Next Materials 9 (2025) 100974

Contents lists available at ScienceDirect

Next Materials

journal homepage: www.sciencedirect.com/journal/next-materials

Review article

Sustainable wastewater treatment: Mechanistic, environmental, and economic insights into biochar for synthetic dye removal

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ARTICLE INFO

Keywords:
Biochar
Dye removal
Adsorption mechanisms
Wastewater treatment
Dye-laden biochar
Machine learning

ABSTRACT

The contamination of aquatic environments by synthetic dyes poses significant environmental and health risks due to their structural complexity, toxicity, and resistance to biodegradation. Traditional treatment materials such as activated carbon, ion-exchange resins, and metal oxides are often limited by high cost, energy requirements, and post-use challenges. Biochar has emerged as a sustainable alternative, offering favourable physicochemical properties and characteristics, including large surface area, porosity, and functional groups, for effective dye adsorption. This review critically examines the production routes of biochar from diverse feedstocks, adsorption mechanisms involved in dye removal, and the influence of operational parameters such as pH, initial dye concentration, and modification techniques. Furthermore, we highlight recent modeling strategies, including machine learning approaches, for predicting dye adsorption performance. The potential for functionalization and activation of biochar to enhance dye removal efficiency is also explored. Beyond removal efficiency, this review evaluates the environmental implications and circular applications of dye-laden biochar, focusing on its stability, reusability, and integration into carbon management approaches. A bibliometric analysis is included to identify active research hubs, funding trends, and underexplored areas, providing a strategic perspective on the global development of this field. Overall, the review aims to support researchers, practitioners, and policymakers in advancing the design and application of biochar for cost-effective and environmentally sound treatment of dye-contaminated water.

1. Introduction

Synthetic dyes are integral to industries like textiles, packaging, printing, cosmetics, paper manufacturing, and pharma, serving as essential components in both everyday consumer products and specialized industrial processes, as outlined in Fig. 1. The global increase in the usage of these coloured compounds has led to a corresponding increase in the industrial release of coloured wastewaters into the rivers and eventually reaching the oceans or seas through runoff or improper wastewater disposal [1,2]. Due to their structural complexity and high chemical stability, most of the dyes are resistant to biodegradation, persisting in aquatic environments for extended periods [3–5]. In addition to lowering the quality of fresh water, the discharge of dye-contaminated water into water bodies puts both aquatic and terrestrial life at potential risk for mutagenesis, carcinogenicity, and various other health complications [4,6]. For example, methylene blue and reactive black 5—along with other commonly detected industrial dyes such as Congo red, crystal violet, and acid orange 7—not only exhibit toxic effects but are also known to disrupt photosynthetic activity in aquatic flora by attenuating light penetration in water bodies,

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https://doi.org/10.1016/j.nxmate.2025.100974
Received 22 June 2025; Received in revised form 16 July 2025; Accepted 17 July 2025
Available online 22 July 2025
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thereby indirectly leading to mutations in organisms by causing stress and damage to their cells and deoxyribonucleic acid (DNA) [7–12].

Numerous traditional materials used for dye adsorption, such as activated carbon, silica gel, activated alumina, zeolites, metal oxides, clays, and synthetic polymers (including ion-exchange resins), pose significant constraints, especially when addressing dyes at trace concentrations and/or within complex mixtures [14–18]. Larasati *et al.* [19] have reported that, despite being commonly used, activated carbon is costly to produce and regenerate, often requiring high energy inputs. According to Perera *et al.* [20], ion-exchange resins and metal oxides are typically expensive, prone to fouling, and may pose environmental concerns because of their limited biodegradability or nanoparticle release. Additionally, it has been demonstrated by Ewis *et al.* [21] that while inexpensive, clays and natural minerals generally offer lower adsorption capacities and limited tunability. On the other hand, Kosloski-Oh *et al.* [22] have emphasized that synthetic polymers, though effective, are often non-renewable and challenging to dispose of sustainably. These material-specific limitations, combined with minimal accessibility in environments having a relative lack of technical and economic resources, highlight the necessity for alternative adsorbents that are not only efficient but also renewable and economically viable [23,24].

Biochar has emerged as a sustainable, standalone adsorbent offering both economic feasibility and eco-compatibility, with considerable potential in industrial wastewater management, particularly in dye-intensive sectors. Produced from agro-wastes (*e.g.,* rice husks, corn stalks, or coconut shells), forestry residues (*e.g.,* sawdust), municipal sludge, and other biomass feedstocks commonly *via* pyrolysis under oxygen-limited or oxygen-free environment—typically at temperatures ranging from 300 to 1000 °C, with heating rates ranging from 5 to 50 °C/min, and residence times of 30 min to several hours—this carbonaceous material possesses physicochemical properties (*i.e.,* large surface area and highly porous structure) and characteristics (*i.e.,* abundant functional groups) [25–27]. Abdelfattah *et al.* [28] systematically illustrated that these controlled conditions are essential, as they prevent combustion and instead promote the thermal decomposition of feedstock into biochar (and by-products). Meanwhile, Laishram *et al.* [29] provided extensive evidence that the physicochemical properties and characteristics of biochar allow for efficient binding with a wide range of dye molecules from aqueous solutions through a combination of physical and chemical interactions. Several other researchers [30–33] have reported that modifying/enhancing these properties and characteristics, typically through activation or chemical impregnation, further increases the adsorption capacity of biochar.

Moreover, although using biochar in hybrid systems increases operational costs, it can be readily integrated into existing industrial frameworks as either a standalone adsorbent or in combination with filtration, oxidation, or membrane technologies, thereby enhancing overall dye removal efficiency [34–37]. As an additional benefit, the use of biochar contributes to waste valorization and carbon sequestration, both of which align with the United Nations' Sustainable Development Goals (SDGs) [38,39]. Importantly, the relative affordability of biochar

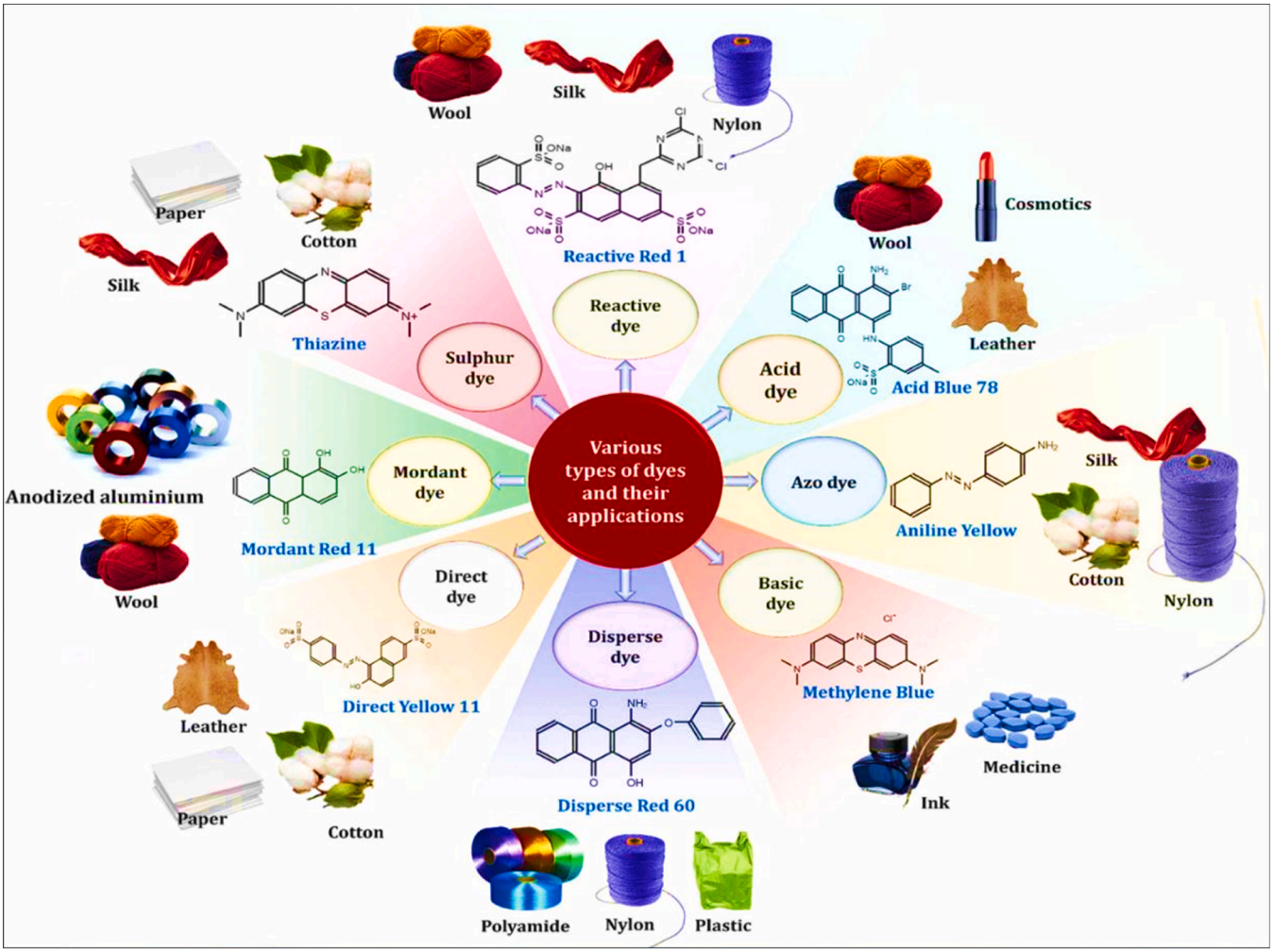

Fig. 1. Applications of various synthetic dyes across sectors. Reproduced from ref. [13] with permission from Ecotoxicology and Environmental Safety, copyright 2022.

offers a compelling alternative to commercial adsorbents, especially in low- and middle-income countries. Notably, textile wastewater is relatively rich in complex, limited-biodegradable mixtures of anionic and cationic dyes in addition to surfactants and heavy metals, making it a common target for biochar-based treatment technologies [13,40,41]. However, for such practical wastewater treatment settings, a more detailed assessment of the operational limitations and performance consistency of biochar as a dye adsorbent is essential to fully realize its potential.

Despite its recent growing appeal, the application of biochar in dye removal is not devoid of limitations. According to several studies [35, 42–46], inconsistent adsorption performance, stemming from fluctuating wastewater composition and heterogeneity in biochar characteristics, poses a significant challenge. These heterogeneities are influenced by variations in feedback stock types, pyrolysis conditions, and post-treatment modifications. Moreover, the long-term reusability and regeneration potential of biochar, which is vital for assessing sustainability and cost-effectiveness, is still insufficiently investigated in real-world contexts. While some studies [47–49] have examined individual mechanisms of dye adsorption, such as surface complexation, pore filling, $\pi-\pi$ stacking, electrostatic interaction, and hydrogen bonding (H-bonding), these processes are often studied in isolation. Although some studies [49,50] have begun to elucidate these mechanisms, there is a lack of integrative studies that holistically connect biochar physicochemical properties, adsorption mechanisms, and performance metrics across various dye classes under different operational conditions. Furthermore, adsorption isotherms and kinetic models are inconsistently applied in the literature [51–54], with minimal unified framework guiding model selection or interpretation, particularly in complex industrial wastewater matrices. This methodological inconsistency impedes the comparability of results and the development of predictive tools for practical applications. Additionally, limited reviews have comprehensively addressed the environmental and economic implications of using biochar for dye removal, especially in low-resource settings. While the advantages of waste valorization and carbon sequestration are often highlighted [55–57], systematic assessments of life cycle impacts, post-adsorption treatment of dye-laden biochar, and techno-economic feasibility are still underexplored. These knowledge gaps are particularly relevant to regions with abundant biomass waste and severe water contamination challenges, where biochar could serve as an inexpensive, sustainable treatment solution—if its limitations are properly addressed.

This review aims to bridge these gaps by providing a holistic and integrative analysis of dye adsorption using biochar, grounded in the "Preparation-Mechanism-Environment-Economy" (PMEE) framework. It begins with an overview of common synthetic dyes found in wastewater, their chemical diversity, and current removal techniques. It then examines biochar production, key physicochemical properties, and dye adsorption mechanisms, followed by a critical discussion of sustainability and economic considerations. By identifying underexplored areas *via* bibliometric analysis and synthesizing the most recent developments, this review seeks to advance the practical deployment of biochar-based systems in dye-laden wastewater treatment and promote informed, context-sensitive innovation.

