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A Critical Review of Carbonization Hydrothermal and Pyrolysis for Adsorbent Production and the Application in Industrial Dye Removal

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ABSTRACT: Biochar is increasingly recognised as a low-cost and efficient adsorbent for removing organic dyes from wastewater. This review outlines recent developments in biochar production, particularly comparing biochars produced via pyrolysis and hydrothermal carbonisation (HTC). While pyrolysis biochar often exhibits a higher surface area, HTC biochar offers improved oxygen-containing functional groups, contributing to enhanced dye affinity. Studies indicate that biochar can achieve adsorption capacities ranging from 2 to 1353.09 mg/g for dyes such as methylene blue and crystal violet, comparable to or exceeding that of pyrolysis-derived biochars. The review also highlights characterisation techniques such as XRD, FTIR spectroscopy, and SEM to evaluate surface functionality, porosity, and morphology, which directly influence adsorption performance. Practical implications include the suitability of HTC biochar for low-energy, decentralised wastewater treatment systems, particularly in textile and dyeing industries. By connecting production parameters with biochar properties, this review provides insights into optimizing biochar as an adsorbent, particularly for the treatment of dye-contaminated wastewater.
Keywords: biochar; hydrothermal carbonization; pyrolysis; dye Removal; methylene blue; crystal violet

1. Introduction

The textile industry holds a significant position in the national economy, particularly due to its contribution to foreign exchange earnings. With continued population growth, urbanization, rising income levels, and shifting consumer preferences, the demand for textile products is expected to increase steadily. This growing demand encourages product innovation and market expansion, enabling the industry to respond to increasingly complex consumer needs at both national and global levels (Suciati et al., 2023). However, behind this rapid growth lies a serious environmental challenge, especially related to the large volume of waste generated during production(Kishor et al., 2021; Ristianingsih et al., 2022).

One of the most critical environmental issues in textile manufacturing is the discharge of dye-contaminated wastewater. Synthetic dyes, widely used for their bright colors and durability, often contain harmful substances such as organic pollutants and heavy metals. When released without proper treatment, these pollutants can severely degrade water quality, harm aquatic life, and potentially affect human health through the food chain (Alsukaibi, 2022). Among the available treatment technologies, adsorption is considered one of the most practical and effective methods due to its simplicity, cost-efficiency, and minimal environmental impact (Fadlilah et al., 2023; Siswanti et al., 2023). Within this context, biochar has emerged as a promising adsorbent material. Derived from biomass through thermal processes, biochar exhibits a large surface area and diverse functional groups, which make it well-suited for capturing contaminants from industrial effluents (Puspitasari et al., 2022; Rathi & Kumar, 2021).

This review aims to explore the production and application of biochar derived from agricultural waste as an adsorbent for removing organic dyes from textile wastewater. It focuses on understanding the parameters that influence adsorption efficiency and the characteristics of biochar that contribute to its performance. Through this review, it is expected that a clearer understanding of the

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relationship between biochar production methods and its adsorption capabilities can be achieved, offering insight into more sustainable and effective solutions for wastewater management in the textile industry. While several existing review articles have addressed the use of biochar for dye adsorption, many tend to focus narrowly on either specific types of biomass or individual production methods without offering a comparative analysis of key influencing factors across various studies. This review seeks to fill that gap by providing a more integrated perspective that links biochar properties, production techniques, and adsorption outcomes in a comprehensive manner.

2. Materials and Methods

This review article employs the Systematic Literature This review article employs the Systematic Literature Review (SLR) approach as its primary method, collecting relevant data and findings from previously published, credible scientific sources. The review process was carried out by systematically searching three major academic databases—ScienceDirect, Scopus, and Google Scholar—using specific keywords such as “biochar,” “hydrothermal carbonization,” “pyrolysis,” “dye removal,” and “adsorption performance.” Inclusion criteria were based on article relevance, publication within the last decade (2013–2024), and empirical focus on biochar synthesis and application in wastewater treatment. Studies focusing solely on agricultural applications or lacking clear performance metrics were excluded.

