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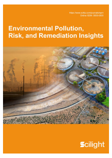

Review

Engineering Biochar Adsorbents for Dye-Contaminated Wastewater: Synthesis–Property–Mechanism Relationships

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Abstract: Synthetic dyes represent some of the most enduring and toxic contaminants in industrial wastewater, attributable to their intricate molecular configurations, elevated chemical stability, and resistance to standard treatment methods. Biochar-based adsorbents have emerged as effective materials for dye removal due to their adjustable surface chemistry, porous architecture, and sustainable manufacture from biomass resources. This study offers a thorough and mechanism-focused synthesis of recent progress in the development and utilization of biochar adsorbents for the treatment of dye-contaminated wastewater. The analysis combines biomass feedstock selection, thermochemical synthesis pathways, surface modification techniques, adsorption mechanisms, and operational performance to create a cohesive framework connecting biochar design with adsorption behavior. The documented adsorption capabilities for dye removal utilizing biochar-based adsorbents vary significantly, often ranging from 10 mg g^{-1} to over 1000 mg g^{-1}, contingent upon feedstock composition, thermochemical conversion conditions, and surface modification techniques. The reported adsorption capacities for different dye classes are rigorously analyzed concerning experimental conditions such as solution pH, dye concentration, adsorbent dosage, and wastewater matrix composition, which substantially affect adsorption performance and hinder direct comparisons among studies. The paper additionally assesses predominant adsorption mechanisms, including electrostatic attraction, π-π interactions, hydrogen bonding, and pore-filling processes, emphasizing the influence of biochar surface characteristics and solution chemistry on the significance of these interactions. The discourse also addresses regeneration efficiency, operational stability, and the constraints related to scaling biochar-based adsorption systems for actual wastewater treatment. The findings underscore that the optimal design of biochar adsorbents necessitates a comprehensive assessment of feedstock properties, synthesis parameters, and ambient factors influencing adsorption mechanisms. Future research must include pilot-scale validation, sustainable regeneration methodologies, and assessment under actual wastewater circumstances to enable the translation of laboratory-scale adsorption studies into effective water treatment technology.

Keywords: biochar adsorption; dye removal; surface engineering; adsorption mechanisms; process optimization; wastewater treatment

1. Introduction

The discharge of synthetic dyes from textile, leather, paper, pharmaceutical, and food-processing industries constitutes a persistent and escalating threat to aquatic ecosystems and public health. Owing to their complex aromatic structures, high chemical stability, and resistance to biodegradation, many synthetic dyes remain largely unaffected by conventional wastewater treatment processes, resulting in long-term environmental persistence and aesthetic degradation of receiving waters [1–3]. Even at low concentrations, dyes can significantly reduce light penetration, disrupt photosynthetic activity, and introduce toxic, mutagenic, or carcinogenic effects within aquatic environments (Figure 1), thereby necessitating the development of efficient remediation strategies [1,4].

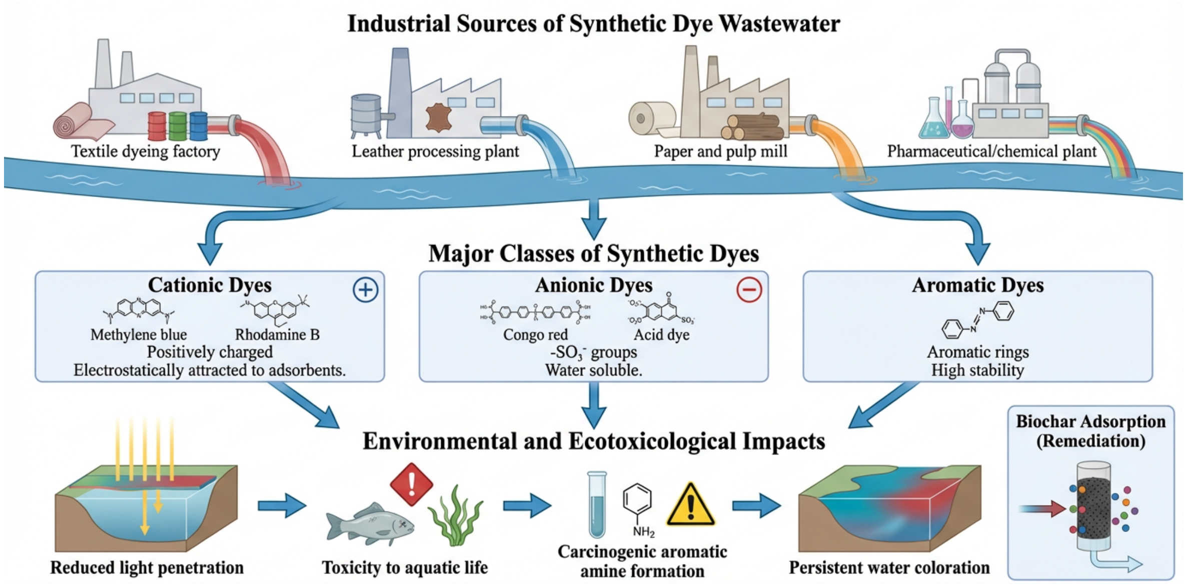

Figure 1. Major industrial sources of synthetic dyes, their principal chemical classifications, and associated environmental impacts in aquatic systems.

Conventional wastewater treatment technologies—including biological degradation, coagulation–flocculation, membrane filtration, and advanced oxidation processes—have demonstrated varying levels of effectiveness for dye removal; however, each approach is associated with notable limitations. Biological treatment is often ineffective due to the recalcitrant nature of dye molecules, while physicochemical methods may suffer from high operational costs, secondary waste generation, membrane fouling, and excessive energy or chemical consumption [1,2,4]. In contrast, adsorption has emerged as one of the most robust and adaptable treatment strategies, offering operational simplicity, high removal efficiency, and applicability across diverse wastewater matrices [5–7]. While activated carbon is the standard adsorbent, its manufacture is energy-intensive and typically depends on non-renewable carbon sources, hence elevating both economic costs and environmental impact. Recent sustainability and techno-economic evaluations have underscored issues related to elevated regeneration energy requirements, carbon emissions during activation procedures, and increasing material costs in extensive wastewater treatment applications. The aforementioned restrictions have fostered heightened interest in renewable carbonaceous adsorbents, such as biochar, which can be synthesized from waste biomass at reduced environmental and economic costs [4,8,9].

Biochar, a carbon-rich material produced through the thermochemical conversion of biomass under oxygen-limited conditions, has gained increasing attention as a sustainable alternative adsorbent for dye-contaminated wastewater. The intrinsic physicochemical attributes of biochar—including porous structure, aromatic carbon domains, surface functional groups, and tunable surface charge—enable effective interactions with a wide range of dye molecules [2,10]. Importantly, biochar production aligns with circular-economy principles by valorizing agricultural residues, forestry waste, manure, sludge, and other organic by-products into functional materials for environmental remediation, thereby reducing waste disposal burdens while contributing to carbon sequestration and resource recovery objectives [11–13].

The adsorption performance of biochar is governed by a complex interplay between feedstock composition, thermochemical conversion pathways, and post-production surface engineering. Feedstock variability determines the relative proportions of cellulose, hemicellulose, lignin, and inorganic minerals, which in turn influence pore development, ash content, aromaticity, and surface reactivity of the resulting biochar [14,15]. Likewise, synthesis parameters such as pyrolysis temperature, heating rate, residence time, and process atmosphere exert critical control over pore size distribution, surface area, and functional group retention [16]. Biochars produced at lower temperatures typically retain higher densities of oxygen-containing functional groups that favor electrostatic attraction and hydrogen bonding, whereas higher-temperature biochars exhibit increased aromaticity and microporosity that promote π-π interactions with aromatic dyes but may suffer from reduced surface polarity [2,4,10].

To address the inherent limitations of pristine biochars, extensive research efforts have focused on surface modification and advanced engineering strategies aimed at enhancing adsorption capacity, selectivity, and durability. Chemical activation using acids or alkalis has been widely employed to remove mineral ash, expand pore networks, and introduce charged surface functionalities, while heteroatom doping alters electronic structure and surface polarity to strengthen dye–biochar interactions [17–19]. In parallel, metal impregnation and nano-engineering approaches have introduced redox-active and catalytic functionalities that enable simultaneous adsorption and degradation of recalcitrant dyes, while magnetic modification improves adsorbent recovery and reuse [11,20].

At the mechanistic level, dye adsorption onto biochar surfaces proceeds through multiple, often synergistic, pathways, including electrostatic attraction governed by surface charge and solution pH, hydrogen bonding between polar functional groups, π-π electron donor–acceptor interactions between aromatic dye structures and graphitic domains, pore filling within hierarchical pore networks, and surface complexation or catalytic reactions on mineral- or metal-enriched sites [1–4]. The dominance of specific mechanisms depends strongly on dye chemistry, solution conditions, and biochar surface properties, underscoring the necessity of mechanism-oriented material design rather than empirical performance optimization alone.

Several recent reviews have examined the role of biochar in water and wastewater treatment, focusing on aspects such as synthesis methods, surface modification strategies, and pollutant removal performance [1,2,4,10]. For example, earlier reviews have summarized the application of biochar for removal of organic pollutants and dyes in aquatic systems, highlighting the versatility of biochar materials but often emphasizing adsorption capacity comparisons rather than mechanistic interpretation [1]. Other studies have focused specifically on textile dye remediation using modified biochars, compiling adsorption performance data and activation strategies but providing limited integration of synthesis pathways with adsorption mechanisms [2]. Mechanistic reviews have also explored the physicochemical interactions governing adsorption, including electrostatic attraction, π-π interactions, and hydrogen bonding, although these discussions frequently remain disconnected from material synthesis conditions and operational performance considerations [3,10]. Additional literature has examined engineered biochars and functionalized carbon materials for environmental remediation, emphasizing material design and surface modification but providing less attention to real wastewater matrix effects and practical treatment applications [4]. Sustainability-focused studies have further highlighted the role of biochar in green remediation and circular resource utilization, emphasizing environmental benefits such as waste biomass valorization, carbon sequestration, and reduced environmental footprint; however, these assessments frequently provide limited focus on dye-specific adsorption mechanisms and material design strategies for wastewater treatment applications [12]. Unlike many existing reviews that summarize synthesis strategies, adsorption capacities, or environmental applications independently, this study systematically integrates feedstock chemistry, thermochemical conversion pathways, surface engineering strategies, and adsorption mechanisms within a unified synthesis–property–mechanism–application framework that links biochar material design with dye removal performance in wastewater treatment systems

In the present review, we develop a mechanism-driven synthesis–property–mechanism–application framework, explicitly linking biomass feedstock characteristics, thermochemical synthesis pathways, and surface engineering strategies with adsorption mechanisms, kinetic behavior, and operational considerations relevant to scalable dye removal from wastewater. Rather than treating adsorption capacity as an isolated performance metric, this work integrates structural properties, surface chemistry, adsorption kinetics, thermodynamic behavior, and regeneration performance within a unified analytical perspective.