2. Overview of synthetic dyes in water bodies: from chemistry to control

The textile industry is a relatively significant contributor to synthetic dye pollution, accounting for *ca.* 60 – 70 % of dye-laden effluents or wastewaters released into aquatic and terrestrial environments [13, 58–61]. Particularly, up to 20 % of dyes used in textile dyeing are

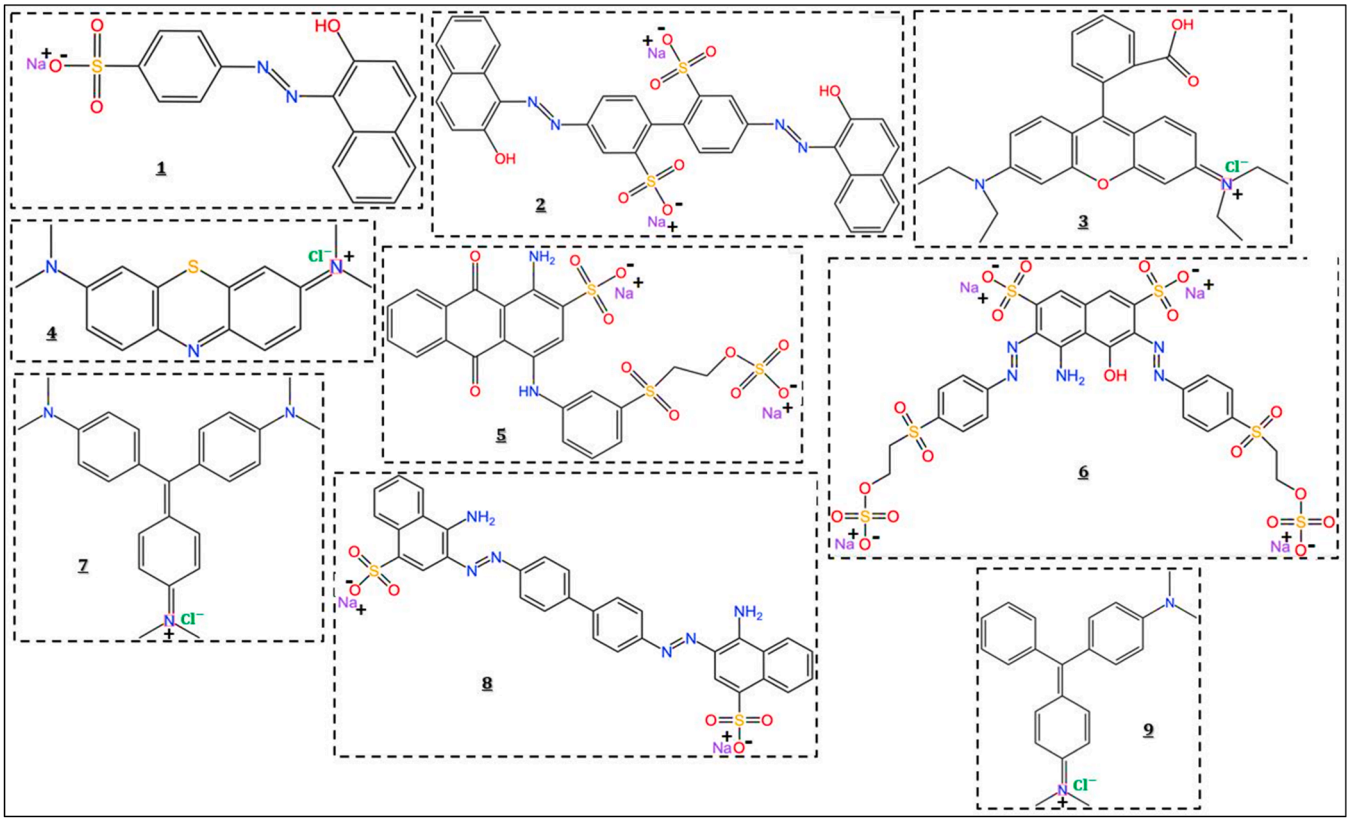

Fig. 2. Chemical structures of representative synthetic dyes relevant to wastewater contamination: 1. Acid orange 7, 2. Acid red 97, 3. Rhodamine B, 4. Methylene blue, 5. Reactive blue 19, 6. Reactive black 5, 7. Crystal violet, 8. Congo red, and 9. Malachite green [3,5,6,13]. Structures drawn by the authors based on data from the cited literature. No copyright permission required.

released as wastewater after failing to physically adsorb or form a covalent bond with the fibres or leather materials, seriously contaminating the environment [5,61,62]. As illustrated by Fig. 2, numerous types of synthetic dyes have complex aromatic structures with chromophoric groups like azo, anthraquinone, or phthalocyanine moieties that provide both chemical stability and vivid colours. Their persistence in the environment is facilitated by the high resistance to microbial and photolytic degradation that these chromophores impart [2,5,63]. Also, because of their high aqueous solubility, chemical stability across a wide range of pH and redox conditions, and resistance to biodegradation, azo dyes like reactive black 5 and direct red 28 are especially concerning among the different dye classes [13,64,65]. This underpins the need for advanced treatment methods that can address the structural complexity and environmental persistence of azo dyes. The chemically stable azo bond (–N = N–) can undergo reductive cleavage anaerobically to produce aromatic amines (reaction scheme 1), which often have toxic and carcinogenic attributes, but it resists cleavage under aerobic conditions, as Singh *et al.* [66] stated.

Moreover, based on their ionic charge, dyes found in wastewater can be broadly classified as either cationic or anionic species, which has a substantial impact on how they behave in the environment and respond to treatment. Strong electrostatic interactions with negatively charged biological membranes and sediment particles are made possible by the positively charged groups (such as quaternary ammonium) carried by cationic dyes like the thiazine dye (methylene blue) and the triarylmethane dye (basic violet 10) [67,68]. Through oxidative stress and ion transport disruption, such interactions lead to considerable toxicity toward aquatic organisms [13,64,69]. On the other hand, anionic dyes like Congo red (an azo dye with sulfonate groups) and acid orange 7 (another sulfonated azo dye) are widely used in the processing of wool, silk, and nylon [3,70]. Such widespread utilization, combined with high water solubility, complicates removal initiatives and poses the risk of environmental accumulation. In addition to the azo and sulfonic acid functional groups ($-SO_3^-$), the nitro-based ($-NO_2$) and quaternary ammonium groups modulate the physicochemical characteristics of dyes, such as their solubility, sorption affinity, and biodegradability [71–73].

$$R-N=N-R' + 4[H] \rightarrow R-NH_2 + R'-NH_2 \quad (1)$$

(Azo dye) → (Aromatic amines)

Furthermore, the specific toxicity concerns associated with synthetic dyes that are frequently encountered in effluents, categorized by their ionic type and industrial application, are summarized in Table 1. For instance, cationic dyes such as methylene blue, which are typically neurotoxic at higher concentrations ($\geq$ 10 μM, *i.e., ca.* 3.2 mg.L^{-1}) to aquatic fauna (*e.g.,* zebrafish (*Danio rerio*), can cause oxidative damage to gill tissues by potentially intercalating with nucleic acids and generating reactive oxygen species [74–77]. In contrast, genotoxic effects have been linked to anionic dyes like Congo red, especially because of their metabolic conversion to aromatic amines. According to studies [78–81], fish species like *Oreochromis niloticus* (Nile tilapia) and *Danio rerio*, as well as aquatic invertebrates like *Daphnia magna*, can suffer DNA damage when exposed to Congo red at concentrations $>$ 1 mg.L^{-1}. Similarly, reactive black 5, commonly utilized in cotton textile manufacturing, constitutes several sulfonate groups that typically increase its solubility and environmental persistence, making remediation particularly difficult [13,82,83].

A toxicological study done by Manimaran *et al.* [84] has demonstrated that this type of synthetic dye induces developmental abnormalities in *Danio rerio* embryos at concentrations as low as 5 mg.L^{-1}, while acute exposure causes significant mortality in *Daphnia magna* at concentrations exceeding 100 mg.L^{-1}, as stated by Meriç *et al.* [85]. Comparatively, researchers [86–88] reported that *Oryzias latipes* exhibits higher tolerance, with LC_{50} (lethal concentration for 50 % of the population) values ranging between 100 and 500 mg.L^{-1}. Nonetheless, the relatively higher tolerance observed in these studies does not diminish the ecological risks posed by reactive black 5 and similar synthetic dyes, underscoring the need for continued search for effective treatment strategies and stricter regulatory measures to mitigate their accumulation in aquatic environments. Collectively, these results suggest that both the type of ionic charge and functional groups play an essential role in determining environmental risk and treatment complexity.

Table 1
Summary of toxicological effects of synthetic dyes on aquatic fauna and invertebrates.

Ionic type	Dye	Industrial Application	Toxicity Concern	Study
Anionic	Congo red	Textile; leather	Genotoxic; potential carcinogenic attributes	[89]
	Reactive black 5	Textile; cotton	Recalcitrant; persistent in water-based media, and toxicity to development in *Daphnia* and zebrafish	[84]
	Acid orange 7	Textile; wool and silk	Hepatotoxic; induces oxidative or metabolic stress and DNA damage	[90]
	Direct red 28	Textile; dyeing cotton	Mutagenic and hepatotoxic in organisms such as fish and rodents	[91]
	Acid red 97	Textile; silk and nylon	Reproductive toxicity in aquatic invertebrates	[92]
	Reactive blue 19	Textile	Persistent; restrains algal photosynthesis	[93]
Cationic	Methylene blue	Textile and paper	Neurotoxic to vertebrates, *i.e.,* disrupts the respiratory organ	[94]
	Basic violet 10	Textile, cosmetics, and paper	Cytotoxic to both vertebrates and algae	[5]
	Malachite green	Textile and aquaculture	Carcinogenic, mutagenic, and teratogenic in both vertebrates and mammals	[95]
	Crystal violet	Textile; biological stains	Affects the renal, hepatic, and reproductive systems	[96]
	Rhodamine B	Textile; leather, paper, and printing	Potential for genotoxicity and endocrine disruption	[97]

As summarized in Table 1, cationic dyes tend to exert neurotoxic and cytotoxic effects, whereas anionic dyes are more linked to genotoxicity and long-term ecological persistence. The effect of dye wastewater extends beyond fish, aquatic invertebrates, marine mammals, and aquatic plants, as dye-producing and dye-consuming plants also percolate into soils and groundwater, posing broader environmental risks [13,98]. According to Sharma *et al.* [99], dye factories along the Yamuna River have contributed $>$ 40 % of the river's overall pollution load. The authors have reported that effluents that these factories release contain complex mixtures of aromatic amines, heavy metals, and salts. By inhibiting enzymes essential to nutrient cycling, such infiltration disturbs soil microbial communities and encourages the bioaccumulation of dyes and metabolites in crops irrigated with contaminated water, introducing secondary contamination pathways to humans and animals [99,100]. Ingestion of contaminated water and food (*i.e.,* fish and crops that accumulate dye residues), dermal absorption during bathing or occupational contact, and inhalation of aerosols near industrial sites are the main exposure pathways that can cause diseases and complications with the central nervous system in humans, as shown in Fig. 3. This interconnection between aquatic contamination and human exposure indicates the need for integrated risk assessment frameworks across ecosystems.

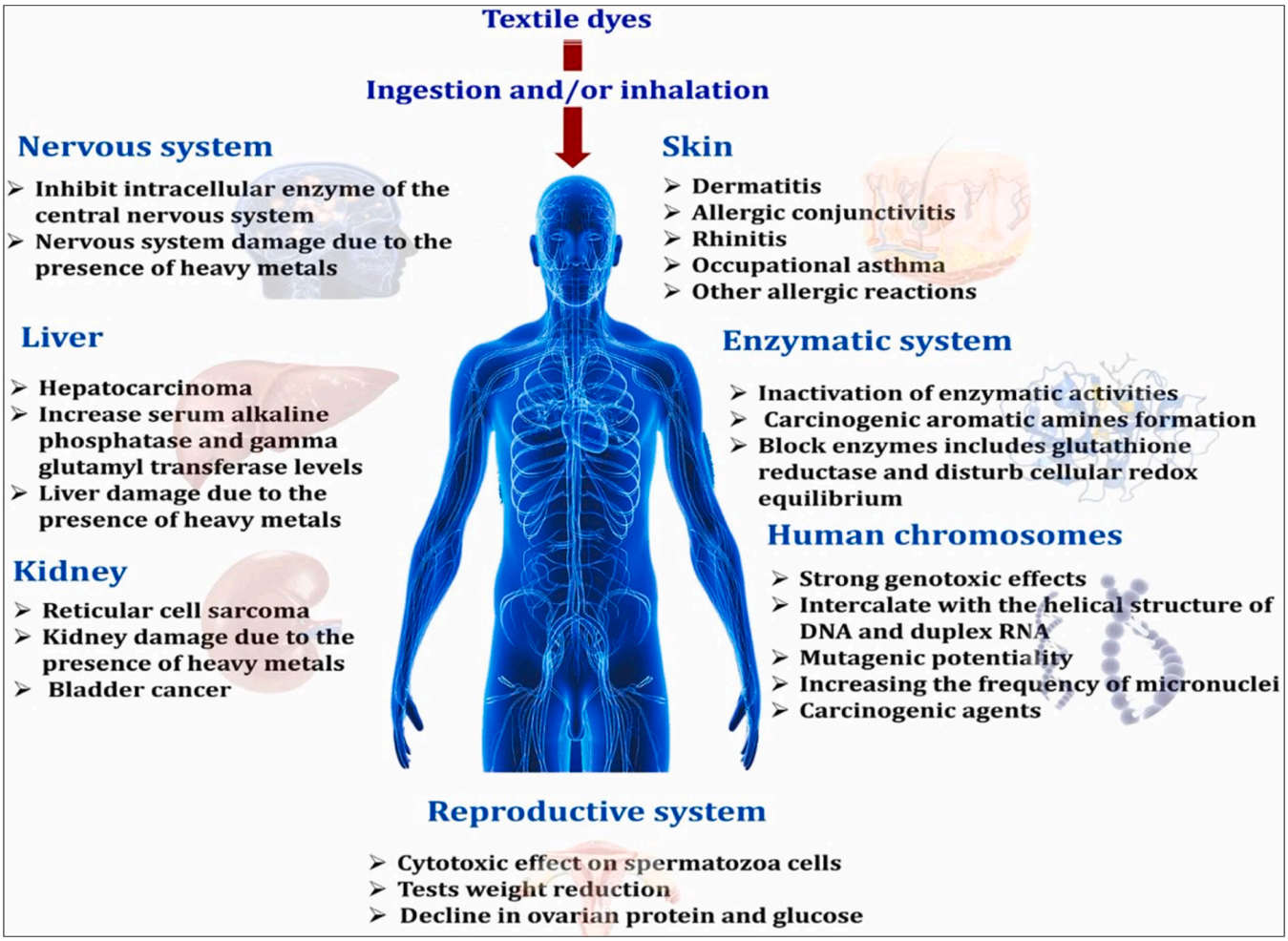

Fig. 3. Detrimental effects of textile industrial sites on human health, ranging from dermatitis to central nervous system disorders. Reproduced from ref. [13] with permission from Ecotoxicology and Environmental Safety, copyright 2022.