Table 1. Literature selection framework

Step	Description
Database	Sciencedirect, Google Scholar, Scopus
Keywords	“biochar”, “pyrolysis”, ”HTC”, “dye removal”
Timeframe	2010 - 2024
Total articles reviewed	120 initially, 68 selected
Inclusion criteria	Peer-reviewed, English language, biochar from natural/agricultural waste, adsorption of CV/MB, biochar characterization
Exclusion criteria	No dye removal data, use of non-biochar adsorbents, lack of experimental or characterization data
Scope	Biochar production methods, characterization, and dye adsorption performance

The search was limited to articles published between 2010 and 2024 and yielded an initial pool of 120 articles. After applying inclusion and exclusion criteria, a final selection of 68 articles was retained for in-depth analysis. The inclusion criteria were as follows: (1) peer-reviewed journal articles; (2) written in English; (3) focused on the use of biochar derived from agricultural or natural waste; and (4) providing characterization of the biochar used (e.g., surface area, porosity, functional groups). Studies were excluded if they (1) did not focus on dye removal, (2) used synthetic or composite adsorbents without biochar, or (3) lacked quantitative data on adsorption or characterization.

The selected studies form the analytical basis of this review. The SLR approach enables a critical and structured assessment of existing research, particularly on strategies to enhance the adsorption performance of biochar, such as increasing its specific surface area, modifying surface chemistry, and improving pore structure. Moreover, this review emphasizes the relevance of utilizing natural and agricultural resources for biochar production and evaluates the performance of such biochars in removing dyes from industrial effluents. To increase transparency, a summary of the literature selection framework is provided in Table 1.

3. Biochar production, characterization, and properties

3.1. Production of Activated Carbon

The process of producing biochar is often accomplished via a variety of techniques, each with unique properties and uses, including pyrolysis, hydrothermal carbonization (HTC), gasification, and torrefaction. The selection of the method used depends on a number of factors, including the type of feedstock available, the desired form and quality of the final product, the chemical composition of the feedstock, economics, and the effectiveness of energy use during the production process. One of the main concerns in biochar production is energy consumption, which includes fuel requirements, use of electrical equipment, and other energy requirements needed during the process. The level of energy consumption is highly influenced by various operational parameters, such as heating rate, production process temperature, duration of process time, composition of biomass used, and particle size of biochar during and after the production process.

Compared with other methods, hydrochar produced through the hydrothermal carbonization (HTC) process has significant advantages in terms of energy efficiency. This is due to the characteristics of the HTC method that does not require high heating temperatures as in pyrolysis, so the overall process is more energy efficient. Thus, HTC is a promising method for biochar production, especially in the context of energy efficiency, without compromising the quality of the product produced (Güleç et al., 2022). Optimization of these parameters is key in choosing the most suitable method for specific applications, both from a technical and economic perspective.

3.1.1 Pyrolysis Method

Pyrolysis refers to the breakdown of biomass or waste sludge at temperatures below 900°C in an environment devoid of oxygen. Slow pyrolysis is widely used due to its higher biochar yield and lower energy requirements. In this type of pyrolysis, a low temperature is used so that the energy consumption is not too high when compared to other methods (Salimbeni et al., 2023). This method is also proven to produce more biochar, about 25-40% of the initial biomass mass, when compared to other pyrolysis methods

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(Selvarajoo et al., 2022). This is related to the relatively small residence time and heating rate of 0.1-10 °C so that the yield produced is more.

3.1.2. Hydrothermal Carbonization Method

Hydrothermal carbonization is a new method of charcoal making that is being widely researched at present. In this process, biomass is transformed into solid carbon with the use of deionized water. The solid carbon resulting from this process is called hydrochar and generally has the highest solid carbon yield when compared to other biochar production methods can be seen in figure 1. HTC production has recently become a very popular method because it has a lower production cost compared to other methods. The HTC process is generally carried out in a batch reactor where biomass will be decomposed with water at a temperature range of 160-300 °C with a pressure of < 35 bar to produce solid carbon in the form of hydrochar (Byambaa et al., 2023). The length of time and high temperature used in the decomposition process will depend on the type and composition of the biomass.

