities could enhance operational efficiency by continuously tracking dye removal performance and saturation levels of the biochar [97]. However, current ML models often lack interpretability. Therefore, future work should focus on explainable AI (XAI) techniques that enhance model transparency and trustworthiness for industrial adoption. These advancements will also require interdisciplinary collaboration among environmental scientists, data engineers, and policymakers to effectively integrate AI in practical wastewater treatment applications [98].

### 5.4 | Biochar-Based Circular Economy and Policy Recommendations

Transitioning to a circular economy is essential for maximizing the sustainability of biochar-based dye removal systems. Future research should prioritize the development of recycling and reuse strategies for spent biochar, reducing environmental burdens associated with disposal and enhancing resource efficiency [99]. Industrial symbiosis, where textile industries, wastewater treatment plants, and agricultural sectors collaborate, can facilitate the creation of closed-loop systems that valorise spent biochar in useful secondary applications such as soil amendments or alternative construction materials [100]. To support these transitions, robust regulatory frameworks must be established to ensure biochar quality, safety, and consistent performance across sectors [101]. Additionally, integrating biochar production with renewable energy initiatives, such as coupling pyrolysis with bioenergy recovery, will enhance the sustainability profile of these systems [102]. Policy development should also include public awareness campaigns and incentive structures that encourage industries to adopt eco-friendly dye removal technologies over conventional chemical treatments

[103]. Lastly, addressing the absence of standardized biochar classification and certification processes will be vital for scaling and regulatory compliance in real-world applications.

## 6 | Conclusion

Water pollution from synthetic dyes poses a significant environmental challenge, necessitating the development of sustainable, cost-effective treatment methods. Biochar, derived from biomass, has emerged as a promising alternative to conventional adsorbents due to its porous structure, diverse surface functionalities, and multifaceted adsorption mechanisms. This review underscores the importance of various biochar activation methods—physical, chemical, and biological—in enhancing dye adsorption efficiency. However, transitioning from laboratory-scale studies to large-scale implementation is constrained by challenges in quality control, sustainability, and standardization of activation protocols. Integrating AI and ML offers a transformative approach to optimizing activation conditions and improving performance predictions. Additionally, incorporating biochar within a circular economy framework linking its reuse in soil, energy, and industry can significantly improve environmental and economic sustainability. To fully harness the potential of activated biochar for dye removal, future efforts must focus on bridging research gaps, ensuring long-term material stability, and developing comprehensive policy frameworks for practical deployment in wastewater treatment systems.

### Author Contributions

All authors contributed to the study conception and design. Material preparation and data collection were done by Avanish Kumar, Amit Kumar Rathoure, and G.L. Devnani. The first draft of the manuscript was written by Avanish Kumar, Ashish Kapoor, and Dan Bahadur Pal, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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### Ethics Statement

The authors have nothing to report.

### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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