According to several toxicological studies [101–103], acute effects like skin irritation and respiratory distress, as well as chronic conditions such as hepatotoxicity, nephrotoxicity, immunosuppression, endocrine disruption, and carcinogenesis linked to aromatic amine metabolites produced by azo bond reduction, can be caused by dyes and their metabolites. Additionally, Singh *et al.* [66] recently showed that liver and kidney tissues of albino rats underwent histopathological changes after consuming vegetables irrigated with dye-contaminated water for an extended period, suggesting systemic toxicity. Concerns regarding endocrine disruption through terrestrial exposure routes were further supported by Islam *et al.* [3], who reported notable hormonal imbalances and decreased fertility in rodents exposed to aromatic amines derived from azo dye degradation. Given the persistence and toxicological risks linked to the synthetic dyes and their degradation products, robust analytical techniques, particularly selective and capable of quantifying trace concentrations within complex matrices, are crucial for the detection and quantification of these contaminants in environmental matrices.

Fernández-Pérez *et al.* [104] have reported that UV-Visible spectroscopy remains a typically employed preliminary method due to its simplicity, rapid analysis, and low-cost quantification of dyes based on their characteristic absorption maxima, normally within the 400 – 700 nm range. However, this technique may lack specificity in complex aqueous media containing multiple chromophores. Millbern *et al.* [105] have suggested that high-performance liquid chromatography and liquid chromatography coupled with mass spectrometry offer higher resolution, selectivity, and sensitivity for distinguishing structurally similar dyes and their degradation products. Devers *et al.* [106] have shown that gas chromatography-mass spectrometry, although more typically applied to dye volatile metabolites (like aromatic amines) formed during azo dye reduction, may provide structural elucidation when dyes are derivatized suitably. Furthermore, Pasieczna-Patkowska *et al.* [107] explored Raman spectroscopy and Fourier-transform infrared spectroscopy for identifying functional groups and structural changes during treatment, but they were determined to be merely better suited for qualitative rather than quantitative analysis.

More recently, Jjagwe *et al.* [108] studied advanced electrochemical sensors that rely on modified electrodes (such as graphene oxide or metal oxide composites) to enable high-sensitivity on-site detection with minimal sample preparation. To enhance analytical reliability, these techniques are typically complemented by solid-phase extraction or membrane filtration to concentrate analytes from environmental samples [109,110]. Collectively, the analytical techniques provide complementary advantages, although their suitability often depends on the nature of the dye, matrix complexity, and detection limits required for regulatory compliance. Even with advancements in detection, effective removal of synthetic dyes from wastewater remains a significant challenge because of their chemical stability and degradation resistance.

Traditional biological wastewater treatments (*e.g.,* activated sludge systems) are generally ineffective for synthetic dyes because of their aromatic structure, electron-withdrawing groups (like nitro and sulfonate), and resistance to enzymatic cleavage [64,66,111]. Although other physicochemical techniques, including membrane filtration, Fenton oxidation, and coagulation-flocculation, have been investigated, they

are usually limited by their high operational costs, complexity, and generation of secondary waste [112,113]. Given these constraints, adsorptive methods have drawn a lot of interest due to their ease of use, affordability, and versatility. A particularly promising option among these is biochar-based adsorbents, which have a large surface area, tunable surface chemistry, and functional groups that allow for efficient interaction with both cationic and anionic dye molecules [29,44,114]. Additionally, biochar is affordably engineered from a variety of biomass feedstocks, supporting the objectives of the circular economy while offering environmental compatibility [115,116]. As such, adsorbent-based approaches, particularly those utilizing sustainable materials like biochar, are increasingly seen as viable, eco-friendly alternatives for addressing dye contamination in aquatic and terrestrial systems.

3. Biochar for dye removal: production and adsorption mechanisms

3.1. Production of biochar

The emerging and important role of biochar as a sustainable adsorbent in wastewater treatment, especially for synthetic dye removal, has prompted extensive research into its production routes and interaction mechanisms with different types of dyes. This section contextualizes the production of this carbonaceous material from different biomass feedstocks, after which the primary mechanisms governing dye adsorption are examined in the subsequent section. Pyrolysis, gasification, hydrothermal liquefaction, and hydrothermal carbonization are the well-known thermochemical methods that can be used to produce biochar [117–119]. Among these, the former is the most widely employed due to its relatively simple setup or operation, scalability, versatility across different biomass feedstocks, and ability to produce biochar with desirable characteristics for contaminant adsorption [117]. As detailed before, pyrolysis involves both thermal and chemical decomposition of a feedstock under specific environmental and operational conditions. The process converts organic matter into three main products: solid biochar, liquid condensate, and non-condensable gases (Fig. 4). The relative proportion of biochar produced—central to its application as an adsorbent—depends heavily on operational conditions like heating rate, peak temperature, and residence time. These production basics lay the groundwork for deeper insight into the functional potential of biochar. While pyrolysis remains the dominant method because of its versatility and relatively high biochar yield, its energy requirements and need for dry feedstock limit its sustainability. In contrast, hydrothermal methods, though less common, offer energy-efficient processing of wet biomass; however, they typically produce hydrochars with different physicochemical properties, potentially limiting their adsorption performance depending on the target dye.

A critical aspect of production, *i.e.,* feedstock selection, normally influences not only process parameters but also operational feasibility and final biochar quality [117,120]. Nut shells, wood chips, and agricultural waste are examples of biomass materials that differ in moisture content, composition, and particle size. Alve *et al.* [121] have highlighted that such lignocellulosic biomasses tend to yield biochars with high fixed carbon content and stable porous structures. In contrast, manure and sludge feedstocks can produce biochars with higher ash and mineral content, according to Guo *et al.* [122]. Although manure-derived biochars contain higher mineral content, which may enhance certain adsorption sites, excessive ash can block pores and reduce overall adsorption capacity, thereby affecting their suitability for dye removal. On the other hand, Rezaei *et al.* [123] reported that pre-processing procedures, such as drying, size reduction, pelletizing, and demineralization, can improve feedstock handling, thermal decomposition behavior, and pyrolysis efficiency. However, it has been found that hydrothermal carbonization can process wet biomass with ease, under moderate temperatures (*e.g.,* 180 – 250 °C) and autogenous pressure [124,125] while hydrothermal liquefaction operates under elevated temperatures (typically, 250 – 374 °C) and high pressures (typically, 10 – 25 MPa) [126,127]. Because both these hydrothermal methods allow for processing of high-moisture feedstocks without the need for drying, they offer energy-efficient alternatives to pyrolysis

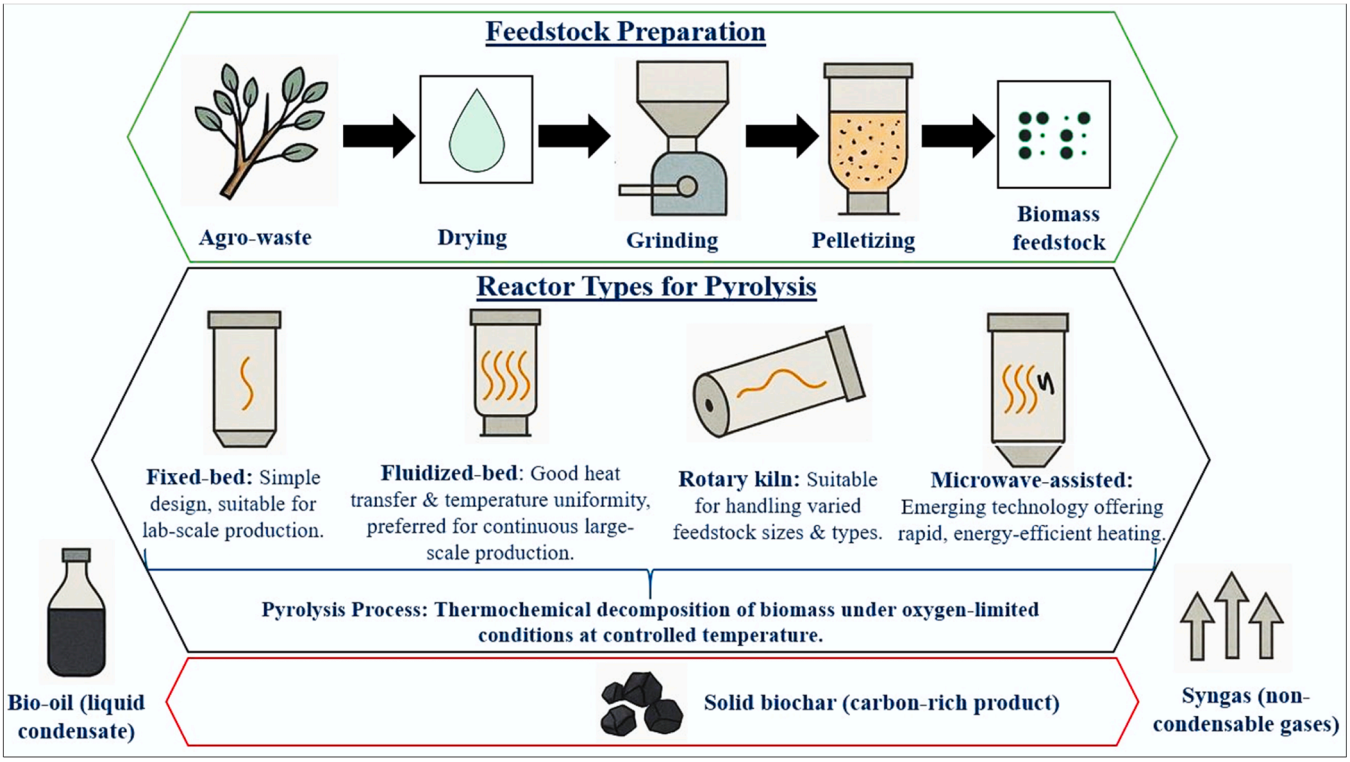

Fig. 4. General schematic overview of the production of biochar through pyrolysis [117,119]. Diagram created by the authors using data interpreted from the cited literature. No copyright permission required.

[125,127]. Additionally, Zhang *et al.* [128] have shown that hydrothermal carbonization yields hydrochars with unique physical forms and potential applications. Specifically, their research demonstrated that organic matter undergoes substantial chemical transformation under hydrothermal carbonization conditions, resulting in hydrochar particles with a higher energy content and different structural characteristics. These alterations are mostly caused by dehydration and decarboxylation reactions, which reduce the hydrogen-to-carbon and oxygen-to-carbon ratios and create a more carbon-rich material suitable for a variety of applications.

Nonetheless, according to a study by Nega *et al.* [129], slow pyrolysis is the recommended method when solid carbonaceous material is the main targeted product because the process maximizes the yield of biochar and is characterized by low heating rates (typically, 5 – 20 °C. min^{-1}), long residence times (from 30 min to several hours), and low to high temperatures (typically, *ca.* 350–600 °C). Slow pyrolysis' higher biochar yield benefits adsorbent quantity, but longer contact times decrease throughput and increase operational costs, likely limiting industrial scalability. Reactor selection, such as fluidized-bed systems, may offset these limitations by improving heat transfer and uniformity; however, equipment complexity and capital investment rise accordingly. Evidently, fast pyrolysis tends to produce less biochar and favors liquid products at heating rates above 100 °C.min^{-1}, residence times under 2 s, and moderate to high temperatures (generally, 450 – *ca.* 650 °C) [120,130,131]. In addition, control of the pyrolysis atmosphere plays a significant role in the thermal decomposition pathway [132]. While limited oxidative (O_2) and steam conditions may be applied in certain processes to change the distribution of the product, an inert atmosphere (usually, nitrogen (N_2) or argon (Ar)) is used to prevent combustion, influencing final biochar composition. Lamichhanae *et al.* [133] have recently emphasized that maintaining strict inert conditions is essential for consistent and high-quality biochar. The biochar production process may also be impacted by the configuration of the pyrolysis reactor, particularly influencing the uniformity and throughput of pyrolysis [130,134]. Fixed-bed, fluidized-bed, rotary kiln, and microwave-assisted reactors are some of the common types of equipment, and each has unique operational benefits and scalability potential. According to Thoharudin *et al.* [135], fluidized-bed reactors offer superior temperature homogeneity and better heat transfer, allowing for more consistent biochar production at industrial scales. Although fluidized-bed reactors offer operational advantages, direct comparisons of biochar adsorption performance across reactor types are still limited, suggesting a need for systematic studies to optimize production for dye removal applications. Overall, the biomass source selection, reactor type, thermal and atmospheric conditions, and process parameters control the biochar production processes. Such fundamental production aspects provide the groundwork for understanding how biochar interacts with dye contaminants to remove them from wastewater. Also, the production parameters affect surface area, porosity, functional groups, and ash content, all of which critically determine the efficacy of biochar as a dye adsorbent. As a result, optimizing production needs balancing yield, material properties, and energy input to maximize adsorption performance while maintaining sustainability.

3.2. Dye adsorption mechanisms

Optimizing the use of biochar in wastewater treatment necessitates an understanding of the methods by which it adsorbs dyes. The adsorption process is inherently complex and multifaceted, involving a variety of physicochemical interactions that often act synergistically [29, 136–138]. Electrostatic interactions, H-bonding, $\pi-\pi$ stacking, surface complexation, ion exchange, van der Waals forces, pore filling, and intraparticle diffusion are some of the key mechanisms that consistently emerge across the literature. Among these mechanisms, electrostatic attraction is typically predominant for cationic dyes under neutral to alkaline conditions, whereas $\pi-\pi$ stacking is critical for aromatic dye adsorption, indicating that the interplay of dye structure and biochar chemistry governs mechanism dominance. Additionally, these mechanisms are largely governed by the surface chemistry and porosity of biochar as well as the functional groups within the material—factors that are in turn influenced by feedstock type, activation method, and pyrolysis temperature [44, 47, 139–141]. Amidst these various adsorption mechanisms, electrostatic attraction is the most frequently reported mechanism, particularly effective when the biochar surface charge is opposite to that of the dye [43, 49, 142–145]. For example, biochars derived from algae [146] and municipal waste [147] often exhibit electrostatic interactions as a primary mechanism in the removal of cationic dyes such as methylene blue and Remazol black B. Similarly, *Lantana camara*-based biochar has shown effective adsorption of methylene blue dye, primarily *via* $\pi-\pi$ interactions (Fig. 5) [148]. These electrostatic attraction processes are sometimes amplified by alkaline (*e.g.,* potassium hydroxide (KOH) or sodium hydroxide (NaOH)) and physical (*i.e.,* ball-milling) activation, which increases negative surface charge. While chemical activation enhances functional groups beneficial for adsorption, the increased processing complexity and cost present challenges for scalability. Similarly, increased pyrolysis temperatures enhance $\pi-\pi$ stacking sites but may diminish polar functional groups necessary for electrostatic and H-bonding interactions, demanding a balanced optimization.