Compared to pyrolysis in table 2, hydrothermal carbonization (HTC) presents several key advantages in the production of biochar intended for dye adsorption applications, particularly from wet biomass sources. While pyrolysis requires high operational temperatures (typically 300–900 °C) and dry feedstocks, HTC operates at milder temperatures (180–250 °C) under autogenous pressure and can process high-moisture biomass directly, eliminating the need for energy-intensive drying. This makes HTC more suitable for resource-efficient treatment of agricultural waste, food residues, and sewage sludge. Furthermore, HTC-derived biochar (commonly referred to as hydrochar) typically retains a greater abundance of surface functional groups, such as hydroxyl and carboxyl moieties, which enhance its affinity toward polar or cationic dye molecules like methylene blue and crystal violet (Rowinski et al., 2015a). These functional groups facilitate electrostatic attraction, hydrogen bonding, and surface complexation with dye molecules in aqueous environments. In contrast, pyrolytic biochar, though often more porous, tends to lose surface functionality due to thermal degradation at high temperatures (Hama Aziz et al., 2024).

Table 2. Comparative summary pirolysis and HTC

Feature	Pyrolysis	Hydrothermal Carbonization
Operating Temp (°C)	300 - 900	180 - 250
Atmosphere	Inert/N_2	Autogenous (closed, water vapor)
Biochar Yield	20–50%	>70%
Energy Consumption (kWh/Kg)	0.8 – 1.5	0.3 – 4.4
Functional Groups	Less oxygenated	Rich in –OH, –COOH, C=O
Surface Area (m^2/g)	500 – 2500	300 – 1800
Applications	hydrophobic dyes	polar dyes

From a yield perspective, HTC offers significantly higher solid recovery compared to pyrolysis. Hydrochar yields from HTC typically range between 50–80%, depending on temperature and feedstock, with lower temperatures (180–200°C) producing the highest yields (Heilmann et al., 2010; Rowinski et al., 2015b). For example, hydrochar from poultry manure processed at 180°C can yield over 70% of the original mass (Valenti et al., 2018). In contrast, biochar yields from pyrolysis generally range from 20–50%, with yields declining at higher temperatures. At 500–600°C, yields are often around 30–40%, depending on the biomass type (Tripathi et al., 2016). These differences in yield, combined with HTC's sealed reaction environment that minimizes harmful gas emissions, position HTC as a more environmentally friendly and functionally rich method for producing adsorbents from

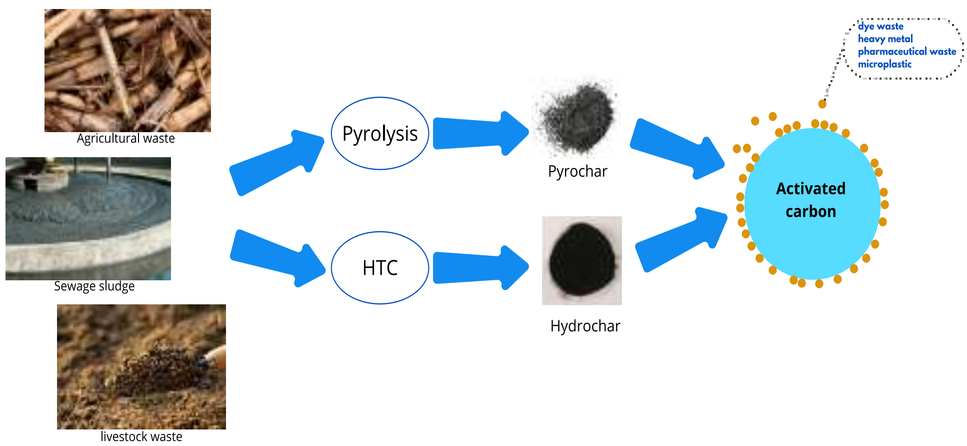

Figure 1. Conceptual Schematic Activated Carbon Synthesis Method

wet biomass, particularly when surface chemistry is critical for dye removal performance.