2. Literature Search and Data Compilation Methodology

To ensure transparent and reproducible coverage of research on biochar-based adsorbents for dye removal from wastewater, relevant literature was systematically surveyed using major scientific databases including Web of Science, Scopus, ScienceDirect, and Google Scholar. The search strategy employed combinations of keywords such as “biochar,” “dye adsorption,” “modified biochar,” “textile wastewater,” and “carbonaceous adsorbents,” together with the names of commonly studied dyes where appropriate. The literature survey primarily focused on studies published between 2005 and 2024, with particular emphasis on recent advances in biochar synthesis, surface modification strategies, adsorption mechanisms, and wastewater treatment applications. The initial database search identified approximately 455 publications potentially relevant to biochar-based dye adsorption. These publications were screened for relevance based on their focus on dye adsorption processes and the availability of experimental or mechanistic information related to biochar-based adsorbents. After removing duplicates and studies unrelated to dye contaminants or lacking adsorption performance data, 199 peer-reviewed research articles were retained for detailed screening. From this dataset, the 137 most relevant studies were selected for comprehensive analysis based on their experimental rigor, relevance to biochar synthesis and modification strategies, adsorption performance evaluation, and mechanistic insights. To facilitate systematic organization and cross-study comparison, the selected publications were compiled into a structured spreadsheet database in which key attributes—including publication year, journal source, adsorption capacity, synthesis and modification methods, targeted dye contaminants, experimental conditions, and identified research gaps—were extracted and categorized. This structured dataset enabled consistent comparison of adsorption performance, synthesis approaches, mechanistic interpretations, and regeneration behavior across studies, thereby supporting the synthesis of trends and research priorities discussed throughout this review. In addition to qualitative synthesis, adsorption performance data reported in the literature—including adsorption capacity, dye class, feedstock type, modification strategy, and experimental conditions—were compiled and comparatively analyzed to identify performance trends and mechanistic relationships among different biochar-based adsorbents.

3. Overview of Synthetic Dyes in Wastewater

Synthetic dyes constitute a chemically diverse group of organic compounds extensively used in textile dyeing, leather processing, paper manufacturing, plastics, cosmetics, pharmaceuticals, and food industries. It is estimated that a significant fraction of dyes employed during industrial processing—often ranging from 10 to 30% depending on dye class and fixation efficiency—is discharged into wastewater streams during manufacturing and finishing operations, leading to persistent environmental contamination [1–3]. Owing to their complex molecular architectures, strong chromophoric groups, and high resistance to physicochemical and biological degradation, these dyes persist in aquatic environments and pose substantial challenges for conventional treatment systems.

3.1. Classification of Synthetic Dyes

Synthetic dyes can be systematically classified based on their ionic nature, chemical structure, and application characteristics, each of which directly governs their environmental behavior, persistence, and interaction with adsorbent surfaces. From an ionic perspective, dyes are commonly categorized as cationic, anionic, and nonionic species, with cationic dyes such as methylene blue and rhodamine B typically exhibiting strong electrostatic affinity toward negatively charged adsorbent surfaces, while anionic dyes—including azo and reactive dyes containing sulfonate groups—display high aqueous solubility and electrostatic repulsion under neutral to alkaline conditions, complicating their removal without surface charge manipulation [1]. Structurally, dyes encompass diverse classes such as azo, anthraquinone, triphenylmethane, sulfur, vat, and phthalocyanine dyes, with azo dyes representing the most widely used group and posing particular concern due to their potential reductive cleavage into toxic aromatic amines under anaerobic conditions [4,10]. Anthraquinone dyes are characterized by fused aromatic ring systems that confer exceptional chemical stability and resistance to biodegradation, whereas triphenylmethane dyes possess bulky aromatic frameworks that influence steric accessibility and adsorption kinetics [1,2]. These ionic and structural distinctions strongly dictate adsorption affinity, dominant removal mechanisms, and treatment complexity, thereby underscoring the importance of dye classification in guiding adsorbent design and performance interpretation. Synthetic dyes encompass several major chemical classes that differ in ionic character, molecular structure, and environmental behavior, all of which influence their adsorption interactions with biochar surfaces. Azo dyes represent the largest class of industrial dyes and are characterized by –N=N– azo linkages connecting aromatic rings; representative examples include Congo Red, Reactive Red 120, and Acid Orange 7 [2,21]. Triphenylmethane dyes such as malachite green and crystal violet possess bulky aromatic frameworks and positive charges that favor electrostatic attraction and π-π interactions with carbonaceous adsorbents [22,23]. Anthraquinone dyes, including Reactive Blue 19 and Disperse Blue 60, contain fused aromatic ring systems that impart high chemical stability and resistance to biodegradation [2,24,25]. Basic dyes such as methylene blue and rhodamine B are typically cationic and readily adsorb onto negatively charged surfaces through electrostatic attraction and pore-filling mechanisms [26–28]. In contrast, acid and reactive dyes contain sulfonated aromatic structures and reactive functional groups that enhance solubility but complicate removal under neutral or alkaline conditions due to electrostatic repulsion between dye molecules and negatively charged adsorbent surfaces [25,29]. The diversity of dye classes targeted by biochar-based adsorbents are schematically summarized in Figure 1.

3.2. Physicochemical Properties Governing Dye Behavior in Aqueous Systems

The behavior and fate of synthetic dyes in aqueous environments are governed by a complex interplay of physicochemical properties, including molecular size, charge density, polarity, aromaticity, solubility, and functional group composition, which collectively influence their environmental persistence and adsorption behavior (Figure 2) [30–32]. Dyes with high molecular weight and extended conjugated aromatic structures typically exhibit strong chromatic intensity and enhanced resistance to chemical and biological degradation, while simultaneously experiencing diffusion limitations during adsorption due to steric hindrance within adsorbent pore networks [33,34]. The presence of ionizable functional groups such as sulfonate, amino, and hydroxyl moieties imparts pH-dependent charge behavior, which strongly governs electrostatic interactions with adsorbent surfaces and determines adsorption affinity under varying solution conditions [35–37]. In addition to intrinsic dye properties, external aqueous-phase parameters—including pH, ionic strength, temperature, and the presence of competing solutes—further modulate dye adsorption by altering both dye speciation and adsorbent surface charge, often shifting the dominant removal pathways among electrostatic attraction, hydrogen bonding, π-π electron donor–acceptor interactions, and pore filling mechanisms [22,23]. Elevated ionic strength may suppress electrostatic interactions through charge screening effects, while natural organic matter and coexisting contaminants can compete for adsorption sites, leading to reduced removal efficiency and highlighting the limitations of idealized single-solute studies [12]. The relationships between dye molecular properties, charge behavior, and adsorption pathways discussed here provide the basis for interpreting the adsorption mechanisms and further analyzed in Section 8.

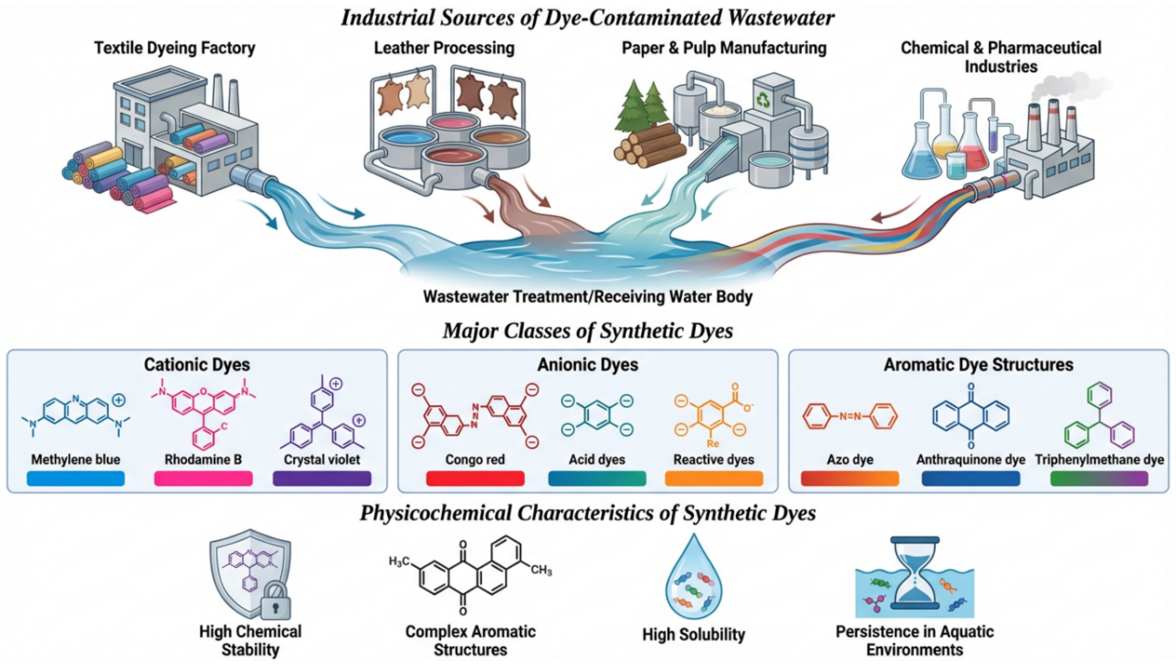

Figure 2. Major industrial sources, classification, and key characteristics of synthetic dyes commonly detected in wastewater systems.

3.3. Environmental and Ecotoxicological Impacts of Dye Pollution

The environmental implications of dye-contaminated wastewater extend well beyond aesthetic degradation. The intense coloration of dye effluents reduces light penetration in receiving waters, impairing photosynthetic activity and disrupting aquatic food webs [32,38], while many dyes and their degradation by-products exhibit acute and chronic toxicity toward aquatic organisms, including fish, algae, and invertebrates [34,39]. Azo dyes are of particular concern, as reductive cleavage under anaerobic conditions may generate carcinogenic aromatic amines that pose significant risks to both ecosystem and human health [40–42]. These ecological and toxicological impacts have driven increasingly stringent regulatory attention to dye-containing effluents, further emphasizing the need for effective and adaptable treatment technologies [12].

3.4. Implications for Adsorption-Based Treatment Strategies

The heterogeneous nature of synthetic dyes necessitates adsorbents with tunable surface chemistry, hierarchical porosity, and multiple interaction pathways. Effective adsorption requires not only high surface area but also appropriate surface charge characteristics and functional group distributions that complement dye molecular properties [1,2,22]. Consequently, a detailed understanding of dye classification and physicochemical behavior is essential for guiding the rational design of biochar-based adsorbents and for interpreting adsorption performance trends reported in the literature. This understanding provides the conceptual foundation for the discussion of biochar properties and synthesis strategies presented in Section 3 and the adsorption mechanisms elaborated in Section 8. These feedstock-dependent structure–function relationships governing dye adsorption performance are illustrated in Figure 3.