Unlike other mechanisms, pore filling and intraparticle diffusion processes are often more associated with the physical structure of biochar. Biochars with highly porous structures, like those from pistachio shells [149], cotton stalks [150], and corn straw [151], allow dye molecules to diffuse into micro- and mesopores. Intraparticle diffusion, particularly, is the mechanism that has been described in systems using wood [152], rice husk [54], and mushroom [153] substrate biochars, highlighting the importance of internal surface area. Furthermore, while generally weaker than chemical interactions, van der Waals forces contribute additional stabilizing interactions, according to Zeeshan *et al.* [154]. These were notably reported in wakame-derived [155] and waste carton-derived [156] biochars, where no pronounced chemical bonding was evident, but overall adsorption performance remained effective as a result of combined weak forces. Surface complexation is also essential, where coordinate bonds are typically produced between dye molecules and surface functional groups or inorganic moieties. This is especially evident in biochars made from pistachio shells [149], industrial sludge [157], and algae [158], where their surface oxygen-containing groups in particular facilitate dye binding.

Another commonly observed adsorption mechanism is H-bonding, which is particularly essential in systems where biochars constitute hydroxyl (–OH), carboxyl (–COOH), or amine (–NH_2) groups on their surface. Such groups facilitate specific interactions with dye molecules bearing donor or acceptor functional sites. For instance, biochars made from palm petioles [159], walnut shells [160], and Southern pine wood [161] showed strong H-bonding interactions that contributed to high adsorption capacities. $\pi-\pi$ stacking interactions, on the other hand, are prevalent in systems targeting dyes constituting aromatic structure. Such interactions typically take place between delocalized π-electron systems of dye molecules and the aromatic domains of carbonized biochars, as Zhao *et al.* [138] stated. Various biochars have exhibited pronounced $\pi-\pi$ interactions, often coupled with other mechanisms, and were effective in adsorbing dyes such as Congo red [149] and methylene blue [155,162]. Ion exchange, however, is less common but still important for dyes with exchangeable ionic groups. For instance, biochar from Opuntia ficus-indica cactus exhibited ion exchange mechanisms that contributed to the malachite green dye removal [163]. Similarly, the multifaceted adsorption seen in biochar made from palm petioles included cation exchange [164]. All of these findings in tandem confirm that a suite of complementary interactions, rather than a single mechanism, are required for dye adsorption onto biochar. Synergistic effects between mechanisms, such as simultaneous electrostatic attraction and $\pi-\pi$ stacking, often result in enhanced adsorption beyond

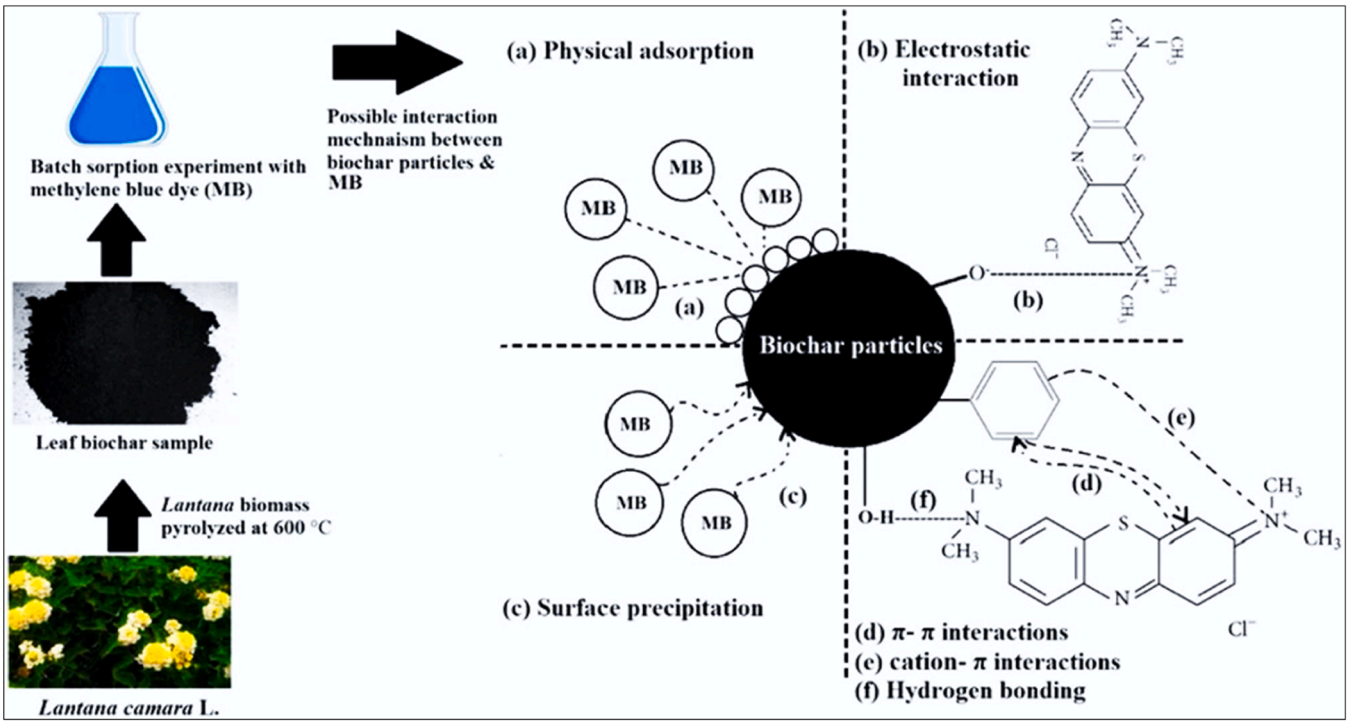

Fig. 5. Synthesis and proposed mechanism of methylene blue (MB) adsorption for its removal using Lantana camara-sourced biochar. Reproduced from ref. [148] with permission from Carbon Research, copyright 2024.

individual contributions. Nevertheless, competition for active sites between different dye molecules or functional groups may also limit adsorption efficiency under mixed-contaminant conditions. Such trends are systematically synthesized and compared in Table 2, which acts as the core visual summary for *Section 3.2* by mapping the dominant adsorption mechanisms to specific dye classes, feedstocks, and processing conditions. The degree to which each mechanism predominates depends on both the physicochemical nature of the dye as well as the specific properties of the biochar. Even in the absence of chemical and physical activation, the biochars can participate in several mechanisms simultaneously, as demonstrated across the dataset (Table 2), supporting their usefulness as sustainable and adaptable adsorbents.

The variation in adsorption performance can also be elucidated by looking at the relationship between specific mechanisms and dye uptake. Higher adsorption capacities are consistently reported by biochars that combine stacking, H-bonding, electrostatic interactions, and pore filling. For example, ion exchange and electrostatic attraction enabled biochar from *Opuntia ficus-indica* (OFI) activated with NaOH to achieve 1341.0 $mg.g^{-1}$ for Malachite green [163], while a synergy between interactions and surface functional groups allowed soybean dreg biochar synthesized at 800 °C to achieve 1273.5 $mg.g^{-1}$ for methylene blue [162]. These examples illustrate how adsorption performance is enhanced by multifaceted interactions. In comparison, as seen with municipal waste biochar (7.2 $mg.g^{-1}$) [147] and hickory chip biochar (9.2 $mg.g^{-1}$) [165], materials that are dominated by single or less interacting mechanisms, such as basic surface adsorption or intraparticle diffusion, typically exhibit moderate capacities. These findings highlight that enhanced adsorption capacity arises not merely from increased surface area, but from the presence of specific functional groups and structural features that facilitate multiple simultaneous interactions, underscoring the importance of tailoring biochar chemistry to target dye molecules. Moreover, activation techniques greatly improve performance by adding reactive functional groups that promote stronger dye–adsorbent interaction in addition to increasing surface area and porosity. Also, the production temperature is particularly crucial because, whereas lower temperatures may maintain more oxygenated groups that are advantageous for H-bonding and electrostatic interactions, higher temperatures encourage the creation of aromatic structures that are conducive to stacking [166,167]. These patterns highlight the significance of mechanism-driven optimization in the design of high-performance adsorbents by confirming that adsorption capacity is closely related to the chemical affinity of biochar for specific dye structures rather than being merely a function of surface area.

Moreover, the versatility of biochar derived from different feedstocks and its consistent engagement in key adsorption mechanisms are further illustrated in Fig. 6 (Ai–Dii). Subfigures Ai and Aii illustrate the effect of adsorbent dosage on dye removal using leaf- and stem-derived biochars, respectively. As dosage increases from 100 to 400 $mg.L^{-1}$, overall removal improves across all tested dye concentrations (5–20 $mg.L^{-1}$), due to the greater number of available surface sites. Nonetheless, at higher dosages, the individual adsorption capacity ($mg.g^{-1}$) tends to decrease, likely due to agglomeration of particles reducing accessible surface area. Furthermore, subfigures Bi and Bii present the influence of solution pH on removal efficiency for the same range of dye concentrations. Both adsorbents exhibit maximum performance at pH 12, consistent with increased deprotonation of surface functional groups and enhanced electrostatic attraction of the cationic dye. Poorer removal at lower pH confirms the role of surface charge interactions. On the other hand, subfigures Ci and Cii show the time-dependent adsorption profiles. Rapid uptake is observed within the first 40–60 min, followed by equilibrium. The stem-derived biochar (Cii) reaches equilibrium faster and achieves higher adsorption capacity, indicating greater pore accessibility or internal diffusion efficiency. Lastly, subfigures Di and Dii analyze equilibrium data *via* Langmuir and Freundlich isotherm models at three temperatures (303, 313, and 323 K). The Langmuir model provides a better fit, confirming monolayer adsorption. Adsorption capacity is highest at 303 K, suggesting an exothermic process, possibly driven by $\pi-\pi$ stacking interactions. Collectively, these subfigures reinforce the mechanistic interpretations discussed in the text and Table 2 and demonstrate the robustness of plant-derived biochars under varying operational parameters. Despite advances, ambiguities still exist regarding the relative contributions of mechanisms under

Table 2
Overview of biochar-based adsorbents: Feedstock, activation, mechanism, and dye removal efficiency.

Biochar feedstock	Activation agent	Production method/temp. (°C)	Targeted dye	Adsorption capacity (mg. g^{-1})	Mechanism of adsorption	Study
Pistachio shells	-	300, 600, and 900	Congo red and methylene blue	614.7 and 384.2	Surface complexation, pore filling, $\pi-\pi$ interaction, electrostatic attraction, and H-bonding	[149]
Industrial sludge	KOH	Pyrolysis	Methylene blue	65.9	Surface complexation, $\pi-\pi$ interactions, and electrostatic interactions	[157]
Wood	-	Gasification	Indosol black	185.0	Surface adsorption and intraparticle diffusion	[152]
Burn straw ash	-	Pyrolysis	Brilliant blue (KNR) and Rhodamine B	-	$\pi-\pi$ interactions	[168]
Soybean dreg	$KHCO_3$	One-pot synthesis method (at 800)	Methylene blue	1273.5	$\pi-\pi$ interaction, electrostatic attraction, and H-bonding	[162]
Bovine bones and fish scales	-	800	Basic red 9	49.5 and 52.3	Surface electrostatic	[169]
Rice husk	NaOH	400 – 600	Malachite green	-	Intraparticle diffusion	[54]
Hickory chips	Ball milling	450 – 600	Reactive red 120	9.2	Intraparticle diffusion	[165]
Municipal waste	-	300	Methylene blue	7.2	$\pi-\pi$ interactions	[147]
OFI cactus	NaOH	400	Malachite green	1341.0	Ion exchange	[163]
Orange peel	-	Microwave pyrolysis 150 – 600	Congo red dye	136.0	Surface electrostatic and $\pi-\pi$ interaction	[170]
Mushroom substrate	Steam activation	450	Crystal violet	1057.0	Intraparticle diffusion and $\pi-\pi$ interaction	[153]
Palm petiole	HCl	700	Crystal violet red	209.0	Pore filling, H-bonding, $\pi-\pi$ interaction, cation exchange, electrostatic attraction, and van der Waals force	[164]
Wakame	KOH	800	Methylene blue, Rhodamine B, and Malachite green	841.6, 533.0, and 4067.0	$\pi-\pi$ stacking, van der Waals force, H-bonding, and electrostatic interaction	[155]
Marine algae	-	300	Remazol brilliant blue R, Remazol brilliant orange 3 R, Remazol brilliant violet 5 R, and Remazol black B	-	Electrostatic interaction	[146]
Mango seeds	HCl	70 (Oven)	Reactive orange 16	71.6	H-bonding	[171]
Cotton stalk	ZnO $ZnSO_4$	800	Congo red	556.6	Pore filling and electrostatic interaction	[150]
Lantana (leaf and stem)	Ball milling	600	Methylene blue	-	H-bonding, $\pi-\pi$ interaction, and electrostatic interaction	[148]
Algae	$AgNO_3$	700	Congo red	34.5	Electrostatic interaction, surface complexation, and H-bonding	[158]
Palm petioles	HCl	500, 600, and 800	Methylene blue	103.9	Surface electrostatic	[159]
Walnut shell	H_2SO_4, HNO_3	700	Methylene blue, Malachite green, and Neutral red (NR)	1494.0, 1182.0, and 1031.6	H-bonding, $\pi-\pi$ stacking, and electrostatic interactions	[160]
Waste cartons	-	700	Rhodamine B (RhB)	222.0	$\pi-\pi$ interactions and van der Waals forces	[156]
Southern pine wood	KOH	700	Congo red and methylene bule	3472.2 and 1112.4	H-bonding, $\pi-\pi$ stacking, and electrostatic interactions	[161]
Corn straw	NaOH	300	Methylene blue	290.7	Pore-filling, H-bonding, and $\pi-\pi$ stacking	[151]

variable environmental conditions, such as pH and ionic strength, pointing to the need for more systematic mechanistic studies employing advanced spectroscopic and modeling tools.