3.2. Characterization

Biochar has great potential in various fields, ranging from agriculture to the environment (Asadi et al., 2021). However, to optimally utilize the potential of biochar, a deep understanding of its physical and chemical characteristics is very important. The characterization of biochar is a series of analyses aimed at understanding the properties of biochar and comprehending the influence of various production process factors so that its application can be optimized. The characterization of biochar involves various methods to identify and analyze the physical, chemical, and thermal properties of the material (Yaashikaa et al., 2020). Here are some commonly used characterization methods in biochar research and has also been tabulated in Table 3:

3.2.1 FTIR

Fourier Transform Infrared Spectroscopy (FTIR) is a spectroscopic technique used to identify and analyze chemical functional groups in a sample (Soni et al., 2022). The FTIR method measures the absorption of infrared light, producing spectra that reflect the vibrational characteristics of functional groups within the material. In the context of dye adsorption, FTIR is essential for detecting polar functional groups such as hydroxyl (–OH), carboxyl (–COOH), and carbonyl (C=O), which contribute significantly to the adsorption of cationic dyes like methylene blue and crystal violet (Ibrahim et al., 2021). These groups enhance adsorption through mechanisms such as electrostatic interactions, hydrogen bonding, and surface complexation. As pyrolysis temperature increases, FTIR spectra reveal a noticeable reduction in oxygen-containing functional groups, especially between 650–800 °C (Guerrero-Pérez & Patience, 2020). This loss indicates a transformation in surface chemistry, particularly the degradation of aromatic and polar groups, which can reduce the number of active adsorption sites. Because FTIR is non-destructive, it is particularly useful for tracking such changes during thermal treatment.

3.2.2 SEM

Scanning Electron Microscopy (SEM) is a powerful analytical tool used to examine the surface morphology and microstructure of biochar at high magnification and resolution (Ural, 2021). Unlike optical microscopy, SEM offers superior depth of field and can reveal the intricate texture, porosity, and topographical features of the material's surface, making it particularly useful for assessing structural characteristics relevant to adsorption applications (Davies et al., 2022). In the context of biochar, SEM images are instrumental in visualizing the presence and distribution of micropores and mesopores, which directly influence the material's adsorption capacity. Differences in surface morphology caused by various production methods, such as pyrolysis or hydrothermal carbonization, and operating conditions, such as temperature and residence time, are clearly observable in SEM micrographs. For example, biochars produced at higher temperatures often exhibit more developed porous networks and fractured surfaces, which contribute to higher surface area and enhanced dye uptake. SEM is also valuable in comparing the material's surface before and after dye adsorption, revealing potential pore blockage or changes in texture due to dye attachment (Pariyar et al., 2020). Representative SEM images (Figure 2) can illustrate these morphological variations, highlighting differences in surface structure, pore development, and particle aggregation across treatment methods (Do et al., 2021).

3.2.3 XRD

X-ray Diffraction (XRD) is a key analytical technique for characterizing the crystallographic structure, phase composition, and average crystallite size of a material (Khan et al., 2020). This technique relies on the diffraction of X-rays when they encounter the orderly lattice of a crystalline material. When the X-ray wavelength is on the order of the interatomic spacing (about 1 Å), it can be diffracted by the crystal planes, producing characteristic diffraction patterns. These patterns provide valuable information about crystal size, degree of crystallinity, and the presence of inorganic phases, such as silica, alumina, or iron oxides. Some of these minerals can enhance the biochar's adsorption performance by contributing to surface charge or offering additional

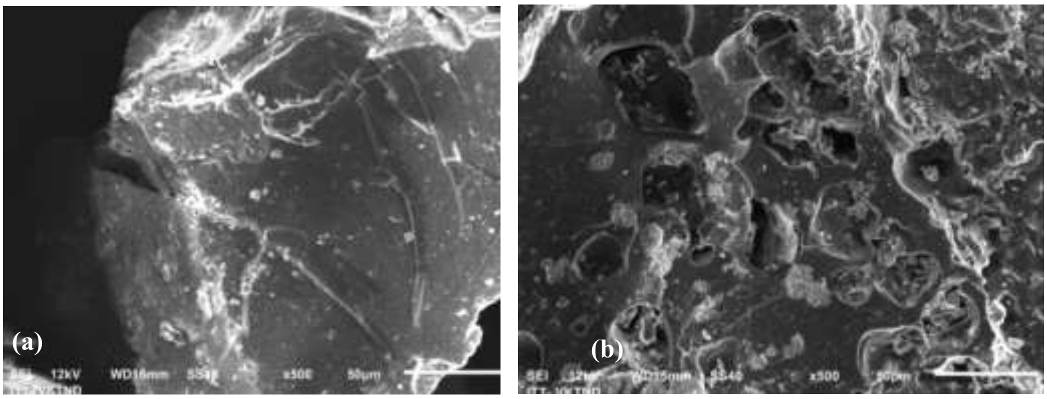

Figure 2. Micrographs of biochar surface before activation (a) and after (b) afrter activation