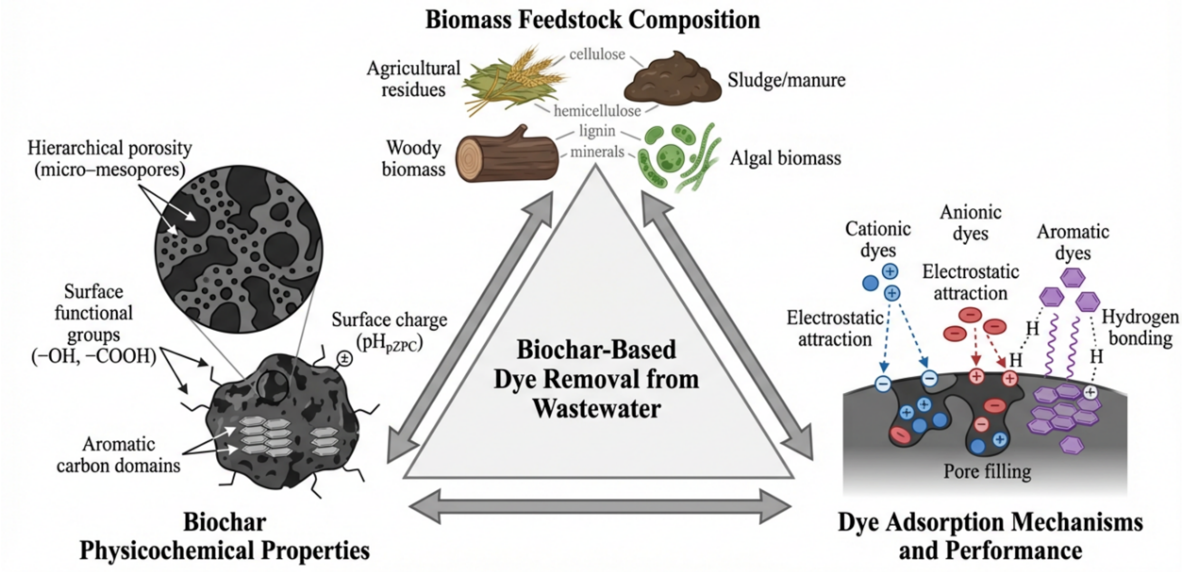

Figure 3. Feedstock–biochar property–dye class relationships governing dye adsorption.

4. Biochar Fundamentals as an Adsorbent

Biochar is a carbonaceous material produced through the thermochemical conversion of biomass under oxygen-limited or oxygen-free conditions, typically via pyrolysis, hydrothermal carbonization, or gasification. Its growing application as an adsorbent for wastewater treatment arises from its intrinsic physicochemical properties, including hierarchical porosity, aromatic carbon domains, diverse surface functional groups, and tunable surface charge, which collectively enable interactions with a broad spectrum of organic contaminants such as synthetic dyes [1,2]. Unlike conventional activated carbon, biochar can be produced from a wide range of low-cost and waste-derived feedstocks, positioning it as a sustainable and circular-economy-compatible material for large-scale environmental remediation [12,13].

4.1. Structural Characteristics and Porosity

The adsorption performance of biochar is strongly governed by its pore structure, which typically comprises a hierarchical network of micro-, meso-, and macropores. Micropores contribute directly to adsorption capacity by providing extensive surface area, whereas mesopores facilitate intraparticle diffusion and improve accessibility for larger dye molecules, particularly bulky azo and triphenylmethane dyes [2,4]. Macropores primarily act as transport channels that reduce mass transfer resistance and enhance adsorption kinetics. The development of this hierarchical pore architecture is closely linked to feedstock composition and thermochemical processing conditions, underscoring the importance of synthesis control for achieving effective dye removal [14,16]. Excessive pore collapse or blockage, particularly in mineral-rich biochars, can limit adsorption efficiency despite high nominal surface area, highlighting the need for balanced pore development rather than surface area maximization alone [3].

4.2. Surface Functional Groups and Chemical Reactivity

Surface functional groups play a central role in governing dye–biochar interactions by providing reactive sites for electrostatic attraction, hydrogen bonding, and surface complexation. Oxygen-containing functionalities such as carboxyl, hydroxyl, carbonyl, and phenolic groups are commonly introduced or retained during low- to moderate-temperature thermochemical conversion and significantly enhance adsorption of ionic and polar dyes [43,44]. These functional groups impart pH-dependent surface charge behavior, influencing adsorption affinity under varying aqueous conditions. Conversely, biochars produced at higher temperatures exhibit increased aromaticity and graphitic ordering but reduced surface oxygen content, which favors π-π electron donor–acceptor interactions with aromatic dyes while diminishing electrostatic and hydrogen-bonding contributions [45,46]. The balance between surface functionality and aromaticity therefore represents a critical design consideration for dye-specific adsorption performance.

4.3. Surface Charge and pH_pZPC Considerations

The surface charge characteristics of biochar, commonly described by the point of zero charge (pH_pZPC), exert a dominant influence on dye adsorption behavior, particularly for ionic dyes. At solution pH values above the pH_pZPC, biochar surfaces acquire a net negative charge that promotes electrostatic attraction of cationic dyes, whereas positively charged surfaces under acidic conditions enhance adsorption of anionic dyes [47,48]. The pH_pZPC of biochar is strongly dependent on feedstock type, ash content, and surface functional group composition, and can be deliberately tuned through synthesis optimization and post-treatment strategies. However, excessive reliance on electrostatic attraction may reduce adsorption stability under fluctuating pH or high ionic strength conditions, emphasizing the importance of complementary interaction mechanisms [12,49].

4.4. Comparison with Conventional Adsorbents

Compared with conventional adsorbents such as activated carbon, clays, and polymeric resins, biochar offers distinct advantages in terms of feedstock flexibility, production cost, and environmental sustainability. While activated carbon generally exhibits higher surface area and more uniform pore structures, its production is energy-intensive and often relies on non-renewable precursors, whereas biochar can be synthesized from locally available waste biomass with lower environmental impact [1,2]. Although pristine biochars may exhibit lower adsorption capacity than activated carbon, surface modification and engineering strategies can substantially bridge this performance gap while maintaining advantages in cost and sustainability [13,50]. These comparative considerations further justify the growing interest in biochar-based adsorbents for dye-contaminated wastewater treatment.

4.5. Implications for Adsorption Performance

The fundamental properties discussed above collectively determine the adsorption behavior of biochar toward different dye classes. Effective dye removal requires a synergistic combination of appropriate pore architecture, surface functionalization, surface charge characteristics, and aromaticity, rather than optimization of any single property in isolation [51,52]. Consequently, pristine biochars often exhibit variable and dye-specific performance, providing a mechanistic rationale for the extensive surface engineering strategies discussed in Section 5 and the adsorption performance trends analyzed in Section 6.

The properties of biochar pertinent to dye adsorption are significantly influenced by the nature of the biomass feedstock, which determines the resulting pore structure, surface functional groups, mineral content, and adsorption affinity toward different dye classes (Figure 3). Agricultural residues like rice husk, wheat straw, and corn cob generally provide biochars characterized by modest surface area and a plethora of oxygen-containing functional groups, which enhance electrostatic attraction and hydrogen bonding with cationic dyes [16,21,53]. Conversely, woody biomass feedstocks (such as sawdust and bark) are abundant in lignin and produce highly aromatic biochars with advanced microporosity, hence augmenting π-π interactions with aromatic dye molecules [14,54]. Biochars generated from sludge possess elevated mineral and metal components that create alkaline surfaces and facilitate metal-assisted adsorption sites; nevertheless, an excessive ash concentration may hinder pore accessibility [1,26]. Likewise, biochars generated from manure possess significant inorganic nutrients that enhance heterogeneous adsorption sites and charge-neutralization processes for anionic dyes [55,56]. Biochars produced from algal biomass frequently possess nitrogen-rich carbon frameworks that augment surface polarity and improve the adsorption of polar pollutants [25,57]. Moreover, agro-industrial leftovers like oil cakes and fruit peels can generate biochars characterized by various functional groups and adjustable porosity, facilitating multiple adsorption mechanisms, including electrostatic attraction, hydrogen bonding, and π-π interactions [29,58]. The differences dependent on feedstock illustrate that the selection of biomass is crucial in establishing the linkages between biochar structure and function, as well as its adsorption efficacy.

5. Biochar Synthesis Pathways

Biochar synthesis pathways play a decisive role in defining pore architecture, surface chemistry, mineral composition, and carbon structure, thereby governing adsorption performance and dominant dye–biochar interaction mechanisms. The combined effects of feedstock composition and thermochemical conversion conditions control devolatilization behavior, aromatization, ash formation, and functional group evolution, which collectively influence adsorption capacity, selectivity, and stability toward different dye classes [2,59,60]. Rather than treating synthesis routes as isolated processes, a comparative and application-oriented understanding of synthesis–property relationships is essential for rational adsorbent design.

5.1. Feedstock Selection and Composition Effects

Feedstock selection constitutes the foundational design variable in biochar synthesis, as biomass composition determines the relative proportions of lignin, cellulose, hemicellulose, proteins, and inorganic minerals that govern char yield, porosity development, ash content, and surface functionality [15,61,62]. Lignocellulosic feedstocks such as agricultural residues, forestry by-products, and woody biomass typically produce biochars with well-developed carbon frameworks, moderate ash content, and tunable porosity that favor π-π interactions and pore-filling mechanisms during dye adsorption [63,64]. In contrast, manure-, sludge-, and algae-derived feedstocks introduce higher mineral content and heteroatom abundance, resulting in alkaline surface characteristics, elevated pH_pZPC values, and enhanced electrostatic interactions with anionic dyes under acidic to neutral conditions, albeit sometimes at the expense of pore accessibility [4,65,66].

5.2. Thermochemical Conversion Routes

Thermochemical conversion governs the evolution of biochar structure through a series of dehydration, depolymerization, decarboxylation, and aromatization reactions that occur during biomass carbonization. Slow pyrolysis, typically conducted between 300 and 700 °C under inert atmospheres, is the most widely employed synthesis route for adsorption applications due to its ability to balance surface area development with retention of oxygen-containing functional groups [2,16]. Increasing pyrolysis temperature generally enhances aromaticity, carbon ordering, and microporosity, but simultaneously reduces surface polarity and oxygen functionality, leading to a trade-off between π-π interaction strength and electrostatic or hydrogen-bonding capacity [67–69]. Alternative pathways such as hydrothermal carbonization and activation-assisted pyrolysis can further tailor pore structure and surface chemistry, particularly for wet biomass feedstocks, although excessive severity may compromise char yield and mechanical stability [68–71].

The methods of biochar synthesis and activation significantly affect pore structure, surface chemistry, and, consequently, the adsorption efficacy for dye molecules. Among these approaches, slow pyrolysis is the most commonly utilized approach as it facilitates the balanced formation of microporosity while maintaining oxygen-containing functional groups that enhance electrostatic attraction and hydrogen bonding interactions with dye molecules [2,16]. Elevating pyrolysis temperature typically improves the development of aromatic carbon structures and micropores, thereby reinforcing π-π interactions with aromatic dye molecules; however, excessive thermal intensity may diminish surface polarity and functional group density, potentially constraining the adsorption of ionic dyes dependent on electrostatic interactions [14,72]. Conversely, hydrothermal carbonization (HTC) generates oxygen-rich biochars characterized by elevated surface polarity, which can improve the adsorption of polar dyes and ionic pollutants; however, the resultant materials typically demonstrate reduced surface area and necessitate further activation to attain competitive adsorption capacities [14,72]. The physical activation with CO_2 or steam markedly enhances microporosity and surface area, thus augmenting pore-filling mechanisms and adsorption capacity for smaller dye molecules; nevertheless, this process is energy-intensive and may diminish surface functional groups critical for electrostatic interactions [17,54]. Alkaline chemical activation with KOH or NaOH is effective for developing extensive pore networks and enhancing adsorption capacity; however, the harsh chemical conditions and necessary post-treatment washing may complicate operations and elevate environmental impact [18,54]. In contrast, acid activation using mineral acids like HCl or H_2SO_4 mainly improves surface functionality by eliminating mineral ash and adding oxygen-containing groups that enhance electrostatic attraction and hydrogen bonding with cationic dyes; however, this method typically results in less significant pore expansion than alkaline activation [3,10,26]. Mechanical activation methods, such as ball milling, enhance adsorption kinetics by decreasing particle size and creating structural defects that improve the accessibility of adsorption sites; however, excessive mechanical processing may compromise pore structures and diminish adsorption efficiency [27,28,73]. In recent years, composite-assisted synthesis methods, which integrate biochar with clays, polymers, or metal species, have emerged as effective strategies to address the limitations of pristine biochars by providing multifunctional adsorption sites, enhanced structural stability, and improved selectivity for specific dye classes [50,74,75]. In summary, these synthesis methods illustrate that enhancing biochar efficacy for dye removal necessitates a balance among pore growth, surface functioning, and structural stability, rather than the maximization of any singular material characteristic.