In general, dye adsorption onto biochar is governed by a synergistic interplay of physical and chemical interactions. Physical processes such as weaker intermolecular forces (*i.e.,* H-bonding, van der Waals forces, *etc*.) enable weak, reversible attachment of dye molecules to the biochar surface, while chemisorption involves stronger, often irreversible bonding *via* covalent interactions with surface functional groups like −OH and −COOH [172]. Electrostatic attraction between charged dye molecules and oppositely charged surface sites plays a crucial role, particularly in the $\pi-\pi$ interactions between aromatic dye structures and the conjugated domains of biochar enhance adsorption affinity [173]. Heteroatom-containing functional groups, like those with oxygen, nitrogen, or sulfur, can further promote dye binding *via* chelation or complexation mechanisms. Finally, the pore structure of biochar must be compatible with the size of dye molecules: limited pore accessibility reduces adsorption efficiency, whereas overly large pores may weaken retention. Thus, researchers [29,43,44,47,144,174,175] have argued that, in addition to activation methods and adsorption mechanisms, optimizing both surface chemistry and porosity is essential for maximizing the adsorption capacity of biochar for dye removal.

3.3. Machine learning insights into dye adsorption prediction

In addition to conventional mechanistic research, recent advances in machine learning (ML) have produced strong analytical and predictive instruments that improve our comprehension of dye adsorption onto biochar. In contrast to traditional methods, which often depend on limited parametric analysis and iterative experiments, ML models are able to detect intricate nonlinear relationships between adsorption performance metrics (such as capacity, removal efficiency, or kinetics) and input variables (such as pH, temperature, surface area, functional groups, and dye concentration) across a variety of datasets [176]. In addition to speeding up material screening and performance forecasting, this new field uses computational intelligence to lower experimental costs and resource consumption, which helps to advance the creation of sustainable adsorbent technologies. Furthermore, to model and forecast dye adsorption behavior, supervised learning algorithms like artificial neural networks (ANN), random forests (RF), support vector machines (SVM), and decision trees have been used extensively. For example, Kaya *et al.* [177] highlighted that surface area and pH were the most important features by using ANN models to predict the adsorption capacity of biochar based on pyrolysis temperature, BET surface area, initial dye concentration, and pH. The optimal ANN model achieved

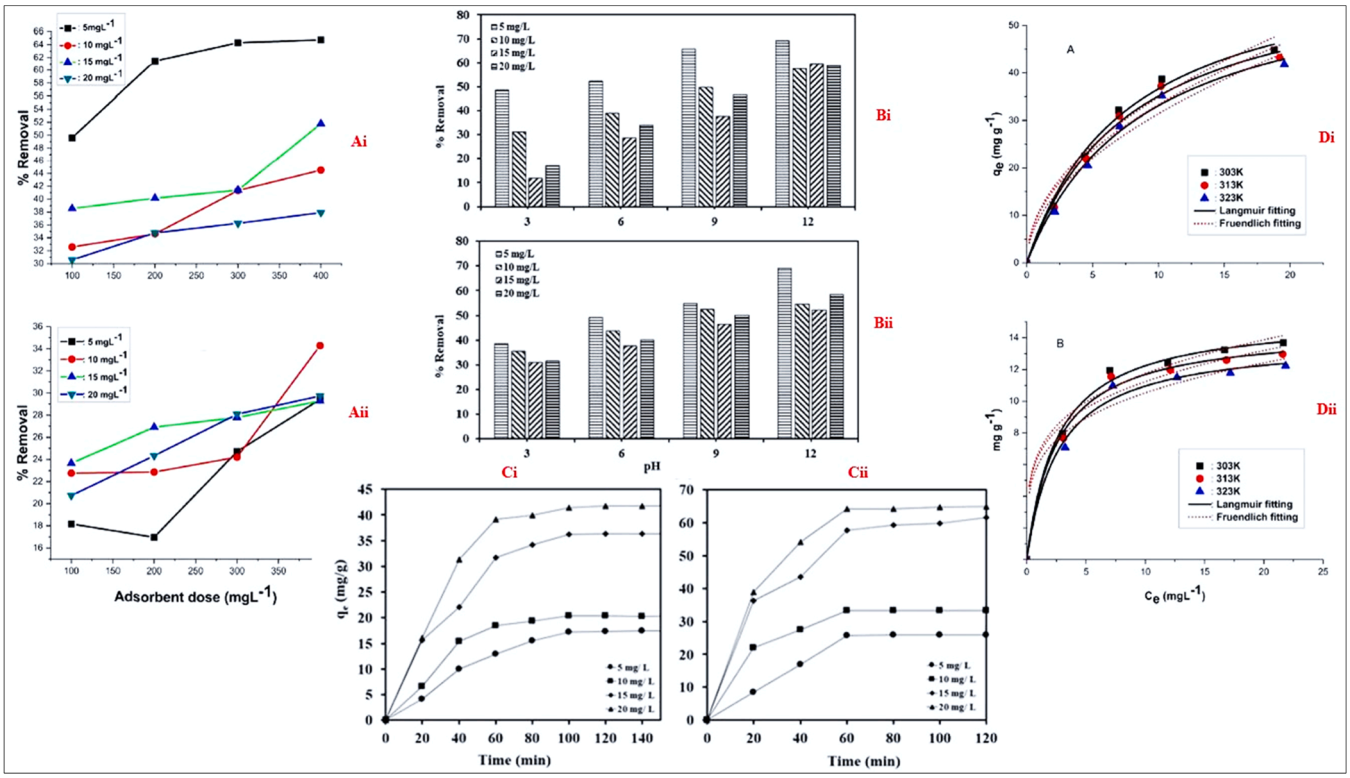

Fig. 6. Findings on adsorption of methylene blue dye onto leaf-based and stem-based adsorbents: A. Effect of adsorbent dose on the adsorption of dye with leaf-based biochar (Ai) and stem-based biochar (Aii). B. Effect of solution pH on the sorption of dye onto leaf-based biochar (Bi) and stem-based biochar (Bii). C. Effect of dye concentration and contact time on adsorption of dye with leaf-based biochar (Ci) and stem-based biochar (Cii). D. Isotherm study of dye on leaf-based biochar (Di) and stem-based biochar (Dii). Reproduced from ref. [148] with permission from Carbon Research, copyright 2024.

strong predictive performance for bromocresol green adsorption, with mean absolute error (MAE), mean bias error (MBE), root mean square error (RMSE), and R^2 values of 0.036, 0.578, 0.947, and 0.999, respectively, suggesting that ANN can reliably simulate and predict dye removal efficiency using biochar, a critical step toward designing more efficient adsorption systems.

Inspired by studies like those by Chandiwana *et al.* [178] that have successfully applied Gaussian Process Regression (GPR) for solar forecasting, GPR is emerging as a powerful tool in modeling dye removal using biochar, as it effectively captures nonlinear relationships and quantifies prediction uncertainty—especially valuable for optimizing adsorption systems under limited experimental datasets. Importantly, by prioritizing feature importance and sensitivity, ML models have been used more and more to investigate the interaction effects between adsorption mechanisms covered in *Section 3.2*, such as electrostatic attraction, $\pi-\pi$ interactions, *etc*. Moreover, the classification of biochar types according to their surface functionality and affinity for particular dye classes (such as cationic *vs.* anionic) has been made possible by unsupervised learning techniques like K-means clustering, which has guided the choice of the best feedstocks and activation strategies [179, 180]. In order to optimize process parameters in real time during the production and functionalization of biochar and enable continuous model retraining with updated experimental data, reinforcement learning and genetic algorithms are also being investigated [181]. Table 3 lists illustrative research in which ML algorithms were used to forecast adsorption patterns or enhance the efficiency of biochar in dye removal systems. These contributions demonstrate how computational modeling can be useful in revealing structure-property-performance relationships that might be difficult to identify using only experimental data.

By finding predictive variables, cutting down on design iterations, and improving the mechanistic understanding described in *Section 3.2*, ML-enhanced adsorption modeling is generally meant to supplement and improve experimental work rather than replace it. A paradigm shift toward data-driven materials engineering is signified by the integration of ML into adsorption science. This is particularly pertinent in the context of the circular economy, where resource efficiency and prediction accuracy are essential.

Table 3
Selected studies applying ML models to predict or optimize synthetic dye adsorption using biochar.

ML model	Target dye	Key input feature	Important outcome	Ref.
ANN	Methylene blue	Surface area, charring temperature, and pH	Predicting adsorption capacity accurately. Surface area and pH are key factors	[182]
GPR	Reactive black 5	Dye structure, zeta potential, and biochar porosity	Nonlinear dependencies are captured by GPR. Charge biochar is critical	[183]
RF	Different azo dye types	Functional groups and biomass source	Carboxyl and hydroxyl content are ranked as the most impactful by RF	[184]
SVM	Congo red	BET, initial concentration, and pH	SVM performed better than linear models. Can be validated by experimental results	[185]
K-means clustering	Multiple dye classes	Biochar FT-IR spectra	Biochars were classified according to their dye class affinity. Feedstock selection can be easily guided	[186]

4. Factors that influence dye removal efficiency

There are several factors that affect the removal of dyes in the contaminated environment. In this section, these factors will be categorised into adsorption pre-process and process conditions. The pre-process conditions include all the steps that are involved in the preparation of the adsorbent, such as physical and thermal treatments, as well as chemical activation. These steps have been proven to have an impact on the adsorption capability of the adsorbent [187,188]. The adsorption process conditions include temperature, pH, contact time, initial dye concentration, and agitation speeds—the factors that have been extensively reported in the literature.

4.1. Effect of pre-process conditions

4.1.1. Physical and thermal conditioning as pre-process factors

The common physical treatment steps, including grinding, sieving, and washing, can affect the surface area, pore structure, and particle size of the material, thereby affecting the adsorbent capabilities. Grinding reduces the particle size, thereby increasing the surface area available for adsorption. As such, the maximum adsorption capacity of the adsorbent increases significantly with decreasing particle size [189]. Sieving ensures uniformity, improving packing and contact efficiency, especially in packed bed adsorption systems. Additionally, washing the adsorbent with water or mild acids can remove impurities or ash content, exposing more active sites. Physical treatments can also affect surface roughness, which has been proven to affect the capabilities of an adsorbent [190,191]. Physical preparatory steps are important when using materials like biochar, activated carbon, or agricultural residues, which vary in structure and composition. Effective physical treatment enhances the accessibility and reactivity of the adsorbent, improving its efficiency in capturing pollutants from water.

Thermal pre-treatment is another important pre-process condition in the adsorbent preparation, with common steps including carbonization, torrefaction, pyrolysis, gasification, and hydrothermal processing. Torrefaction is a mild thermal treatment (200 – 300 °C) that dries biomass and improves its energy density [117]. Carbonization involves heating biomass in limited oxygen to produce carbonaceous material. As highlighted before, pyrolysis decomposes biomass at 300 – 700°C without oxygen, yielding biochar, bio-oil, and syngas [192]. Gasification partially oxidizes biomass at high temperatures (700 – 1000 °C) to mainly produce syngas. Hydrothermal treatment, including hydrothermal carbonization, uses hot compressed water (180 – 250°C) to convert wet biomass into biochar, offering an efficient method without prior drying [117]. Each process yields different products and properties, with biochar being the product of interest for adsorption. In these thermal processes, conditions such as temperature, heating rate, and residence time strongly influence the adsorption capabilities of biochar. Higher temperatures increase surface area and porosity, enhancing adsorption, but may reduce functional groups, the biochar characteristic that is important for its chemical interactions with dyes. For example, slow pyrolysis generally yields biochar with better structural stability, while activation methods further improve adsorption performance for specific pollutants.

4.1.2. Chemical modification/activation

Chemical treatment typically modifies an adsorbent by introducing surface functional groups, increasing active sites, and altering surface charge. Acidic, alkaline, or oxidizing agents can improve porosity, reactivity, and selectivity toward specific pollutants. This enhances adsorption capacity, especially for complex contaminants like dyes, heavy metals, and organic compounds. While Table 2 outlined general findings that aided in a clear discussion of adsorption mechanisms, Table 4 presents studies that explicitly illustrate the improvements in biochar performance (dye removal efficiency) resulting from chemical modifications. Chemical changes greatly increase the adsorption efficiency of biochar, as detailed in Table 4, often by improving the surface area, pore structure, and surface functional groups. The impact of pore development and surface activation was demonstrated, for example, by the dramatic increase in BET surface area from 6.16 to 105.99 $m^2 \cdot g^{-1}$ and the corresponding 1.36-fold enhancement in ammonia-nitrogen adsorption that followed sulfuric acid treatment of rice hull biochar. Similarly, almond shell biochar activated with KOH and EDTA-4Na showed a significant surface area increase from 2.3 to 1050 $m^2 \cdot g^{-1}$, which translated into a phenol adsorption capacity of 270 $mg \cdot g^{-1}$, far surpassing the unmodified version. Notably, vermiculite-modified biochars (made from mulberry twigs, reeds, and rice husks, for example) showed notable decreases in removal cost per gram of mercury and moderate increases in BET, indicating both improved performance gains and cost-efficiency. The effect of pre- and post-pyrolysis modifications on metal ion adsorption is further highlighted by acid and base treatments of date seed biochar, with acid-washed samples exhibiting increased uptake of lead, copper, and nickel. In addition to demonstrating the variety of functional improvements possible with comparatively easy processing methods, these examples highlight the crucial role that chemical modification plays in optimizing biochar for targeted pollutant removal.