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reactive sites. XRD can also distinguish between amorphous and crystalline phases. Amorphous biochar tends to exhibit greater surface reactivity, making it more suitable for interactions with dye molecules or other pollutants (Gonzalez et al., 2020). In the context of biochar, XRD especially provides important insight into the degree of crystallinity and the presence of graphitic or amorphous carbon phases. While biochar is predominantly amorphous, increased treatment temperatures or specific production methods (e.g., catalytic pyrolysis) may induce partial ordering or graphitization of carbon domains. These crystallinity traits are relevant because more ordered carbon structures can contribute to enhanced π–π electron donor–acceptor interactions, especially in the adsorption of aromatic dyes such as methylene blue and crystal violet (Tam et al., 2020). Furthermore, the presence of crystalline mineral phases (e.g., SiO_2, $CaCO_3$, Fe oxides) can influence ion exchange and surface complexation, thereby contributing to the material's overall adsorption performance. Thus, XRD is not only useful for structural characterization but also for understanding how crystalline or semi-crystalline features support specific adsorption mechanisms (Abdu et al., 2024).

Table 3. Link between Characterization Techniques and Adsorption-Relevant Properties of Biochar

Technique	Property Evaluated	Relevance to Adsorption
FTIR	Functional groups	Indicates dye-binding sites such as –OH, –COOH, or C=C that interact with dye molecules through hydrogen bonding, electrostatic interaction, or π–π stacking.
SEM	Surface morphology	Reveals pore structure and surface roughness, which influence surface area and accessibility for dye adsorption.
XRD	Crystallinity	Determines the degree of carbon ordering, which affects dye diffusion and potential electron transfer during adsorption.

3.2. Influencing factors of the biochar's properties

The process of making biochar involves a complex transformation of biomass into a product with unique properties, so its production can be influenced by various factors. These variables can modify the properties of the produced biochar, including its physical, chemical, and biological attributes (Kamarudin et al., 2021; Setyorini et al., 2023). A deep understanding of these factors is crucial for producing biochar of optimal quality that meets specific needs. Thus, biochar can be maximally utilized for various applications. Summary of the Effects of Production Parameters on Biochar Properties can be seen in Table 5.

3.3.1 Temperature

Temperature is a critical operational parameter in the biochar production process, both through pyrolysis and hydrothermal carbonization, as it directly regulates the reactivity of the biomass and the physicochemical characteristics of the biochar produced (Kaczor et al., 2020). Changes in temperature can trigger different chemical reactions in the biomass, resulting in final products with varying characteristics. Higher temperatures, typically from 300°C up to around 600°C will produce biochar with increased fixed carbon content, although surface area and porosity may decrease beyond this range (X. Sun et al., 2017).

3.3.2 Type of biomass

The kind of biomass utilized in biochar production is essential in shaping the physicochemical characteristics and effectiveness of the final material. This factor is due to differences in the chemical composition and physical structure of the biomass, which directly affects its reactivity during the carbonization process. Lignocellulosic biomass, such as hardwood and agricultural waste, contains major components of lignin, cellulose, and hemicellulose with varying thermal decomposition characteristics, thus significantly affecting the pore structure development and pore size distribution of the resulting biochar (Xu et al., 2021).