5.3. Influence of Synthesis Parameters

Beyond feedstock and conversion route, synthesis parameters such as heating rate, residence time, and process atmosphere exert secondary yet significant influence on biochar properties. Slower heating rates and longer residence times promote greater carbon rearrangement and pore development, whereas rapid heating may preserve labile functional groups but limit pore connectivity [2]. Process atmosphere, including the presence of activating agents or limited oxidizing conditions, further affects surface chemistry and mineral transformation, altering adsorption affinity toward specific dye classes. However, excessive activation severity can lead to pore collapse or excessive ash formation, underscoring the need for balanced synthesis optimization rather than aggressive parameter escalation [76,77].

5.4. Synthesis–Property–Performance Relationships

The synthesis pathway ultimately governs the relative contribution of adsorption mechanisms, including electrostatic attraction, hydrogen bonding, π-π interactions, pore filling, and surface complexation. Pristine biochars produced through optimized feedstock selection and controlled thermochemical conversion typically exhibit moderate and dye-specific adsorption performance that is highly sensitive to solution conditions [78,79]. Comparative adsorption capacities of pristine biochars synthesized via different routes are summarized in Table S1, illustrating that synthesis optimization alone is often insufficient to achieve consistently high removal efficiencies across diverse dye classes. These synthesis-driven limitations provide the mechanistic justification for post-synthesis surface engineering strategies discussed in Section 5.

5.5. Integration with Engineered Biochars

While synthesis pathways establish the foundational structure and chemistry of biochar, achieving high-performance and broad-spectrum dye removal generally requires integration with post-synthesis modification approaches. Surface activation, heteroatom doping, and composite formation build upon synthesis-derived frameworks to introduce targeted surface charge, functional group density, and catalytic activity, thereby overcoming the intrinsic limitations of pristine biochars [17–19]. The performance gains achieved through coupling optimized synthesis with surface engineering are quantitatively demonstrated in Table S2, while the mechanistic implications of synthesis-driven property evolution are further analyzed in Section 8. Collectively, this synthesis-oriented framework emphasizes that biochar adsorption performance is governed by the integrated design of feedstock, thermochemical conversion pathway, and subsequent surface modification strategy rather than by any single synthesis variable in isolation.

6. Surface Engineering and Modification of Biochars

Although pristine biochars possess favorable structural and chemical attributes for dye adsorption, their performance is often constrained by limited surface functionality, suboptimal surface charge characteristics, and insufficient affinity toward structurally diverse dye molecules. The major surface engineering and modification strategies employed to enhance dye adsorption on biochar—including chemical activation, heteroatom doping, metal impregnation, composite formation, mechanical activation, and magnetic modification—are summarized in Figure 4. Surface engineering and modification strategies have therefore emerged as essential tools for enhancing adsorption capacity, selectivity, and operational robustness by deliberately tailoring pore structure, surface chemistry, and interfacial reactivity [80,81]. Unlike synthesis optimization alone, surface modification enables precise control over adsorption mechanisms, allowing biochars to be designed for specific dye classes and wastewater conditions.

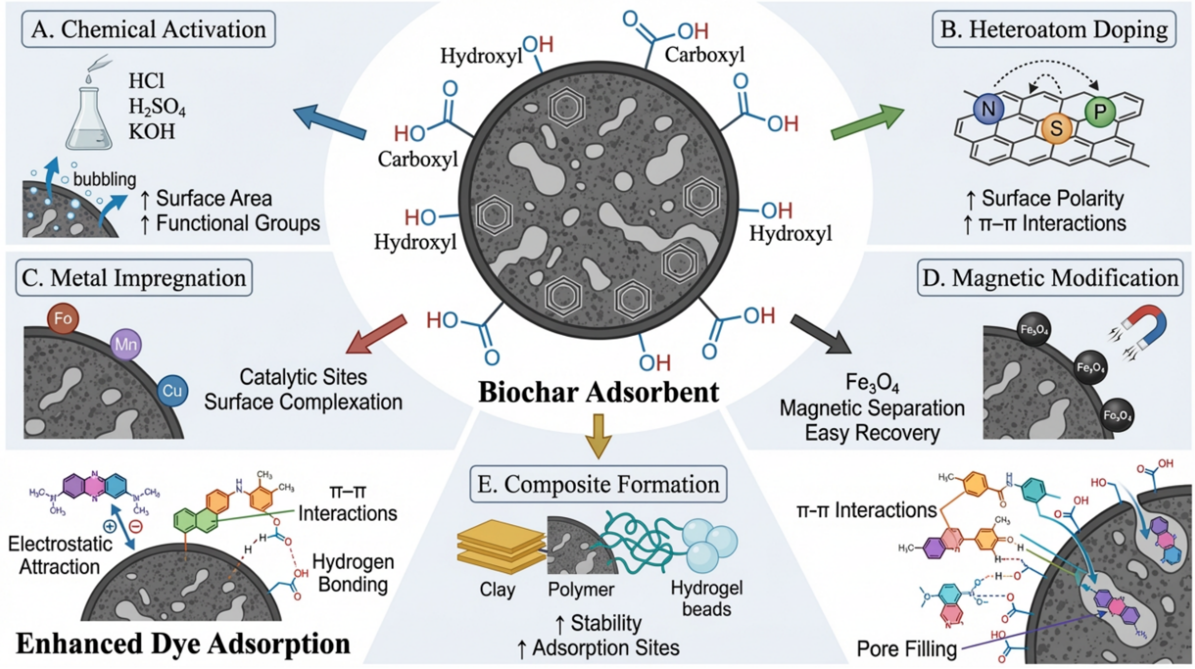

Figure 4. Surface engineering and modification strategies to enhance dyes adsorption onto biochar.

6.1. Chemical Activation and Functional Group Enrichment

Chemical activation using acidic or alkaline reagents is among the most widely employed surface modification approaches for improving dye adsorption performance. Acid treatment, commonly using HCl, H_2SO_4, or HNO_3, removes mineral ash, enhances pore accessibility, and introduces oxygen-containing functional groups such as carboxyl, hydroxyl, and carbonyl moieties, thereby strengthening electrostatic attraction and hydrogen bonding with cationic and polar dyes [82–84]. In contrast, alkaline activation using NaOH or KOH promotes pore expansion, increases surface basicity, and enhances the density of deprotonated functional sites, which is particularly beneficial for adsorption of anionic dyes under acidic to neutral conditions [85,86]. These chemically induced modifications significantly alter pH_pZPC values and surface charge distribution, enabling broader operational pH windows for dye removal.

Surface engineering techniques are crucial for addressing the inherent constraints of unmodified biochars, specifically their irregular pore architecture and restricted surface functionality. Acid oxidation treatments, commonly employing HCl, H_2SO_4, or HNO_3, predominantly alter surface chemistry rather than pore structure by eliminating mineral ash and incorporating oxygen-containing functional groups such as –COOH and –OH, which augment electrostatic attraction and hydrogen bonding with cationic dyes [3,26,85]. Conversely, alkaline activation using reagents like NaOH or KOH is markedly more efficient in creating hierarchical porosity and augmenting accessible surface area, thus facilitating diffusion-controlled adsorption processes and enhancing uptake capacity for both cationic and anionic dyes [54,86]. The harsh chemical conditions linked to alkaline activation may complicate processing and necessitate considerable post-treatment washing. Doping with heteroatoms, specifically nitrogen, sulfur, or phosphorus, modifies the electronic configuration of the carbon matrix and creates polar adsorption sites that enhance π-π electron donor–acceptor interactions with aromatic dye molecules, thereby improving adsorption stability across varying pH and ionic strength conditions [8,17,87,88]. Metal impregnation techniques, which involve the integration of Fe, Mn, or Cu species, create coordination sites that can establish surface complexes with dye functional groups and may promote catalytic degradation pathways; however, the risks of metal leaching and the complexity of synthesis are significant operational concerns [11,19,89,90]. The addition of Fe_3O_4 or γ-Fe_2O_3 nanoparticles for magnetic modification significantly improves the practical utility of charcoal adsorbents by facilitating fast separation and recovery via external magnetic fields, all while preserving adsorption capability [20,91,92]. Moreover, composite-based modification techniques, such as biochar–clay, biochar–polymer, and biochar–hydrogel systems, can concurrently enhance structural stability, adsorption selectivity, and resistance to competitive interference in intricate wastewater matrices [75,84,93]. The various modification options collectively illustrate that enhancing biochar efficacy for dye removal necessitates a balance of pore formation, surface functionality, and operational stability, rather than depending on a singular modification method.

6.2. Heteroatom Doping and Electronic Structure Modification

Heteroatom doping represents an advanced strategy for modifying the electronic structure and surface polarity of biochars to enhance dye–adsorbent interactions. Incorporation of nitrogen, sulfur, or phosphorus atoms into the carbon matrix introduces electron-rich or electron-deficient sites that strengthen π-π electron donor–acceptor interactions with aromatic dye molecules and improve adsorption affinity under competitive conditions [94–96]. Nitrogen-doped biochars, in particular, exhibit enhanced basicity, increased surface polarity, and improved affinity toward anionic dyes due to the presence of pyridinic, pyrrolic, and graphitic nitrogen functionalities [97–99]. These modifications extend adsorption beyond electrostatic control, enabling stable dye removal under fluctuating pH and ionic strength conditions.

6.3. Metal Impregnation and Composite Formation

Metal impregnation introduces additional adsorption and catalytic pathways by incorporating metal oxides or metal ions onto biochar surfaces. Iron-, manganese-, or copper-modified biochars provide coordination sites for dye functional groups and can facilitate redox-mediated degradation of recalcitrant dyes through Fenton-like or catalytic mechanisms [90,91]. These multifunctional systems not only enhance adsorption capacity but also reduce dye accumulation on the adsorbent surface, improving regeneration efficiency and operational longevity. Composite formation with clays, polymers, or metal nanoparticles further improves mechanical stability, pore accessibility, and selectivity toward bulky or highly substituted dyes [1,93]. Representative metal-modified and composite biochar systems and their adsorption performance are summarized in Table S2.