4.2. Effect of process conditions

The adsorption of dyes from wastewater using biochar is influenced by several key operational parameters, including pH, contact time, temperature, agitation speed, and adsorbent dosage. These factors have been extensively investigated, as virtually every study on adsorption from water or wastewater begins by examining one or more of these variables. Consequently, there exists a substantial body of databases addressing their influence. The degree of acidity or alkalinity of the solution (*i.e.,* pH) affects the surface charge of both the biochar and the dye molecules. At lower pH values, the surface of biochar tends to become protonated, thereby improving the electrostatic attraction for dyes that have a net negative charge, such as Congo red, but repelling positively charged dyes such as methylene blue [197]. On the other hand, at higher pH levels, deprotonation of biochar surfaces promotes the adsorption of positively charged dyes due to increased negative surface charges. Also, pH often exerts the most significant influence on adsorption capacity, as it governs electrostatic interactions but beyond optimal ranges, further pH adjustment has minimal effect. Therefore, optimizing pH is important for maximizing adsorption depending on the type of dye.

Furthermore, contact time influences the equilibrium state of adsorption. Initially, dye molecules rapidly occupy available active sites on the biochar surface. Over time, the rate slows as sites become saturated, eventually reaching equilibrium. Kurniawati *et al.* [198] studied the adsorption of rhodamine B, methyl orange, and methylene blue dyes using biochar derived from langsat shells. They reported adsorption capacities of 11.6, 3.8, and 36.7 $mg.g^{-1}$ for rhodamine B, methyl orange, and methylene blue, respectively, with optimum contact times of 60, 90, and 150 min, correspondingly. Determining the optimal contact time is essential to achieving a balance between adsorption efficiency and process duration.

As for agitation speed, this parameter increases the chances of interaction between dye molecules and biochar by minimizing external mass transfer resistance. With an increase in the agitation rate, the film resistance to mass transfer surrounding the sorbent particles decreases [199]. The increase in the collision frequency between adsorbent and dye molecules accelerates the adsorption process. However, excessive agitation might lead to the physical breakdown of biochar particles.

Moreover, the amount of adsorbent is directly proportional to the number of available adsorption sites. Hence, increasing biochar dosage generally enhances dye removal efficiency by providing more active sites. However, beyond a certain threshold, further increases in dosage result in diminishing returns due to site aggregation or saturation,

Table 4
Results of studies that focused on biochar chemical modifications.

Adsorbent	Modification procedure	Property improvement	Adsorption process	Process enhancement	Study
Corn stalk biochar prepared at 450 ℃.	Mixing biochar with 0.2 M H_2SO_4 using the ratio of 1:50, shaking the mixture for 24 h at 200 rpm at 60 ℃, and then filtering. Solids were rinsed with distilled water and dried.	BET – 9.44 $m^2.g^{-1}$ BET* – 2.89 $m^2.g^{-1}$ Pore volume – 0.0119 Pore volume* – 0.0034 Carboxyl – 2.34 $mmol.g^{-1}$ Carboxyl* – 0.35 $mmol.g^{-1}$ Total acid – 3.45 $mmol.g^{-1}$ Total acid* – 12.2 $mmol.g^{-1}$	Adsorption of NH_4^+-N from ammonia-nitrogen solutions in anaerobic digestion.	Maximum adsorbance was 1.57 times higher than that of the original biochar.	[193]
Rice hull biochar prepared at 550 ℃.	Mixing biochar with 0.2 M H_2SO_4 using a ratio of 1:50, shaking the mixture for 24 h at 200 rpm at 60 ℃, and then filtering. Solids were rinsed with distilled water and dried.	BET – 6.16 $m^2.g^{-1}$ BET* – 105.99 $m^2.g^{-1}$ Pore volume – 0.014 Pore volume* after – 0.062 Carboxyl – 1.14 $mmol.g^{-1}$ Carboxyl* – 0.23 $mmol.g^{-1}$ Total acid – 1.64 $mmol.g^{-1}$ Total acid* – 12.1 $mmol.g^{-1}$	Adsorption of NH_4^+-N from ammonia-nitrogen solutions in anaerobic digestion.	Maximum adsorbance was 1.36 times higher than that of the original biochar.	[193]
Almond shells biochar.	Combined pyrolysis with KOH and EDTA−4Na at 750 ℃, yielding almond shell-based modified activated carbon.	SEM – smooth surface with micropores SEM* – honeycomb microstructure BET – 2.3 $m^2.g^{-1}$ BET* – 1050 $m^2.g^{-1}$ Pore volume – 0.0029 $cm^3.g^{-1}$ Pore volume* – 0.42 $cm^3.g^{-1}$	Removal of phenol from water.	q_e – 270 $mg.g^{-1}$ q_e* – 18 $mg.g^{-1}$	[194]
Rice husks pyrolyzed at 500 ℃.	An amalgamation of vermiculite and biomass was placed in a crucible and subjected to pyrolysis within a muffle furnace under an atmosphere of N_2.	BET – 67.1 $m^2.g^{-1}$ BET* – 78.2 $m^2.g^{-1}$ Pore volume – 0.061 $cm^3.g^{-1}$ Pore volume* – 0.065 $cm^3.g^{-1}$ DOC – 288.8 $g.kg^{-1}$ DOC* – 198.5 $g.kg^{-1}$	Mercury adsorption.	q_m – 40.8 $mg.g^{-1}$ q_m* – 62.8 $mg.g^{-1}$ Cost per removal – $2.45 /g Hg Cost per removal* – $1.52 /g Hg	[195]
Mulberry twig pyrolyzed at 500 ℃.	An amalgamation of vermiculite and biomass was placed in a crucible and subjected to pyrolysis within a muffle furnace under an atmosphere of N_2.	BET – 168.3 $m^2.g^{-1}$ BET* – 186.1 $m^2.g^{-1}$ Pore volume – 0.108 $cm^3.g^{-1}$ Pore volume* – 0.137 $cm^3.g^{-1}$ DOC – 371.3 $g.kg^{-1}$ DOC* – 237.7 $g.kg^{-1}$	Mercury adsorption.	q_m – 46.4 $mg.g^{-1}$ q_m* – 67.6 $mg.g^{-1}$ Cost per removal – $3.09 /g Hg Cost per removal* – $1.72 /g Hg	[195]
Reeds pyrolyzed at 500 ℃.	An amalgamation of vermiculite and biomass was placed in a crucible and subjected to pyrolysis within a muffle furnace under an atmosphere of N_2.	BET – 49.1 $m^2.g^{-1}$ BET* – 76.6 $m^2.g^{-1}$ Pore volume – 0.047 $cm^3.g^{-1}$ Pore volume* – 0.071 $cm^3.g^{-1}$ DOC – 244.9 $g.kg^{-1}$ DOC* – 194.2 $g.kg^{-1}$	Mercury adsorption.	q_m – 33.6 $mg.g^{-1}$ q_m* – 53.7 $mg.g^{-1}$ Cost per removal – $3.09 /g Hg Cost per removal* – $1.72 /g Hg	[195]
Date seeds heated in a furnace at 550 ℃ under anaerobic conditions.	Pre-treatment of biomass by soaking in NaOH or HCl solution then filtered, washed, dried, and pyrolyzed under anaerobic conditions at 550 °C.	BET – 104.2 $m^2.g^{-1}$ BET* – 119.1 $m^2.g^{-1}$ (acid wash) BET* – 101.7 $m^2.g^{-1}$ (base wash)	Adsorption of lead, copper and nickel.	For lead q_m – 0.718 $mmol.g^{-1}$ q_m* – 0.911 $mmol.g^{-1}$ (acid wash) q_m* – 0.897 $mmol.g^{-1}$ (base wash)	[196]

(*continued on next page*)

Table 4 (*continued*)

Adsorbent	Modification procedure	Property improvement	Adsorption process	Process enhancement	Study
				For copper q_m – 0.421 mmol.g^{-1} q_m* – 0.705 mmol.g^{-1} (acid wash) q_m* – 0.550 mmol.g^{-1} (base wash) For nickel q_m – 0.333 mmol.g^{-1} q_m* – 0.664 mmol.g^{-1} (acid wash) q_m* – 0.436 mmol.g^{-1} (base wash)	
Date seeds heated in a furnace at 550 ℃ under anaerobic conditions.	Post-treatment of biomass pyrolyzed at 550 ℃ by soaking in NaOH or HCl solution.	BET – 104.2 m^2.g^{-1} BET* – 89.1 m^2.g^{-1} (acid wash) BET* – 106.2 m^2.g^{-1} (base wash)	Adsorption of lead, copper, and nickel.	For lead q_m – 0.718 mmol.g^{-1} q_m* – 0.911 mmol.g^{-1} (acid wash) q_m* – 0.897 mmol.g^{-1} (base wash) For copper q_m – 0.421 mmol.g^{-1} q_m* – 0.575 mmol.g^{-1} (acid wash) q_m* – 0.532 mmol.g^{-1} (base wash) For nickel q_m – 0.333 mmol.g^{-1} q_m* – 0.635 mmol.g^{-1} (acid wash) q_m* – 0.434 mmol.g^{-1} (base wash)	[196]

* - modified adsorbent; DOC – dissolved organic carbon.

causing adsorption efficiency to plateau. At very high dosages, this plateau is often attributed to overlapping adsorption sites and agglomeration [200,201].

However, these process parameters often interact in complex ways. For instance, increasing adsorbent dosage may alter the effective pH of the system or require longer contact times to achieve equilibrium. Similarly, excessive agitation, while improving mass transfer, can lead to biochar attrition, compromising adsorbent reusability and lifetime. Also, although lab studies show clear trends, real wastewater treatment scenarios present challenges such as variable pH, presence of competing contaminants, and limited control over agitation or contact time, necessitating process designs that accommodate such complexities. Essentially, optimizing these operational parameters is key to maximizing dye removal from wastewater using biochar. pH must be tailored to the dye and adsorbent nature, contact time should ensure equilibrium, agitation should be sufficient to enhance mixing without causing degradation, and the adsorbent dose must balance efficiency with cost and system performance. Fig. 7 gives the results of studies that focused on the effect of pH on the adsorption processes involving the use of biochar. The variability in pH trends observed across studies likely arises from differences in biochar feedstock, activation methods, dye chemistry, and experimental conditions, highlighting the demand for standardized testing protocols and system-specific optimization. It is evident that the trend is not the same for the six selected case studies, supporting the notion that pH must be tailored to suit the dye and adsorbent's physical and chemical nature. Future studies should focus on multi-parameter optimization using design-of-experiments approaches to identify synergistic effects and establish robust operational windows suitable for real-world wastewater treatment.

5. Adsorption isotherms and kinetics

5.1. Isotherms

Adsorption isotherms are models that help in understanding how dye molecules interact with biochar adsorbents. These models provide a quantitative basis for analyzing equilibrium data and are essential for designing adsorption systems and predicting performance under various conditions. Isotherms more often describe the relationship between the amount of dye adsorbed on the biochar surface and its concentration in the aqueous phase at equilibrium and a constant temperature [208]. Furthermore, several isotherm models have been developed; the most common ones are based on assumptions such as adsorbent surface homogeneity, monolayer or multilayer adsorption, or interactions between adsorbed molecules, namely the Langmuir, Freundlich, Temkin, Dubinin-Radushkevich, Redlich-Peterson, Sips, and Toth. Among these models, Langmuir often provides a good fit for biochars with relatively homogeneous surfaces and monolayer adsorption behavior; however, it may oversimplify complex biochar pore structures. Freundlich, with its empirical basis, better accounts for surface heterogeneity and multilayer adsorption typical of diverse feedstocks-derived biochars. The application of these models to dye adsorption using biochar helps to elucidate the nature of adsorption processes, whether they are physical or chemical, homogeneous or heterogeneous, and allows the calculation of key parameters such as adsorption capacity, intensity, and affinity. These parameters are an important consideration when selecting adsorbents for industrial use. As such, accurate isotherm modeling is not only essential for understanding fundamental adsorption mechanisms but also critical for scaling up the process. Although isotherm parameters such as adsorption energy derived from Dubinin-Radushkevich models are often used to infer physical or chemical adsorption, these interpretations must be validated by complementary techniques (such as spectroscopy), given the complexity of biochar surfaces. Parameters obtained *via* isotherm models can be used in adsorption column design, economic analysis, and optimization of operating parameters (*e.g.,* contact time, dosage, initial dye concentration). Despite their utility in design and optimization, the extrapolation of isotherm parameters from batch experiments to continuous systems necessitates caution, as dynamic conditions and competing interactions in practical wastewater can change adsorption equilibria. For studies of complex adsorbents