3.3.3 Heating time

The reaction duration is a parameter that significantly affects the efficiency of the biochar production process, particularly in terms of yield, pore structure, and the chemical characteristics of the produced material. In the pyrolysis process, a longer residence time allows for more thorough biomass decomposition, resulting in biochar with higher carbon content and a more defined micropore structure. However, excessive reaction time can lead to further thermal degradation, contributing to yield reduction due to the evaporation of light carbon compounds. For instance, pyrolysis at 300 °C shows that yield decreases gradually from approximately 48% at 30 minutes to around 40% at 120 minutes, with limited additional gain in carbonization beyond 2 hours (Goglio et al., 2012). On the other hand, in hydrothermal carbonization (HTC), the reaction duration plays a crucial role in controlling the dynamics of hydrolysis, condensation, and polymerization reactions, which significantly affect the formation of oxygen functional groups on the surface as well as the development of mesoporous structures. When HTC is extended, the stability of biochar carbon is generally improved. For example, studies have shown that HTC yield can decline from 46.6% at 0.5 hours to about 39–41% after 6 hours at 250°C due to continued decomposition of volatile compounds (Chen et al., 2013). Additionally, the material is enriched with oxygen functional groups, including carbonyl and hydroxyl, enhancing its affinity for target pollutants (Kazemi Shariat Panahi et al., 2020).

3.3.4 Rate of heating

The rapid heating rate can lead to the formation of larger and more irregular pores. This is caused by the quick release of gases from within the biomass. Conversely, a slow heating rate allows for the formation of smaller and more uniform pores (Fu et al., 2020).

4. Biochar as adsorbent for Dye Removal Agent

Among the various methods available for biochar production, hydrothermal carbonization (HTC) and pyrolysis are considered two quite effective approaches with relatively low costs. Both methods are widely used because they offer high efficiency as well as flexibility in the use of various types of biomasses as feedstock (Neolaka et al., 2023). Hydrothermal carbonization and pyrolysis have the ability to expand the specific surface area of biochar significantly, while removing volatile substances contained in biochar. This provides an advantage in increasing the efficiency of biochar as an adsorbent, especially in the absorption of dyes from industrial wastewater (Janu et al., 2021; Song et al., 2023).

The effectiveness of these two methods has been the subject of research in various previous studies, where the results show a consistent improvement in the quality of the biochar produced. Data on the efficiency of each process, including operational parameters and results, are summarized and presented in Table 1 to provide a more comprehensive overview. The table contains detailed information on the performance of each method in producing high-quality biochar, which contributes to the further development of biochar-based waste treatment technologies.

Pyrolysis and hydrothermal methods affect the adsorbent's sorption efficiency through modifying its structure and surface properties. Pyrolysis produces adsorbents with large surface areas and predominantly micro-mesopore structures, making them highly effective in adsorbing small molecules. The process also reduces polar functional groups on the surface, making it more suitable for sorption that relies on hydrophobic or van der Waals interactions (Feng et al., 2022). In contrast, hydrothermal produces adsorbents with surfaces rich in oxygen functional groups, such as carbonyl or hydroxyl, which increase the affinity towards polar pollutants, such as water-soluble organic substances. The combination of pore structure and surface chemistry produced by these two methods determines the adsorbent's ability to adsorb certain types of pollutants (Krysanova et al., 2022).

The surface area and the presence of functional groups on the adsorbent significantly increase the sorption capacity of dye effluents. A large surface area provides more active areas for contact with dye molecules, thus allowing adsorption of larger amounts. In addition, a suitable pore structure (micro- or mesopores) facilitates the diffusion of dye molecules into the adsorbent. Functional groups that interact chemically with the dye molecules through complexation, electrostatic interactions, or hydrogen bonding include hydroxyl, carbonyl, and carboxylic acids. This is especially crucial when adsorbing polar or charged dyestuffs since the functional groups boost the adsorbent surface's affinity for these substances (Selhami et al., 2024a). The combination of a large surface area and active functional groups results in adsorbents with high efficiency in removing dyes from effluents. Therefore, the combination of pyrolysis and hydrothermal provides potential because it can provide higher sorption ability and sorption capacity. This has been studied previously in (Garlapalli et al., 2016), where the pyrohydrochar a material produced through sequential hydrothermal carbonization followed by pyrolysis demonstrated enhanced sorption capacity due to the synergistic effect of both methods. The hydrothermal step enriches oxygen-containing functional groups, while subsequent pyrolysis increases surface area and pore structure. This synergy results in improved dye adsorption performance compared to using each method alone. In (Cruz Briano et al., 2024), the use of the pyrolysis-hydrothermal method (pyrohydrochar) was applied in the manufacture of adsorbents with fish bone base material; the data showed that pyrohydrochar was able to increase the specific surface area by 137 m^2/g compared to hydrothermal alone by 119 m^2/g. The adsorption capacities of pyrohydrochar and hydrochar are 16 and 20.9 mg/g, respectively, indicating that the use of combination methods has the potential to increase the capacity and surface area of activated charcoal.