6.4. Magnetic Modification for Recovery and Reuse

Magnetic modification of biochars has gained increasing attention as a practical solution for adsorbent recovery and reuse. Incorporation of magnetic phases such as Fe_3O_4 enables rapid separation of spent biochars from treated effluents using external magnetic fields, minimizing material loss and operational complexity [11,20,89]. Importantly, magnetic modification does not inherently compromise adsorption performance and can be combined with chemical activation or metal impregnation to achieve synergistic improvements in capacity, selectivity, and reusability. These attributes are particularly advantageous for continuous-flow or large-scale treatment systems where efficient solid–liquid separation is critical.

6.5. Mechanistic Implications of Surface Engineering

Surface modification fundamentally alters the dominant adsorption mechanisms governing dye removal. Chemical activation enhances electrostatic attraction and hydrogen bonding, heteroatom doping strengthens π-π interactions and surface polarity, while metal impregnation introduces surface complexation and catalytic degradation pathways [2,99,100]. The synergistic integration of these mechanisms results in higher adsorption capacity, improved resistance to competitive interference, and enhanced regeneration stability compared with pristine biochars. These mechanistic relationships provide the basis for the adsorption performance trends discussed in Section 6 and the mechanistic synthesis presented in Section 8.

7. Adsorption Performance of Biochar-Based Adsorbents

The adsorption performance of biochar-based adsorbents for dye removal is strongly governed by feedstock selection, pore structure, surface chemistry, and surface engineering strategies, as evidenced by representative systems and adsorption capacities summarized in Table 1 and in Tables S1 and S2. The major material and operational factors controlling dye adsorption performance in biochar-based systems are summarized conceptually in Figure 5. Across a wide range of biomass-derived biochars, significant dye removal capacities have been reported for both cationic and anionic dyes, with performance generally improving following chemical activation, physical modification, or composite formation. For example, biochars derived from agricultural residues, wood wastes, and sludge exhibit effective uptake of dyes such as methylene blue, malachite green, azo dyes, and anthraquinone dyes, reflecting the inherent affinity of carbonaceous surfaces for aromatic and ionic dye molecules [24,26,101,102]. However, pristine biochars often display moderate adsorption capacities due to limited surface area and heterogeneous functional group distribution, highlighting the necessity of targeted surface engineering to enhance performance and consistency.

Table 1. Biochar-based adsorbents for dye removal, their adsorption capacity, and dominant adsorption mechanisms.

Biochar	Active Functional Groups	Dye Type	Maximum Adsorption Capacity (mg g^{-1})	Isotherm Model	Kinetic Model	Mechanism	Ref
Algal biochar	O–H, NH_2, SO_3^-	CR	186.94	Langmuir	Pseudo-nth order	Electrostatic interaction, π-π stacking interaction, hydrophobic attraction	[103]
Alkali intercalated and acid exfoliated biochars	-	MG	107.64	Langmuir	PSO	-	[104]
Phosphoric Acid-Activated Biochar	−OH, C−H, ester C=O, aromatic C=C, alcohol C−O, and ether C−O−C	MO	239.1	Langmuir	PSO	H-bonding, π-π interactions, dipole interactions, and hydrophobic forces	[48]
		RhB	2821.8				
		MB	580.5				
		CV	396.6				
KOH-activated biochar and chitosan composites	-COOH, -NH_2, and -OH	MB	62.04	Temkin	PFO	Ion exchange, pore filling, electrostatic attraction, π-π interactions, and hydrogen bonding	[105]
Reed straw-based biochar	-	MV	35.7	Langmuir	PSO	Intra-particle and boundary layer diffusion	[106]
Alkali-modified corn straw biochar	–OH, C=C, C–C, C–N, C–O, and C=O	MB	290.71	Freundlich	-	π-π interaction, H-bonding, and pore-filling	[107]
Metal Oxide-Impregnated Biochar	C=C, C=O, −OH, −CH3, Fe-O, −CH=CH2	AD	72.4	Langmuir	PSO	Electrostatic attraction	[89]
Activated Wheat Straw Biochars	C=C, C=O,	RhB	36.01	Freundlich	PSO	π-π interactions, H-bonding	[108]
		MB	96.69				
		MO	119.76				
Composite hydrogel PAS/aBC-CD	C-O-C, C = O, –OH, C = C, C-H,	MB	1494	Langmuir	PSO	π-π stacking, H- bonding, pore filling, host-guest interaction	[109]
		MG	1182				
		NR	1031.6				
Magnetic activated carbon (MAC)	–OH, C = C, C-H, C-O, Fe-O	RhB	198.529	Freundlich	PSO	-	[110]
		RB	42.551				
PAA-based composite hydrogel	C=C, C=O, C–O, O–H	MG	521	Langmuir	PSO	H-bonding, charge assisted H-bonding, p-p, and Lewis's acid–base interactions	[111]
		Rho	741				
SFS-AC-K-13	C-H, OH, C-O, C=C	AB 158 Dye	388	Freundlich	-	-	[112]
$ZnCl_2$ doped pyrolyzed biochar	–OH, C=C, C=O	MG	318.47	Langmuir	PSO	hydrogen bonding, π-π bonding, and electrostatic interactions	[113]
		MO	225.73				
Stem Biochar	–OH, C=C, C=O	MB	285.71	Langmuir	PSO	hydrogen bonding, π-π bonding, electrostatic repulsion, hydrophobic interaction	[114]
Leaf Biochar			322.58				
$KMnO_4$-Modified Biochar		MG	1111.11	Freundlich	PFO PSO	pore filling, π-π interactions, and functional group complexation	[115]

Note: MB = Methylene blue; MO = Methyl orange; MG = Malachite green; CR = Congo red; NR = Neutral red; MV = methylene violet; CV = Crystal violet dye; RhB = Rhodamine B; AD = Azo Dye; RB = Rose Bengal; AB = Acid Blue; IB = Indigotin blue; TY = Tartrazine yellow; PFO = pseudo-1st-order; PSO = pseudo-2nd-order.

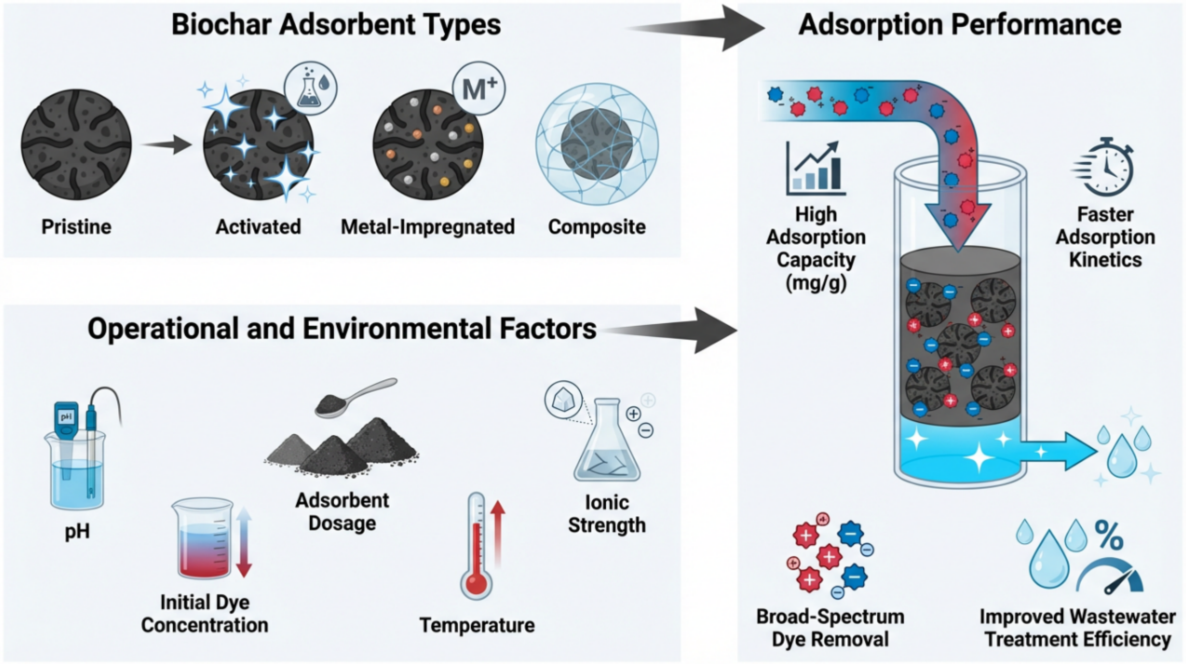

Figure 5. Schematic overview of factors influencing dye adsorption performance of biochar-based adsorbents.

A comparative evaluation of adsorption capacities presented in Tables S1 and S2, and Table 1 indicates distinct performance disparities between virgin and modified biochar systems. In the assembled dataset, pristine biochars generally demonstrate modest adsorption capabilities primarily influenced by feedstock composition, intrinsic pore structure, and surface functional groups [24,26,102]. Chemically activated and composite biochars often exhibit significantly greater adsorption capacities and accelerated adsorption kinetics owing to the formation of hierarchical porosity, augmented surface area, and improved surface functionality [27,55]. Chemical activation, metal impregnation, and composite formation consistently represent the most efficacious strategies for enhancing adsorption performance, especially for cationic dyes like methylene blue and malachite green, where electrostatic attraction and π-π interactions predominantly govern adsorption behavior [42,55,116]. The observed adsorption capacities exhibit significant variability between studies due to major differences in experimental circumstances, including initial dye concentration, solution pH, adsorbent dosage, and contact time [6,11,14]. Thus, adsorption capacity values must be interpreted with caution and regarded as context-dependent performance indicators rather than definitive measures of adsorbent superiority. This underscores the necessity of assessing adsorption performance in conjunction with experimental conditions, material characteristics, and prevailing adsorption mechanisms when comparing various biochar-based adsorbents.

Chemical activation emerges as one of the most effective strategies for improving adsorption capacity, primarily through the development of hierarchical micro–mesoporous structures and increased aromaticity. KOH-activated spruce bark biochar, for instance, demonstrated substantially enhanced adsorption of azo dyes, attributable to increased surface area, expanded pore networks, and strengthened π-π interactions between the dye molecules and graphitic domains [54]. Similarly, $ZnCl_2$-doped and metal-impregnated biochars exhibited improved adsorption of anionic and coordinating dyes due to the introduction of Lewis acid sites and surface complexation mechanisms, as reported for $ZnCl_2$-modified and Fe(III)-treated biochars [113,117]. These findings confirm that chemical modification not only increases adsorption capacity but also imparts selectivity toward specific dye classes. Besides, physical and mechanical surface engineering approaches further contribute to enhanced adsorption performance by improving mass transfer and accessibility of active sites. Ball milling of biochar and biochar–fly ash composites generated defect-rich surfaces and reduced particle size, leading to faster adsorption kinetics and higher effective utilization of adsorption sites for methylene blue and related dyes [27]. Likewise, optimized pyrolysis conditions and feedstock-specific tailoring, such as in areca husk and palmyra fiber biochars, produced surfaces with favorable aromatic structures and charge characteristics that enhanced adsorption capacity without the need for aggressive chemical treatment [24,102]. These approaches demonstrate that performance gains can be achieved through controlled physical processing and feedstock optimization.