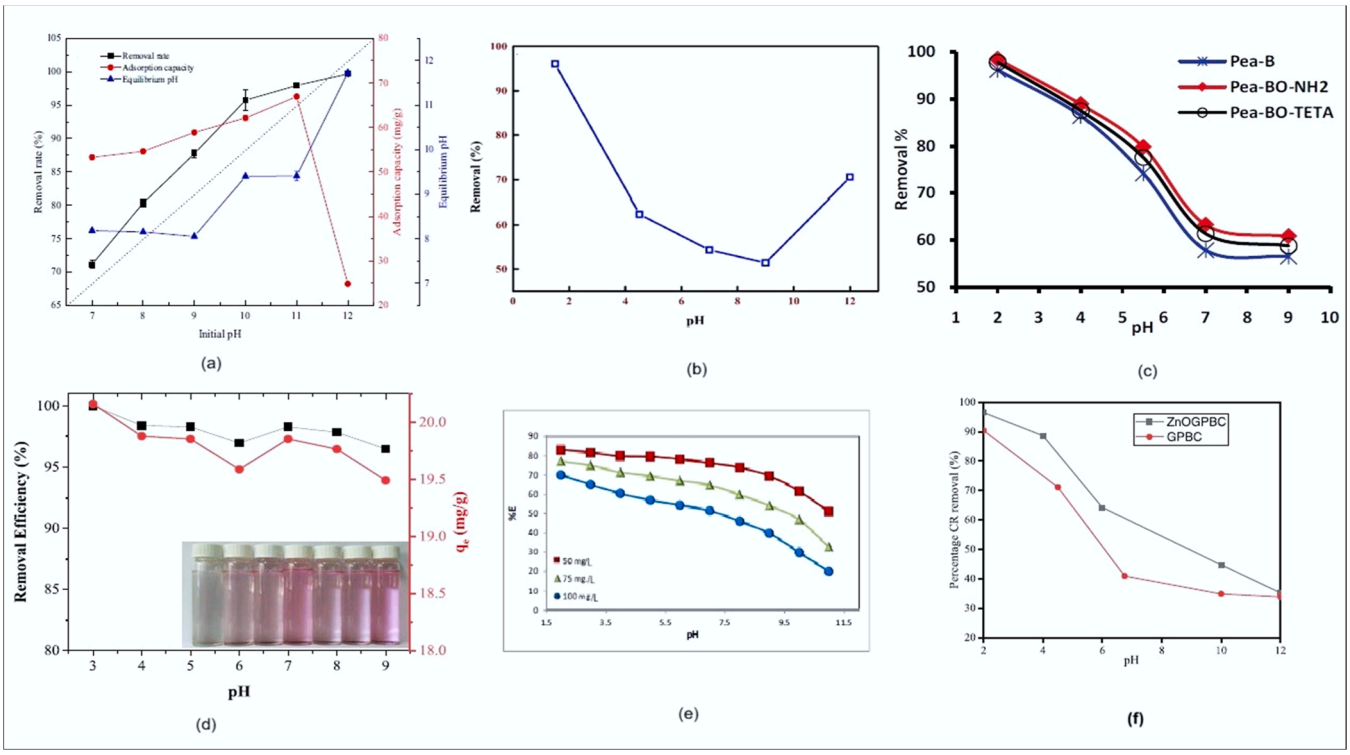

Fig. 7. Results from different studies showing different effects of pH on the adsorption process: (a). removal of methylene blue by porous biochar obtained by KOH activation from bamboo biochar. (Reproduced from ref. [202] with permission from Bioresources and Bioprocessing, copyright 2023.); (b). acid orange 7 dye absorption using sulphonated mandarin biochar treated with triethylenetetramine (TETA). (Reproduced from ref. [203] with permission from Biomass Conversion and Biorefinery, copyright 2023.); (c). removal of acid orange 7 using modified biochar from pea-peels. (Reproduced from ref. [204] with permission from Desalination and Water Treatment, copyright 2020.); (d). removal of rhodamine B using modified biochar from waste pine nutshell. (Reproduced from ref. [205] with permission from Biomass Conversion and Biorefinery, copyright 2024.); (e). adsorption of sunset yellow dye onto TETA-treated biochar. (Reproduced from ref. [206] with permission from Journal of Molecular Liquids, copyright 2020.); and (f). biosorption of Congo red dye from aqueous solutions using pristine biochar and ZnO biochar from green pea peels. (Reproduced from ref. [207] with permission from Chemical Engineering Research and Design, copyright 2023.).

such as biochar, fitting multiple models to the same experimental data is encouraged because it allows for a more comprehensive understanding of the adsorption process. While fitting multiple isotherm models improves understanding, it can lead to conflicting interpretations if goodness-of-fit criteria are not rigorously applied. Thus, researchers should complement isotherm fitting with mechanistic studies and ensure statistical robustness to avoid misleading conclusions. Notably, discrepancies often arise due to variability in biochar characteristics and dye chemistry, highlighting the need for harmonized testing conditions and models better tailored to heterogeneous biochar materials. Nevertheless, the following sub-sections give a brief description of the four most commonly used adsorption isotherms.

5.1.1. *Langmuir isotherm*

The Langmuir isotherm is one of the most widely used models for describing dye adsorption onto biochar. This model assumes that adsorption occurs at specific homogeneous sites within the adsorbent and that once a dye molecule occupies a site, no further adsorption can occur at that location, implying monolayer coverage. The model also assumes no interaction between adsorbed molecules. Furthermore, the energy of adsorption is constant all over the adsorbent surface [209, 210].

The linear form of the Langmuir equation is:

$$\frac{1}{q_e} = \frac{1}{q_m K_L C_e} + \frac{1}{q_m} \tag{2}$$

where:

- q_e is the amount of dye adsorbed at equilibrium ($mg.g^{-1}$),
- C_e is the equilibrium concentration of dye in solution ($mg.L^{-1}$),
- q_m is the maximum adsorption capacity ($mg.g^{-1}$),
- K_L is the Langmuir constant related to the affinity of binding sites ($L.mg^{-1}$).

When applied to experimental data, a high correlation with the Langmuir model suggests uniform adsorption sites on biochar adsorbent and chemisorption mechanisms. The dimensionless separation factor R_L, calculated as:

$$R_L = \frac{1}{1 + K_L C_0} \tag{3}$$

where C_0 is the initial dye concentration. An R_L value between 0 and 1 indicates favourable adsorption. Furthermore, the Langmuir isotherm is used for evaluation of q_m, which facilitates the evaluation of the material's adsorption capacity [210].

5.1.2. *The Freundlich isotherm*

In contrast to the Langmuir model, the Freundlich isotherm is an empirical equation that assumes adsorption on a heterogeneous surface and the possibility of multilayer adsorption. This is particularly relevant for biochars, which often possess diverse surface properties due to variations in feedstock and pyrolysis conditions.

The Freundlich equation is expressed as:

$$q_e = K_F C_e^{1/n} \tag{4}$$

where:

- K_F is the Freundlich constant indicative of adsorption capacity,

- 1/n indicates the adsorption intensity or surface heterogeneity.

The Freundlich model is suitable for describing the adsorption of dyes on biochars with irregular pore structures and diverse surface functional groups. Notably, 1/n reflects the heterogeneity of the adsorbent surface and the nonlinearity of the adsorption process [210]. For example, when 1/n approaches 0 (with larger n), surface heterogeneity increases; conversely, $1/n = 1$ indicates a linear adsorption process on a homogeneous surface. A value of 1/n less than 1 implies a favourable adsorption process and suggests a strong interaction between the dye and biochar. The adsorbent has a high affinity, and its adsorption capacity increases more rapidly as the adsorbate concentration rises. On the other hand, the value of 1/n, which is higher than 1, is an indication of minimal surface heterogeneity and limited adsorption capacity, with a slower increase in adsorption as adsorbate concentration increases. In situations where there is minimal heterogeneity, the adsorption is most likely a multilayer process. Multilayer adsorption occurs mostly due to physisorption, whereby the heat of adsorption of the first layer is comparable to the heat of adsorption of the subsequent layer [209].

5.1.3. The Temkin isotherm

The Temkin isotherm incorporates the effects of indirect adsorbate–adsorbate interactions on adsorption and assumes that the heat of adsorption of all molecules in the layer decreases linearly with coverage. This makes it suitable for systems with high concentrations, where chemical adsorption or other strong interactions predominate [210]. This model is useful for distinguishing between physical and chemical adsorption and is expressed as:

$$q_e = BInA + BInC_e \tag{5}$$

$$B = \frac{RT}{b} \tag{6}$$

where:

- B is the Temkin constant related to the heat of adsorption
- A is the equilibrium binding constant ($L.g^{-1}$),
- R is the universal gas constant (8.314 $J.mol^{-1}{\cdot}K^{-1}$),
- T is temperature in Kelvin.

A good fit to the Temkin model may suggest the involvement of chemisorption and may be used to understand the energetic distribution of adsorption sites. The coefficient B, related to adsorption heat, represents the strength of interaction between the adsorbate and adsorbent [210].

5.1.4. The Dubinin-Radushkevich (D-R) isotherm

The D–R isotherm is commonly used to distinguish between physical and chemical adsorption mechanisms. It assumes a Gaussian energy distribution onto a heterogeneous surface and does not assume a homogeneous surface or constant adsorption potential.

The linear form of the D–R equation is:

$$Inq_e = Inq_m - \beta\varepsilon^2 \tag{7}$$

where:

- q_e is the theoretical saturation capacity,
- q_m is the theoretical maximum capacity
- β is a constant related to the mean free energy of adsorption,
- ε is the Polanyi potential, calculated as

$$\varepsilon = RT\left(1 + \frac{1}{C_e}\right) \tag{8}$$

This model is more applicable to reactions under low temperature and low concentration conditions; the mean adsorption energy (E) is calculated as:

$$E = \frac{1}{\sqrt{2\beta}} \tag{9}$$

The adsorption energy, also known as bonding energy, calculated via the D-R model can be used to predict the sorption nature; predominantly physical ($E < 8$ $kJ.mol^{-1}$) or dominated by chemisorption and ion exchange ($8 < E < 16$ $kJ.mol^{-1}$) [208]. As mentioned earlier, the application of these models to dye adsorption using biochar helps to elucidate the nature of adsorption processes, whether they are physical or chemical, and allows the calculation of key parameters such as adsorption capacity, intensity, energy, and affinity. These parameters are an important consideration when selecting adsorbents for industrial use. Table 5 gives a list of previous studies, where important adsorption process parameters for biochar were determined by the use of various adsorption isotherms. The insights obtained from these models reveal the diverse adsorption behaviors of biochar systems. Favorable monolayer adsorption across pollutants like Congo red, rhodamine B, and heavy metals like Pb and Cu was indicated by the Langmuir model, which was commonly used in these investigations and frequently produced RL values between 0 and 1. Particularly on biochars with comparatively homogeneous surface properties, high R^2 values for Langmuir fits—such as in the adsorption of basic fuchsin red and crystal violet—reinforce the dominance of monolayer adsorption mechanisms.

On the other hand, Freundlich parameters (particularly 1/n values below 1) indicate surface heterogeneity and multilayer adsorption in a number of cases, including the adsorption of methyl red and acid yellow 11. The nature of the adsorption energy was further clarified by the Dubinin–Radushkevich (D–R) model. For instance, low E values (typically < 8 $kJ{\cdot}mol^{-1}$) in the sorption of As, Cu(II), and Congo red indicate physisorption, while higher E values—as observed with methyl red and rhodamine B—suggest chemical interactions. In certain instances, such as Cd and Pb sorption, where exceptionally low E values ran counter to other mechanistic evidence, the applicability of the D–R model was questionable. Studies using the Redlich–Peterson, Sips, and Toth models also demonstrate the presence of both monolayer and heterogeneous multilayer adsorption, as evidenced by high R^2 values and a variety of isotherm fits, particularly in the case of methylene blue and fuchsin red. Altogether, the isotherm-derived parameters in Table 5 not only confirm the efficacy of biochar in pollutant removal but also highlight the importance of model selection in revealing the underlying adsorption mechanisms.

5.2. Kinetics

Understanding the kinetics of dye adsorption onto biochar is helpful in designing and optimizing adsorption processes. Kinetic studies not only reveal the rate of dye uptake but also provide insights into the controlling steps of the adsorption process—whether they are governed by surface adsorption, intraparticle diffusion, or a combination of both. Furthermore, in order to efficiently incorporate biochar into existing wastewater treatment processes, kinetic modeling is crucial for determining the dynamics of dye removal and predicting system behavior under different conditions. Several kinetic models have been employed to interpret the adsorption of dyes onto biochar. The most frequently used models are the pseudo-first-order, pseudo-second-order, Elovich, and intraparticle diffusion models. In the same manner as isotherm models, each kinetic model is based on assumptions regarding the nature of the adsorption process and rate-limiting steps. Several variables can influence the kinetic behavior of dye adsorption onto biochar; these are surface area and porosity, functional groups, pyrolysis temperature, and pH of solution. By optimizing these parameters, the kinetics of dye removal can be significantly enhanced for specific applications.

Moreover, the pseudo-second-order model generally provides a better fit to experimental data than the other models, particularly for

Table 5
Studies that used adsorption isotherm models to determine important process parameters.