Table 4. Adsorption Capacities by Dye Type

Type of Dye	Dye	Adsorbent	Method	Adsorption Capacity (mg/g)	References
Cationic Dye	Methylene Blue	*Shorea* spp.	Hydrothermal	37.8	(Elhassan et al., 2025)
	Crystal Violet	Hazelnut	Hydrothermal	22.74	(Saleh et al., 2021)
	Malachite Green	Textile sludge and sawdust	Pyrolysis	395	(Tang & Ahmad Zaini, 2020)
	Rhodamine B	Banana peel	Pyrolysis	952.38	(Singh et al., 2020)
Anionic Dye	Congo Red	Wallnut shell	Pyrolysis	632	(Li et al., 2020)
	Acid Orange 7	Orange peel	Pyrolysis	357.14	(Khalil et al., 2024)
	Methyl Orange	Mahagoni	Pyrolysis	6.071	(Ghosh et al., 2020)
	Reactive Black 5	coffee waste	Pyrolysis	77.52	(Ishak et al., 2021)

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In research (Haris et al., 2022), the synthesis of biochar with the HTC (hydrochar) method provides an increase in adsorption ability along with the increase in temperature. In the study, higher HTC temperatures have the ability to increase the surface area of the adsorbent and the formation of C=C and C=O functional groups, where the formation of these functional groups is able to increase the active surface area of the adsorbent so that the adsorption capacity increases (Selhami et al., 2024b). Adsorption Capacity Based on Dye Type can be seen in Table 4. This is evident in the adsorption test using methylene blue; hydrochar is able to absorb methylene blue by 100%. In the research described in the article (Congsomjit & Areeprasert, 2021), feedstock in the form of sugarcane bagasse is processed into adsorbents through a synthesis process that specifically considers the effect of hydrothermal carbonization temperature (HTC) and process time duration. According to the findings, the ideal temperature and process duration pairing of 240°C and 90 min residence time produced the best yield of activated carbon. Furthermore, a physical activation process using steam was carried out to enlarge the specific surface area and increase the number of pores in the resulting activated carbon. However, analysis showed that the surface area of activated carbon produced from sugarcane bagasse decreased as the activation temperature increased. This decrease is due to the collapse of the carbon structure at higher temperatures, which reduces the stability of the material and negatively affects its adsorption capacity. This phenomenon is different from the results of another study (Pinheiro Nascimento & Barros Neto, 2021) that studied hard biomass materials, such as coconut shells. In this material, increasing the activation temperature resulted in a directly proportional relationship with the surface area of the activated carbon produced. This is due to the structural properties of hard biomass that are more stable and able to withstand temperature increases without experiencing significant damage, thus allowing the formation of more pores and larger surface areas.

It has also been researched in article (Saner et al., 2022); another factor that can increase functional groups is chemical activation. From the article, the use of the HTC method with HCl activation obtained that the adsorption capacity of activated carbon increased by 55%. The percentage of methylene blue dye removal from activated carbon and HCl-activated HTC-activated carbon is 55% and 70%, respectively. The use of acid as an activator in the activated carbon production process has been known to form carbonyl (C=O) functional groups on the carbon surface, which significantly contributes to increasing the active surface area of carbon (Rong et al., 2023). In another study (Zhou et al., 2022), sugarcane bagasse feedstock was synthesized using a combination of the hydrothermal carbonization (HTC) method with the addition of acidic activator (H_3PO_4) and basic activator (NaOH). The results showed that the surface area of activated carbon generated by two activators differed significantly, where HTC with acidic activator produced a surface area of 7.84 m²/g, while HTC with basic activator produced a larger surface area of 15.34 m²/g. This difference is explained through the chemical reaction that occurs during the hydrothermal process, where the base (NaOH) reacts with the carbon in the feedstock, forming Na_2CO_3 crystals. These crystals then dissolve during the washing stage, which in turn helps to clear the clogged pores and enlarge the surface area of the activated carbon. This increase in surface area directly affects the capacity of adsorption of the activated carbon, as evidenced by the HTC-base capacity of adsorption reaching 357.14 mg/g. These results indicate that choosing the right type of activator, whether acidic or basic, greatly influences the final characteristics and performance of the activated carbon produced and shows the great potential of combining the HTC method with basic activators in waste treatment applications.