Composite and immobilized biochar systems represent an advanced class of engineered adsorbents with superior performance and operational robustness. Biochar–hydrogel composites exhibited ultra-high adsorption capacities for mixed dye systems due to the synergistic combination of porous carbon matrices and polymer networks providing multiple binding sites and improved mass transport [109]. Immobilization within alginate beads or incorporation of magnetic phases further enhanced practical applicability by stabilizing the adsorbent structure, facilitating recovery, and reducing secondary pollution risks, while maintaining high adsorption efficiency [58,110]. In continuous-flow and fixed-bed configurations, engineered biochars also demonstrated stable dye removal performance under realistic conditions, bridging the gap between laboratory-scale batch studies and real-world wastewater treatment [20]. Overall, the expanded adsorption performance data and surface engineering evidence indicate that the transformation of biochar from a low-cost sorbent into a high-performance, application-ready adsorbent relies on deliberate modification strategies that enhance porosity, surface functionality, and structural stability. The strong correlation between surface engineering approaches and improved adsorption capacity, kinetics, and selectivity underscores the importance of mechanism-informed design in advancing biochar-based dye removal technologies toward scalable and sustainable wastewater treatment solutions.

Reported adsorption capacities for biochar-based adsorbents vary widely across studies (Table 1), and direct comparison of these values should therefore be interpreted cautiously because adsorption performance is strongly influenced by experimental conditions and material characteristics [14,15]. Parameters such as solution pH, initial dye concentration, adsorbent dosage, temperature, and contact time can significantly influence the measured equilibrium adsorption capacity of a material by altering adsorption driving forces and surface interaction mechanisms [11]. For example, higher initial dye concentrations often increase calculated adsorption capacities because stronger concentration gradients enhance mass transfer between the solution phase and available adsorption sites on biochar surfaces [14]. Conversely, lower adsorbent dosages may produce apparently higher capacity values because adsorption sites become saturated more efficiently under limited adsorbent availability [15]. Solution pH further plays a critical role by controlling both the ionization state of dye molecules and the surface charge characteristics of biochar materials, thereby influencing electrostatic attraction or repulsion between adsorbent and adsorbate species [6]. In addition, differences in experimental design, including batch versus continuous systems and equilibrium versus kinetic evaluation methods, can lead to substantial variability in reported adsorption capacities across studies [7,11]. Consequently, adsorption capacities summarized in the literature should be interpreted as context-dependent performance indicators rather than absolute metrics of adsorbent superiority, and careful consideration of experimental conditions is required when evaluating the effectiveness of different biochar-based adsorbents for dye removal. This constraint signifies a crucial methodological aspect in adsorption research, since directly comparing adsorption capacities across studies without normalizing experimental circumstances may result in erroneous interpretations of adsorbent efficacy. Therefore, adsorption capacities must be assessed in conjunction with experimental parameters and system design, rather than being regarded as definitive measures of adsorbent excellence.

8. Adsorption Kinetics, Isotherms, and Thermodynamics

The adsorption behavior of dyes on biochar-based adsorbents is commonly interpreted using non-linear kinetic and equilibrium models that describe adsorption rates, surface heterogeneity, and equilibrium capacity. The mathematical expressions and physical interpretations of the most frequently applied kinetic and isotherm models are summarized in Table 2. This review exclusively presents adsorption models in their non-linear variants. Linearized transformations of adsorption models were deliberately excluded due to their potential to induce statistical bias and distort parameter estimation in model fitting. Modern adsorption research increasingly utilizes non-linear regression techniques to derive more dependable kinetic and equilibrium parameters for heterogeneous adsorbent systems, including biochars. The interrelationships among adsorption kinetics, equilibrium behavior, thermodynamic feasibility, and dominant dye–biochar interaction mechanisms are schematically integrated in Figure 6 and quantitatively summarized in Table S3. Across a wide range of feedstocks, surface modifications, and dye classes, pseudo-second-order (PSO) kinetics predominates, indicating that adsorption rates are primarily controlled by the availability and reactivity of surface sites rather than by external mass transfer alone, and suggesting the involvement of chemisorption-like interactions or strong physicochemical binding between dye molecules and biochar surfaces [26,101,118]. While the pseudo-second-order model often yields the most accurate statistical fit for dye adsorption onto biochar-based adsorbents, such alignment should not be construed as conclusive proof of chemisorption, as kinetic model fitting alone cannot definitively ascertain adsorption mechanisms without supplementary physicochemical characterization and diffusion analysis. In several systems, particularly those involving larger or more complex dye molecules, intraparticle diffusion contributes to the overall adsorption process, as evidenced by multi-linear kinetic plots, although it rarely constitutes the sole rate-limiting step, highlighting the combined influence of surface reaction and internal diffusion mechanisms [25,119].

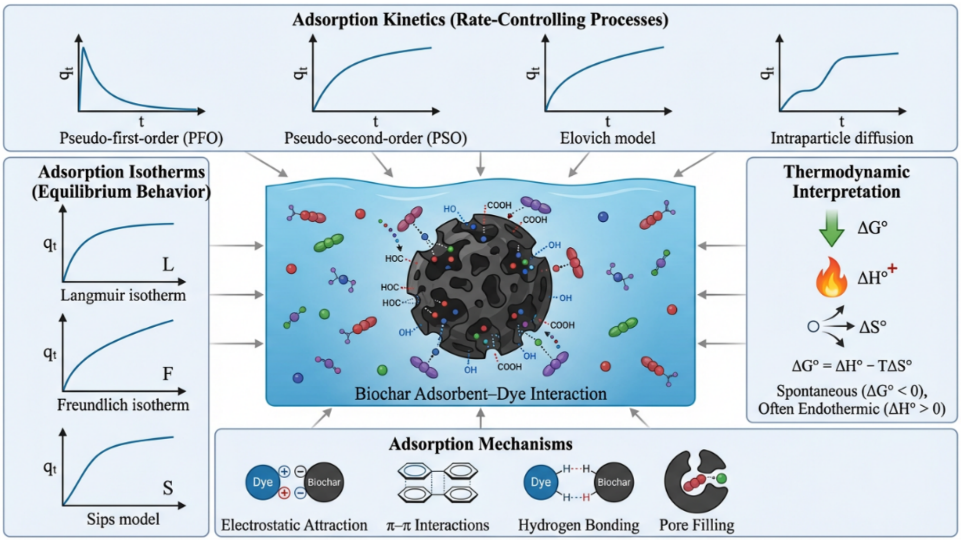

Figure 6. Integrated mechanistic framework for dye adsorption onto biochar-based adsorbents.

Table 2. Common adsorption kinetic and isotherm models applied for dye adsorption on biochar-based adsorbents.

Model	Non-Linear Equation	Key Parameters	Interpretation in Biochar–Dye Systems
Adsorption Kinetic Models			
Pseudo-first-order (PFO)	$q_t = q_e(1-e^{-k_1 t})$	q_e(mg g^{-1}), k_1(min^{-1})	Represents physisorption-dominated uptake; often inadequate over the full adsorption period
Pseudo-second-order (PSO)	$q_t = \frac{k_2 q_e^2 t}{1+k_2 q_e t}$	q_e, k_2(g mg^{-1} min^{-1})	Dominant kinetic model across pristine, activated, and composite biochars, indicating surface-controlled adsorption
Elovich	$q_t = \frac{1}{\beta}\ln(1+\alpha\beta t)$	α, β	Applicable to heterogeneous surfaces with chemisorption characteristics
Intraparticle diffusion (IPD)	$q_t = k_{id}t^{1/2} + C$	k_{id}, C	Used to evaluate diffusion contribution; multilinearity indicates multiple rate-controlling steps
Langmuir	$q_e = \frac{q_{max}K_L C_e}{1+K_L C_e}$	q_{max}(mg g^{-1}), K_L(L mg^{-1})	Indicates monolayer adsorption on energetically uniform or effectively homogenized surfaces; most frequently reported model
Freundlich	$q_e = K_F C_e^{1/n}$	K_F, n	Describes adsorption on heterogeneous surfaces and multilayer uptake
Adsorption Isotherm Models			
Langmuir–Freundlich (Sips)	$q_e = \frac{q_{max}K_s C_e^n}{1+K_s C_e^n}$	q_{max}, K_s, n	Accounts for surface heterogeneity while retaining monolayer saturation behavior
Temkin	$q_e = \frac{RT}{b_T}\ln(K_T C_e)$	K_T, b_T	Considers adsorbate–adsorbent interactions and linear decrease in adsorption energy
Dubinin–Radushkevich (D–R)	$q_e = q_m \exp(-\beta\varepsilon^2)$	q_m, β	Used to assess micropore filling and adsorption energy

Equilibrium adsorption behavior is most frequently described by the Langmuir isotherm model, implying monolayer coverage of dyes on energetically uniform or effectively homogenized adsorption sites, especially in chemically activated and engineered biochars with well-developed pore structures and tailored surface chemistry [24,54,120]. In contrast, Freundlich or Langmuir–Freundlich models are often more suitable for pristine or composite biochars characterized by surface heterogeneity and a distribution of adsorption energies, reflecting the coexistence of multiple interaction mechanisms such as electrostatic attraction, π-π stacking, and hydrogen bonding [27,101]. These isotherm trends underscore the importance of surface engineering in transforming heterogeneous natural biochars into more uniform and predictable adsorbents.

Thermodynamic analyses reported in primary studies consistently indicate that dye adsorption onto biochar is spontaneous, as evidenced by negative Gibbs free energy changes ($\Delta G^\circ < 0$) across the investigated temperature ranges, confirming the inherent affinity between dyes and biochar surfaces [116,118,121]. Many adsorption systems also exhibit endothermic behavior, with positive enthalpy changes ($\Delta H^\circ > 0$), suggesting that higher temperatures enhance dye uptake by increasing molecular mobility, promoting pore diffusion, and facilitating the formation of stronger surface interactions, particularly in activated and composite biochars [54,98,109,122]. High-affinity adsorption sites and endothermic behavior have also been reported for super-adsorbent engineered biochars in multi-dye systems [123]. Entropy changes (ΔS°) are generally positive, indicating increased randomness at the solid–liquid interface during adsorption, which is commonly attributed to the displacement of water molecules from biochar surfaces by dye molecules with higher affinity [124]. Collectively, the kinetic, isotherm, and thermodynamic evidence demonstrates that dye adsorption on biochar-based adsorbents is a rapid, energetically favorable, and surface-controlled process, with performance strongly influenced by surface modification and pore architecture, thereby providing a quantitative foundation for the rational design and optimization of biochar adsorbents for wastewater treatment applications.

9. Adsorption Mechanisms and Mechanistic Insights

The adsorption of synthetic dyes by biochar-based adsorbents arises from the combined action of multiple physicochemical interaction pathways, the relative importance of which is controlled by biochar surface characteristics, dye molecular properties, and solution chemistry, as summarized in Table 3 and illustrated in Figure 7. Although multiple adsorption mechanisms have been proposed for dye removal using biochar-based adsorbents, the relative importance of these mechanisms depends strongly on wastewater chemistry and operational conditions [14]. Electrostatic attraction is frequently identified as a dominant mechanism for adsorption of cationic dyes such as methylene blue; however, this interaction can be weakened in high-ionic-strength wastewater systems where dissolved salts screen surface charges and reduce electrostatic interactions between dye molecules and biochar surfaces [11]. Under such conditions, adsorption may shift toward alternative mechanisms such as pore filling or π-π interactions between aromatic dye structures and graphitic domains present on highly carbonized biochar materials, which are commonly associated with high-temperature pyrolysis processes (Figure 7) [14]. Contradictory adsorption trends reported across studies further highlight the importance of experimental conditions, as some investigations report strong adsorption of anionic dyes on unmodified biochar surfaces whereas others observe limited adsorption due to electrostatic repulsion between negatively charged dye molecules and biochar surfaces [6]. These discrepancies are often associated with differences in pH conditions, mineral composition, and surface functional groups that modify the surface charge characteristics of the adsorbent, thereby altering the dominant adsorption pathways summarized in Table 3. In addition, adsorption capacities reported for similar biochar materials frequently vary depending on experimental parameters such as initial dye concentration, adsorbent dosage, and equilibrium conditions, which complicates direct comparison of adsorption performance across studies [6,11]. In realistic wastewater systems, adsorption mechanisms rarely operate independently because industrial effluents commonly contain mixtures of dyes, salts, surfactants, and natural organic matter that compete for adsorption sites and alter the surface chemistry of biochar materials, thereby influencing the mechanisms illustrated in Figure 7 [19,54,101,123]. Competitive adsorption among dye molecules, along with the presence of natural organic matter, dissolved ions, and coexisting pollutants in actual wastewater, can markedly affect adsorption behavior compared to simplified laboratory systems. Natural organic matter might compete with dye molecules for adsorption sites or obstruct the pore architectures of biochar, thereby diminishing effective adsorption capacity [7,13,44]. Likewise, increased ionic strength and dissolved salts can diminish electrostatic interactions via charge-screening effects, hence reducing the adsorption of ionic dyes and altering the primary removal mechanisms towards pore filling or π-π interactions [13,16,56]. The matrix effects underscore a significant limitation of laboratory studies utilizing synthetic dye solutions and stress the necessity of assessing adsorption efficacy under authentic wastewater conditions, encompassing multi-contaminant systems and continuous-flow treatment setups [31,56]. Consequently, adsorption efficiencies reported for simplified laboratory systems may overestimate removal performance when applied to complex wastewater matrices, emphasizing the importance of evaluating adsorption mechanisms under environmentally relevant conditions [7].

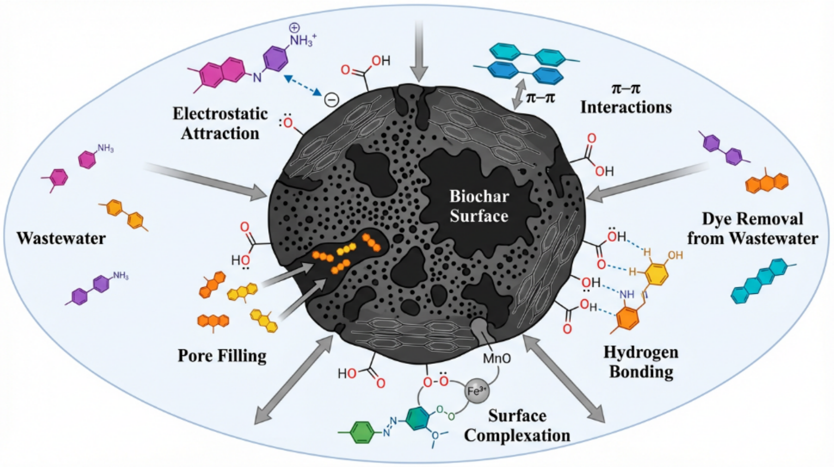

Figure 7. Multimodal mechanisms governing synthetic dye adsorption on to biochar-based adsorbents.

Table 3. Relationship between adsorption mechanisms, biochar surface features, and dye classes.

Adsorption Mechanism	**Supporting Surface Feature(s)**	**Dye Class/Examples**	**Primary Experimental Evidence Reported**	**Key Implication for Design**	**Ref**
Electrostatic attraction	Negative surface charge at working pH; suitable pH relative to pH_pZPC	Cationic (e.g., methylene blue, malachite green, crystal violet)	Strong pH-dependence consistent with charge-controlled adsorption; improved uptake under conditions favoring opposite charges	Tune pH and surface charge (oxidation/activation/metal sites) for ionic selectivity	[118,121,125]
Electrostatic attraction	Positively charged or metal-enriched sites	Anionic (e.g., Direct Red 28, Acid Red 88)	Enhanced anionic dye uptake attributed to favorable charge conditions and engineered surfaces	Introduce positively charged sites (metal treatment/functionalization) to overcome anion repulsion	[25,116]
π-π stacking / EDA interactions	Aromatic/graphitic domains; high carbonization; conjugated surfaces	Aromatic dyes (azo, anthraquinone, triarylmethane)	Spectroscopic/adsorption trends consistent with aromatic–aromatic interactions; improved performance with activated/graphitized biochars	Increase aromaticity (activation/optimized pyrolysis) for dyes with extended π-systems	[24,28,54]
Hydrogen bonding	–OH, –COOH, –C=O functional groups; oxygenated surfaces	Polar dyes (e.g., sulfonated dyes, MB derivatives)	FTIR band shifts and improved adsorption with functionalized surfaces consistent with H-bonding contribution	Enrich oxygenated groups (mild oxidation, controlled activation) to strengthen polar interactions	[54,101]
Pore filling	Micropore/mesopore hierarchy; high surface area; connected porosity	Small–medium dyes (e.g., MB)	Capacity trends aligned with pore development; activated and engineered biochars show higher uptake	Engineer hierarchical porosity to maximize accessible adsorption volume	[26,54,86]
Intraparticle diffusion control	Limited mesoporosity; tortuous pores; particle size effects	Bulky dyes (e.g., AR88; large anionic dyes)	Multi-stage kinetic profiles and intraparticle diffusion behavior indicating diffusion-limited uptake	Improve mesoporosity and reduce particle size to relieve diffusion constraints	[25,119]
Surface complexation/coordination	Metal/mineral sites (Fe^{3+}, Zn^{2+}, sludge minerals); Lewis acid sites	Anionic/sulfonated dyes and strongly coordinating dyes	Enhanced adsorption attributed to formation of surface complexes on metal/mineral sites; improved affinity after impregnation/activation	Introduce metal/mineral sites for selective adsorption and stronger binding	[26,113,121,126]
Synergistic multi-mechanism adsorption	Composite phases; multi-functional surfaces; polymer networks	Mixed dye systems	Composite/hydrogel systems show high capacity and robust performance due to multiple binding modes acting together	Use composites to combine charge sites + porosity + functional groups in one material	[28,109]
Competitive adsorption in complex matrices	Surface heterogeneity; mineral phases; pore accessibility under co-solutes	Real wastewater/mixed solutes	Real effluents show competition effects; performance depends on multifunctional sites and accessible porosity	Validate in real wastewater; design for selectivity under competition	[20,29]
Immobilization-enhanced stability (mass transfer + handling)	Alginate beads/immobilized structures; mechanical integrity	Anionic dyes (e.g., eosin yellow)	Improved reuse and stable operation due to reduced loss of fine particles and improved handling	Immobilization improves practical applicability and reuse	[58]
Column/continuous-flow transport effects	Bed packing, hydrodynamics, residence time	Reactive dyes (industrial wastewater)	Fixed-bed breakthrough modeling and stable operation demonstrate transport-limited behavior in continuous systems	Use column tests to translate batch results to scale	[20]
Integrated process synergy (biochar + digestion)	Biochar as adsorbent + process aid (system-level)	Dye wastewater + organics	Coupled systems show improved treatment with resource recovery potential	Integrate adsorption with biological treatment for circularity	[127]

Electrostatic attraction represents a primary driving force for the removal of ionic dyes and is strongly controlled by the solution pH relative to the biochar point of zero charge; negatively charged biochar surfaces at neutral to alkaline pH favor the adsorption of cationic dyes such as methylene blue, malachite green, and crystal violet, whereas positively charged or metal-enriched surfaces enhance the uptake of anionic dyes including sulfonated and azo dyes by mitigating electrostatic repulsion [116,118,125]. In parallel, π-π electron donor–acceptor interactions play a critical role in the adsorption of aromatic and conjugated dye molecules, particularly on biochars with high aromaticity and graphitic domains produced via optimized pyrolysis or chemical activation, as evidenced by enhanced adsorption performance for azo and anthraquinone dyes on KOH-activated and highly carbonized biochars [24,28,54]. Hydrogen bonding further contributes to dye uptake, especially for polar dyes bearing hydroxyl, amino, or sulfonate groups, with FTIR-based evidence demonstrating the involvement of oxygen-containing functional groups such as –OH, –COOH, and –C=O in stabilizing dye–biochar interactions [19,54,101,123]. Pore filling and diffusion-related mechanisms are particularly important for small to medium-sized dye molecules, where hierarchical micro–mesoporous structures provide accessible adsorption volume and enhance capacity, while limited mesoporosity or tortuous pore networks can impose intraparticle diffusion constraints that slow adsorption kinetics and reduce desorption efficiency for bulky dyes [25,26,119]. Surface complexation mechanisms become dominant in biochars containing mineral phases or impregnated metal species, where coordination interactions between dye functional groups and metal or Lewis acid sites significantly enhance the adsorption of anionic and strongly coordinating dyes, as demonstrated in metal-treated, sludge-derived, and $ZnCl_2$-doped biochars [26,113,126]. Surface complexation on metal-impregnated biochars has been directly demonstrated for sulfonated dyes through coordination interactions [126]. This behavior has been reported for Fe-, Zn-, and mineral-rich sludge-derived biochars, where enhanced affinity toward anionic dyes was attributed to the formation of inner-sphere surface complexes. In complex systems, particularly those involving mixed dyes or real industrial effluents, no single mechanism operates in isolation; instead, multifunctional surfaces enable synergistic adsorption through the combined action of electrostatic attraction, aromatic stacking, hydrogen bonding, pore filling, and surface complexation, as observed in composite and hydrogel-based biochar systems that exhibit high capacity and robustness under competitive conditions [20,29,109]. Additionally, immobilization and structural stabilization strategies, such as alginate encapsulation, enhance practical applicability by improving mass transfer control, reducing particle loss, and maintaining adsorption efficiency over repeated use without altering the fundamental adsorption mechanisms [58]. Overall, mechanistic evidence from primary experimental studies confirms that high-performance dye adsorption by biochar-based materials arises from the deliberate integration of complementary surface features tailored to dye chemistry and operating conditions, providing a mechanistic foundation for rational adsorbent design and scalable wastewater treatment applications.

10. Regeneration, Reusability, and End-of-Life Management

Regeneration and reusability are critical parameters governing the long-term applicability and economic viability of biochar-based adsorbents for dye-contaminated wastewater treatment, as sustained performance over multiple cycles directly influences operational cost and environmental sustainability. Primary experimental evidence demonstrates that well-engineered biochars can maintain a substantial fraction of their initial adsorption capacity following repeated adsorption–desorption cycles, indicating that dye removal is largely driven by reversible physicochemical interactions rather than irreversible surface degradation. Many biochar systems retain more than 80% of their adsorption capacity after 4–6 regeneration cycles, highlighting their strong potential for repeated use in practical treatment scenarios [26,109,118]. A thorough evaluation of regeneration strategies documented in the literature reveals that regeneration efficacy and structural stability significantly differ according on the regeneration method and biochar content. Solvent and mild chemical washing techniques often maintain pore architecture and surface functionality; nevertheless, they may fail to entirely eliminate highly bound dye molecules, leading to progressive capacity degradation over subsequent cycles [43,56]. Conversely, heat regeneration can efficiently breakdown residual pollutants and restore adsorption capacity; but, repeated high-temperature treatments may result in pore collapse, surface oxidation, and structural degradation of the biochar matrix [60,116]. In numerous systems, incremental declines in adsorption efficacy are ascribed to pore obstruction, insufficient desorption, and the depletion of active surface sites across successive regeneration cycles [34,44]. These discoveries underscore the necessity for a thorough assessment of regeneration efficiency, structural integrity, and long-term cycling performance in evaluating the practical usability of biochar-based adsorbents for wastewater treatment.