Table 5. Summary of the Effects of Production Parameters on Biochar Properties

Parameter	Yield	Surface Area	Functional Groups	References
Temperature	↓ Higher temperature decreases yield	↑ Increases up to optimal temperature	↓ Oxygenated groups diminish at high temperatures	(Kaczor et al., 2020; Leng et al., 2021)
Biomass Type	Varies depending on composition	Depends on natural porosity and ash content	Determines the type of initial surface functional groups	(Xu et al., 2021b)
Residence Time	↑ Can enhance carbonization	↑ Supports pore development	↓ Unstable groups may degrade	(Kazemi Shariat Panahi et al., 2020)
Heating Rate	↑ Rapid rate → lower yield	↓ Rapid rate → limited pore formation	↓ Limits the formation of stable functional groups	(Fu et al., 2020)

Nouioua et al. (2023b) reported that biochar produced from *Melia azedarach* seeds using a hybrid method hydrothermal carbonization followed by pyrolysis at 700 °C (HB-700) achieved a crystal violet adsorption capacity of 209 mg/g, significantly higher than that of biochar produced by pyrolysis alone (B-700), which was 119.4 mg/g. The hybrid biochar exhibited improved physicochemical properties, including a surface area of 606.1 m²/g and increased mesoporosity, along with a higher concentration of oxygen-containing functional groups such as –OH and –CO, as indicated by FTIR analysis. The FTIR spectra showed stronger –OH and C=O peaks in HB-700, reflecting enhanced surface functionality due to the hydrothermal pretreatment. SEM analysis revealed a more developed porous structure in HB-700, with better pore distribution and higher surface roughness compared to the compact and less porous morphology observed in B-700. These characteristics enhanced electrostatic interactions and hydrogen bonding with dye molecules, contributing to better adsorption performance. The adsorption kinetics followed the Avrami model, and isotherm analysis indicated a favorable fit to the Freundlich model, suggesting multilayer adsorption on a heterogeneous surface.

5. Conclusions

The comparative review of pyrolysis, hydrothermal carbonization (HTC), and their hybrid applications reveals that no single method universally outperforms the others across all performance metrics; instead, their effectiveness is highly context-dependent and governed by biomass type, process parameters, and target pollutants. Pyrolysis consistently delivers higher surface area and porosity, particularly beneficial for adsorption of smaller, nonpolar dye molecules, but suffers from diminished surface functionality due to thermal degradation at high temperatures. In contrast, HTC offers superior retention of oxygenated functional groups (e.g., –OH, –COOH), which are crucial for electrostatic interactions with polar or cationic dyes, yet tends to generate lower surface areas and less thermally stable structures. The hybrid method, involving sequential HTC followed by pyrolysis, emerges as a promising strategy by combining the strengths of both processes—retaining active functional groups while improving surface area and mesoporosity. Evidence such as the 209 mg/g crystal violet adsorption capacity and 606.1 m^2/g surface area reported for HB-700 biochar confirms this synergistic effect. However, the application of hybrid methods must be critically evaluated in terms of energy input, scalability, and environmental trade-offs, particularly when considering the additional step and complexity introduced. Furthermore, despite promising results, adsorption mechanisms remain only partially understood, with many studies lacking kinetic and thermodynamic modeling depth beyond conventional Langmuir/Freundlich or pseudo-second-order approaches. Future research should integrate advanced modeling, real effluent testing, and lifecycle assessments to optimize hybrid biochar systems for industrial-scale wastewater treatment.

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CRediT authorship contribution statement

Retno Dwi Nyamiati and Putri Restu Dewati conceptualized the research, A Hidayat and Nabila wrote the manuscript, M. Redo Ramadhan and Ika Wahyuning Indiarti revised the contents of the manuscript. All authors agreed to the final version.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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