Regeneration performance of biochar-based adsorbents varies depending on the regeneration method, dye chemistry, and structural stability of the adsorbent. Many studies report that biochar materials retain a substantial fraction of their adsorption capacity after multiple regeneration cycles, although gradual decreases in performance are commonly observed due to pore blockage, structural degradation, or incomplete desorption of dye molecules. A detailed compilation of regeneration studies is provided in Supplementary Table S4. Solvent-based regeneration methods, particularly ethanol washing or mild alkaline treatment, are commonly employed and have proven effective in restoring adsorption capacity while preserving biochar structural integrity, as evidenced by modified Pinus brutia biochar and KOH-activated spruce bark biochar, which retained approximately 82% and 80% of their initial capacities after five cycles, respectively [54,118]. Composite and immobilized biochar systems generally exhibit superior regeneration stability, with biochar–hydrogel composites maintaining over 90% capacity after five cycles and alginate-immobilized okara biochar retaining around 85% capacity after six cycles, reflecting the protective role of polymer networks and immobilization in preventing structural collapse and adsorbent loss [58,109]. Feedstock composition and surface chemistry further influence regeneration performance, as demonstrated by sludge-derived activated biochar, which preserved nearly 88% of its methylene blue adsorption capacity after five regeneration cycles due to the stabilizing effect of mineral-rich surfaces [26], whereas macroalgae-derived biochar showed comparatively lower retention (~76% after four cycles) because diffusion-limited adsorption hindered complete desorption from internal pore structures [25]. Performance under realistic wastewater conditions is generally reduced relative to single-solute systems, with oil-cake-derived biochar retaining approximately 70% capacity after three cycles when treating real dyehouse effluent, reflecting the impact of competitive adsorption and organic fouling [29]. Continuous-flow and column studies further confirm the operational robustness of biochar-based systems, as stable breakthrough behavior and sustained dye removal have been reported in fixed-bed biochar columns treating industrial dyeing wastewater [20], while magnetic biochar systems demonstrate additional practical advantages by enabling rapid recovery and reuse, retaining nearly 90% of adsorption capacity after six cycles through magnetic separation [110]. Collectively, these primary studies indicate that chemically activated, composite, immobilized, and magnetically recoverable biochars offer the most promising regeneration performance and stability, although long-term operation in complex wastewater matrices remains challenging, underscoring the need for standardized regeneration protocols, extended cycling tests, and integration of regeneration behavior into techno-economic and life-cycle assessments to support scalable implementation.

Although numerous studies report successful regeneration of biochar adsorbents, regeneration efficiency often declines after repeated adsorption–desorption cycles due to gradual loss of active adsorption sites and structural alterations of the biochar surface. Chemical regeneration methods using acids, bases, or organic solvents can effectively desorb adsorbed dye molecules; however, these treatments may also modify surface functional groups or partially degrade the porous structure of the adsorbent [15]. Thermal regeneration approaches can restore adsorption capacity by decomposing retained dye molecules, yet repeated high-temperature treatments may lead to pore collapse and reduced surface area [58,109]. In addition, incomplete desorption during regeneration cycles may result in gradual accumulation of residual contaminants on the biochar surface, thereby reducing adsorption efficiency over time [29]. Environmental considerations must also be taken into account because regeneration processes involving strong chemicals or high energy inputs may reduce the overall sustainability advantages associated with biochar-based treatment systems [7]. Consequently, future research should focus on developing regeneration strategies that maintain adsorption performance while minimizing energy consumption, chemical usage, and environmental impacts.

11. Challenges, Limitations, and Critical Gaps

Despite substantial progress in the development of biochar-based adsorbents for dye removal, several interrelated challenges and critical gaps continue to constrain their practical implementation and scientific generalization. A primary limitation arises from the inherent variability of biomass feedstocks and synthesis conditions, which leads to pronounced heterogeneity in biochar surface chemistry, porosity, mineral content, and adsorption performance, thereby hindering reproducibility and cross-study comparability [57,128]. This challenge is further exacerbated by the lack of standardized experimental protocols and reporting practices, as adsorption capacities are often evaluated under disparate conditions without normalization to intrinsic material properties such as surface area, functional group density, or pore structure, limiting mechanistic interpretation [129,130]. Moreover, a large fraction of existing studies relies on idealized single-solute systems, which do not adequately represent real industrial wastewaters containing mixed dyes, salts, surfactants, and organic matter, where competitive adsorption and site blocking can substantially alter adsorption behavior [12,128].

Although numerous laboratory studies demonstrate high adsorption capacities for dye removal using engineered biochar materials, translation of these results to real wastewater treatment systems remains challenging. Industrial effluents often contain complex mixtures of dyes, salts, surfactants, and natural organic matter that compete for adsorption sites and alter adsorption mechanisms relative to simplified laboratory systems [11,15]. In addition, variations in wastewater pH, ionic strength, and temperature can significantly influence surface charge characteristics and adsorption kinetics of biochar materials [110]. Operational considerations such as hydraulic loading, column fouling, adsorbent regeneration efficiency, and long-term structural stability also represent important challenges when scaling biochar-based adsorption systems for continuous treatment processes [58,109]. While laboratory batch studies provide valuable mechanistic insights, future research should prioritize pilot-scale evaluations and continuous-flow systems that more closely represent realistic wastewater treatment conditions in order to assess the long-term feasibility and operational sustainability of biochar-based adsorbents for dye removal.

Mechanistic interpretations are also frequently inferred from adsorption kinetics or isotherm fitting without sufficient validation using complementary spectroscopic or surface characterization techniques, increasing the risk of oversimplifying complex dye–biochar interactions [13,131]. In addition, regeneration and reusability assessments are often limited to a small number of cycles, with insufficient evaluation of long-term structural stability, surface degradation, secondary pollution risks, and the environmental and economic costs associated with regeneration processes [130,132]. From a translational perspective, most investigations remain confined to batch-scale experiments, with limited exploration of continuous-flow systems, column operation, hydraulic performance, and material attrition, thereby impeding scale-up and process integration [12]. Finally, uncertainties related to end-of-life management, potential dye leaching, lifecycle sustainability, and regulatory acceptance of spent biochars remain insufficiently addressed, underscoring the need for integrated, application-oriented research frameworks that move beyond adsorption capacity metrics toward holistic performance, sustainability, and risk assessment [57,130].

12. Future Research Directions

Future research on biochar-based adsorbents for dye removal should prioritize mechanism-guided material design, standardized evaluation frameworks, and translational validation to bridge the gap between laboratory-scale success and practical implementation. A critical priority is the establishment of systematic structure–function relationships that link feedstock composition, synthesis conditions, and surface engineering strategies to predictable adsorption mechanisms and performance outcomes, thereby reducing variability and improving reproducibility across studies [57,128,133]. Standardized adsorption testing protocols—incorporating normalized performance metrics, consistent reporting of physicochemical properties, and unified modeling approaches—are urgently needed to enable meaningful benchmarking and cross-study comparison [129,130]. Greater emphasis should also be placed on multi-component and real-wastewater systems to capture competitive adsorption effects, matrix interferences, and operational constraints that are absent in idealized single-solute experiments [12]. Mechanistic validation must move beyond model fitting toward integrated use of advanced spectroscopic, microscopic, and surface analytical techniques to directly confirm dye–biochar interactions and adsorption pathways [13,131]. From an application standpoint, future studies should expand beyond batch experiments to include continuous-flow, column-scale, and pilot-scale demonstrations, coupled with hydraulic performance assessment, regeneration longevity testing, and techno-economic evaluation. Finally, lifecycle assessment, environmental risk analysis, and regulatory alignment should be embedded into biochar research from the design stage to ensure that adsorption performance gains translate into environmentally responsible and economically viable wastewater treatment technologies. Collectively, these research directions provide a roadmap for advancing biochar-based dye remediation from promising laboratory materials toward scalable, resilient, and sustainable treatment solutions.

Future research should also focus on the development of hierarchically structured biochars and hybrid composite materials that combine high surface area with tailored surface functionality to enhance adsorption capacity and selectivity. Integration of biochar with polymers, clays, and metal oxides can create multifunctional adsorbents capable of improving both adsorption efficiency and structural stability under complex wastewater conditions [52,77,95]. In addition, greater emphasis should be placed on evaluating adsorption performance in continuous-flow reactor systems, including fixed-bed and column configurations, to better assess hydraulic performance and long-term operational stability under realistic treatment conditions [31]. Coupling biochar-based adsorption with advanced oxidation processes, such as Fenton-like or catalytic oxidation systems, also represents a promising strategy to enhance pollutant degradation and improve regeneration of adsorption sites in wastewater treatment systems [13,30,92].

13. Conclusions

This review provides a comprehensive synthesis of current advances in biochar-based adsorbents for dye-contaminated wastewater treatment by integrating biomass feedstock selection, thermochemical synthesis pathways, surface engineering strategies, adsorption mechanisms, and operational performance. The analysis highlights that adsorption efficiency is governed not only by intrinsic biochar properties such as pore structure, surface functional groups, and aromaticity, but also by environmental conditions including solution chemistry, competing solutes, and wastewater matrix complexity. A key insight emerging from the literature is that adsorption performance cannot be evaluated solely on the basis of reported capacity values because experimental conditions and system design strongly influence observed removal efficiencies. Consequently, rational development of high-performance biochar adsorbents requires an integrated design framework that links feedstock characteristics, synthesis conditions, and surface modification strategies with targeted adsorption mechanisms and real wastewater treatment requirements. Future research should prioritize pilot-scale validation, improved regeneration strategies, and environmentally sustainable production pathways to ensure that biochar-based adsorption technologies can transition from laboratory-scale demonstrations to reliable and scalable wastewater treatment solutions.

Supplementary Materials

The additional data and information can be downloaded at: https://media.sciltp.com/articles/others/2605141334081724/EPRRI-26030062-SM.pdf. Table S1: Adsorption performance of pristine biochar for dye removal from wastewater. Table S2: Adsorption performance of engineered and composite biochar-based adsorbents. Table S3: Kinetic, isotherm, and thermodynamic models applied to dye adsorption on biochar-based adsorbents. Table S4: Regeneration, reusability, and end-of-life management of dye-loaded biochar-based adsorbents. Reference [134] is cited in the supplementary materials.

Author Contributions

M.N.U.: conceptualization, methodology, literature search and data curation, writing—original draft preparation, table and figure preparation, critical analysis and synthesis of literature, visualization; A.S.: supported systematic literature collection, screening, table and figure preparation and technical editing of the manuscript; D.H.K.: review, revision and editing; G.B.O.: writing, review and editing. All authors have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used Quillbot to enhance the clarity, tone, and style of the scientific writing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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