Adsorption process	Isotherms evaluated	q_m (mg. g^{-1})	K_L (L. mg^{-1})	R_L	1/n	B_T (kJ. mol^{-1})	E (kJ. mol^{-1})	R^2	Insights gained	Study
Biosorption of Congo red dye using pristine biochar from green pea peels	Langmuir Freundlich Temkin D-R	62.1 48.3	0.03	0.29	0.38	0.014	79.1	- - - -	The Langmuir R_L value is between 0 and 1, indicating that biochar favoured dye adsorption. E values are higher, proposing that the adsorption is a chemical phenomenon.	[207]
Removal of arsenic from water by biochar adsorbent made from *Sesbania bispinosa*	Langmuir Freundlich Temkin D-R	7.33	0.30		0.59	2.03	0.08	- - - -	The Freundlich 1/n parameter is less than 1, and the E values given by the D-R model are low, which shows that arsenic was removed *via* physical adsorption.	[211]
Sorption of Cd onto biochar made from pyrolyzing the organic fraction of municipal solid waste at 700 ℃	Langmuir Freundlich Temkin D-R	47.7 58.9	0.23	0.3 – 1.0	0.26	3.03	0.04	- - - -	The R_L values lie between 0 and 1, indicating that the adsorption was favourable. Low values of E suggest physical sorption; however, extremely low values cast doubt on the suitability of the D-R model in this case.	[212]
Sorption of Pb onto biochar made from pyrolyzing the organic fraction of municipal solid waste at 700 ℃	Langmuir Freundlich Temkin D-R	246.2 46.5	0.002	0 – 0.8	0.87	2.60	0.05	- - - -	The R_L values lie between 0 and 1, indicating that the adsorption was favourable. Low values of E suggest physical sorption; however, extremely low values cast doubt on the suitability of the D-R model in this case	[212]
High-performance capacitive deionization process of Cu (II) using biochar derived from *Sargassum hemiphyllum*	Langmuir Freundlich Temkin D-R	93.5 80.9	1.04		0.28	0.2	2.26	- - - -	The electro-sorption process was likely dominated by physisorption, with E < 8.0 kJ. mol^{-1}. The parameter 1/n was between 0.1 and 0.5, indicating that the pollutant is easily adsorbed. B_t < 4.2 kJ.mol^{-1}, further indicating that the electro-sorption is physical.	[213]
Acid yellow 11 dye adsorption from wastewater using *Pisum sativum* peels microporous activated carbon	Langmuir Freundlich Temkin	515 758	1.46		0.23	0.06		0.99 0.99 0.98	The adsorbent can easily absorb the adsorbate due to a physical process because 1/n is less than 1. The extremely low B_T indicates a physical process and minimal ionic contact between the adsorbent and the adsorbate.	[204]
Bio-adsorption of Methylene blue onto biomass obtained from the Algae *D. antarctica*	Langmuir Freundlich R-Peterson Sips Toth	765 148 702	0.06		0.27			0.98 0.87 0.99 0.87 1.00	R^2 value for Redlich–Peterson and Troth models is high, which suggests that the adsorption occurred in multilayers.	[214]
Removal of basic fuchsin red dye by turmeric leaf waste biochar	Langmuir Freundlich R-Peterson Sips	283	0.03		0.61			0.98 0.91 0.95 0.96	The high R^2 value for the Langmuir isotherm indicates that the adsorption occurred via a monolayer adsorption manner. The energy of adsorption is uniform throughout the adsorbed layer on the biochar adsorbent surface, at a constant temperature.	[215]
Removal of Methyl Red from aqueous solutions using biochar derived from fennel seeds	Langmuir Freundlich Temkin D-R	130 133	1.26		0.05	3.43	1119	0.89 0.99 0.73 0.79	The low value of 1/n indicates a greater degree of heterogeneity. The high value of B_T suggests high adsorption energy.	[216]
Adsorption of rhodamine B using groundnut husk biochar	Langmuir Freundlich Temkin D-R	2.37 1.31	0.804	0.21	0.86	16.8	31.3	0.52 0.99 0.96 0.98	The R_L values lie between 0 and 1, indicating that the adsorption was favourable. The parameter 1/n was between 0.1 and 0.5, indicating that the pollutant is easily adsorbed.	[217]
Adsorption of crystal violet dye using oil palm frond magnetic biochar	Langmuir Freundlich Temkin D-R	149		0.0001	0.17	21.0	85.3	0.98 0.97 0.98 0.83	Adsorption occurred on the monolayer surface of the magnetic biochar. Low R_L values indicate favourable adsorption. Occasionally, the process occurred on the surface of the biochar as a result of unequal sites for adsorption on layers of the adsorbent surface.	[218]
Adsorption of sunset yellow dye using oil palm frond magnetic biochar	Langmuir Freundlich Temkin D-R	342		0.0001	0.48	87.7	169.5	0.98 0.96 0.98 0.88	Adsorption occurred on the monolayer surface of the magnetic biochar. Low R_L values indicate favourable adsorption. Occasionally, the process occurred on the surface of the biochar as a result of unequal sites for adsorption on layers of the adsorbent surface.	[218]

-: not reported.

systems involving strong chemisorption and heterogeneous biochar surfaces [219]. This is because biochar is a complex, heterogeneous material with various functional groups, pores, and surface charges [188,220]. A summary of selected studies presented in Table 6 clearly shows that most dye adsorption processes that utilise biochar as an adsorbent are better described by the pseudo-second order kinetics model. Across a wide range of dyes—including acid orange 7, methylene blue, rhodamine B, methyl red, crystal violet, sunset yellow, *etc.*—pseudo-first-order models consistently demonstrate high correlation coefficients (R^2 values ranging from 0.98 to 1.00). This strong statistical

Table 6
Selected studies on the application of kinetic models on dye adsorption using biochar.

Dye	Biochar material	Kinetics model fit				Study
		PFO model (R^2)	PSO model (R^2)	ELO model (R^2)	IPD model (R^2)	
Acid orange 7	Pea peels	0.26 – 0.99	0.99 – 1.00	0.34 – 0.99	0.46 – 0.99	[204]
Methylene blue	Algae	0.89 – 0.99	0.99 – 1.00	0.94 – 0.99	0.90 – 0.99	[214]
Rhodamine B	Groundnut husk	0.11	1.00	0.86	0.63	[215]
Methyl red	Fennel seeds	0.93 – 0.98	0.99 – 1.00	0.91 – 0.99	0.93 – 0.97	[216]
Crystal violet	Oil palm frond	0.91	0.95	0.74	0.81	[218]
Sunset yellow	Oil palm frond	0.91	0.95	0.81	0.88	[218]
Sunset yellow	Coconut	0.87	0.89	-	0.88	[221]
Tartrazine	Coconut	0.92	0.82	-	0.89	[221]
Sunset yellow	Groundnut	0.83	0.78	-	0.97	[221]
Tartrazine	Groundnut	0.94	0.85	-	0.96	[221]
Rhodamine B	*Callophyllum Inophyllum* seeds	0.47	0.99	-	-	[222]
Reactive blue 19	Sugarcane bagasse	0.98	0.99	-	-	[223]
Acid yellow 11	*Pisum sativum* peels	0.71 – 0.99	0.99 – 1.00	0.60 – 0.99	0.61 – 0.99	[224]
Methylene blue	Sawdust	0.01 – 0.98	0.94 – 1.00	-	0.26 – 0.98	[225]
Congo red	Orange peel	0.94	1.00	-	0.93	[226]
Basic blue 41	Groundnut husk	0.99 – 1.00	0.99 – 1.00	-	-	[227]
Basic red 09	Groundnut husk	0.99 – 1.00	0.99 – 1.00	-	-	[227]
Rhodamine B	Groundnut husk	0.01 – 0.93	0.99 – 1.000	0.19 – 0.63	0.79 – 0.86	[215]
Crystal violet	Chinar tree	0.85	1.00	-	0.30	[228]
Methylene blue	*Fagus sylvatica*	0.85	0.99	-	0.98	[175]
Basic red 09	Turmeric leaf	0.90 – 0.99	0.98 – 0.99	-	-	[217]
Remazol yellow FG	Coffee fruit shell	0.22	0.97	-	-	[229]
Methyl red	Rumex Abyssinicus	0.98	0.99	-	0.96	[230]
Malachite green	Algae	0.94 – 0.98	0.98 – 0.99	-	0.90 – 0.99	[48]

PFD: pseudo-first-order, PSD: pseudo-second-order, ELO: Elovich, and IPD: intraparticle diffusion.

fit suggests that the rate of adsorption is more dependent on the availability of adsorption sites and involves chemical interactions between the dye molecules and functional groups on the biochar surface. Nonetheless, the consistent utilization of pseudo-second-order fits based solely on correlation coefficients could overlook mechanistic complexities. Without validating the assumptions of the model—like uniform active sites and constant adsorption energy—the conclusions about chemisorption dominance may be overstated. On the other hand, the pseudo-first-order model, while occasionally demonstrating moderate fits (R^2 values varying widely from as low as 0.01 up to 0.99), generally fails to describe the adsorption process as reliably as the pseudo-second-order model. The Elovich and intra-particle diffusion models also show varying and generally lower correlation values, indicating that they may only capture specific aspects of the adsorption mechanism or may be applicable in certain stages or conditions, but not as a comprehensive kinetic description. In fact, combining kinetic models across different adsorption phases can yield more nuanced insights—for instance, the initial phase may be better described by external mass transfer models, while the equilibrium stage aligns with chemisorption kinetics. The predominance of the pseudo-second-order model infers that chemisorption governs the adsorption mechanism, where electron sharing or exchange, chemical bonding, or stronger molecular interactions occur, rather than simple physical adsorption. This chemical nature of adsorption aligns with the surface chemistry of biochar, which frequently contains functional groups that can form chemical bonds with dye molecules. Nonetheless, deviations from pseudo-second-order behavior have been reported in systems involving low-activation biochars or weakly interactive dyes, suggesting that adsorption kinetics are sensitive to both material chemistry and dye properties.

In addition, Table 6 indicates that biochar derived from diverse biomass sources—such as pea peels, algae, groundnut husk, fennel seeds, oil palm frond, *etc.*—demonstrates consistent pseudo-second-order kinetics behavior, suggesting the broad applicability of the model across different biochar types and dye molecules. This insight is valuable for designing and optimizing biochar-based adsorption systems, as it emphasizes the importance of surface chemistry and reactive sites in achieving dye removal efficiency. Overall, these findings provide strong evidence for the suitability of the pseudo-second-order kinetic model in describing the dynamics of dye adsorption onto biochar, reinforcing a clear understanding of the adsorption mechanisms and aiding in the prediction and scaling up of treatment processes involving biochar adsorbents. Nevertheless, translating batch kinetic insights to continuous or column-based systems requires careful calibration, as flow dynamics, diffusion limitations, and real effluent variability may change observed kinetics significantly.

5.2.1. Pseudo 1st order

The pseudo-first-order model, also known as the Lagergren model, assumes that the rate at which the adsorbed material occupies the adsorption sites is proportional to the number of unoccupied sites [210]. It is mathematically expressed as:

$$\frac{dq_t}{dt} = k_1(q_e - q_t) \tag{10}$$

where:

- q_t = amount of dye adsorbed at time t ($mg.g^{-1}$),
- q_e=amount of dye adsorbed at equilibrium ($mg.g^{-1}$),
- k_1=pseudo-first-order rate constant ($1.min^{-1}$).

The equation can be integrated and linearised such that a plot of log ($q_e - q_t$) versus t provides a straight line if the process follows pseudo-first-order kinetics. However, in many studies involving biochar, the pseudo-first-order model does not fit well across the entire time range, especially during the initial rapid uptake phase, suggesting that it may be limited in describing dye adsorption involving chemisorption or heterogeneous surface interaction.

5.2.2. Pseudo 2nd order model

The pseudo-second-order model, proposed by Ho and McKay, is based on the assumption that the rate-limiting step may involve chemical adsorption or valence forces through sharing or exchange of electrons between adsorbent and adsorbate [210]. The model is represented by:

$$\frac{dq_t}{dt} = k_2(q_e - q_t)^2 \tag{11}$$

where:

- k_2 = pseudo-second-order rate constant ($g.mg^{-1}.min^{-1}$).

The pseudo-second-order model generally provides a better fit to experimental data than the first-order model, particularly for systems involving strong chemisorption and heterogeneous biochar surfaces [219]. A high correlation coefficient (R^2) and agreement between experimental and calculated q_e values indicate the suitability of this model. It is widely reported in literature that dye adsorption onto biochars, such as those derived from agricultural residues, typically follows pseudo-second-order kinetics.

5.2.3. Elovich model

The Elovich model is often used to describe chemisorption on highly heterogeneous surfaces, such as biochar. It assumes that the number of available sites decreases exponentially with adsorption [210]. The Elovich equation is:

$$q_t = \frac{1}{\beta} In(\alpha\beta) + \frac{1}{\beta} Int \quad (12)$$

where:

- α = initial adsorption rate ($mg.g^{-1}.min^{-1}$),
- β = desorption constant ($g.mg^{-1}$).

A plot of q_t versus ln t yields a straight line if the model is applicable. The Elovich model is particularly useful when the adsorption process is not linear and does not conform to simple kinetic models, which is common in the adsorption of dyes onto chemically diverse biochars [219].

5.2.4. Intraparticle diffusion model

To further understand the rate-limiting steps in dye adsorption, the Weber–Morris intraparticle diffusion (IPD) model is commonly applied. This model considers the possibility that the diffusion of dye molecules into the pores of biochar could be the controlling mechanism [210]. The model is given by:

$$q_t = k_{id} t^{0.5} + C \quad (13)$$

where:

- k_{id} = intraparticle diffusion rate constant ($mg/g.min^{0.5}$),
- C = constant related to the boundary layer effect.

If the plot of q_t versus $t^{0.5}$ is linear and passes through the origin, intraparticle diffusion is the sole rate-limiting step. However, in most cases, the plot shows multiple linear regions, indicating that dye adsorption onto biochar typically involves multiple stages, *i.e., (i).* external film diffusion, *(ii).* intraparticle diffusion, and *(iii).* adsorption onto active sites [210,219].

6. Environmental and economic considerations

6.1. Sustainability aspects of pristine and dye-laden biochar

As global efforts intensify to transition toward more sustainable and circular resource management systems, biochar has gained increasing attention as a biomass waste-derived multifunctional material. It presents a promising solution for addressing environmental challenges while contributing to resource efficiency. Additionally, a typical reliance on renewable feedstock waste for biochar production promotes waste valorization and is consistent with SDGs, including Target 12.3 (*i.e.,* to halve global per capita food waste); Target 12.5 (*i.e.,* to substantially decrease waste generation *via* prevention, reduction, recycling, and reuse); and Target 13.2 (*i.e.,* to integrate climate change measures into national policies, strategies, and planning) [231,232]. Accordingly, the sustainability of biochar stems from its ability to close resource loops and lower environmental impacts associated with virgin resource extraction, toxic emissions, and waste management [26,233].

Unlike traditional wastewater treatment technologies that often rely on finite raw materials and generate secondary contaminants, biochar production processes minimize dependency on virgin resources and divert waste from landfills. This not only mitigates landfill pressure but also lowers the associated greenhouse gas (GHG) emissions and environmental degradation [43]. Moreover, the biochar production commonly requires significantly less energy input compared to conventional materials like activated carbon, especially when optimized using low-temperature processes such as metallocene-assisted pyrolysis [234,235]. These catalytic methods enhance carbon yield and surface functionality at minimal thermal thresholds, thereby decreasing the overall energy intensity of production [235]. As a result, the minimized energy demand directly contributes to a decrease in lifecycle GHG emissions, making biochar a more climate-resilient and energy-efficient alternative for adsorption-based environmental applications. Ultimately, a significant benefit is the potential of biochar for waste-to-resource conversion.

A circular production model using agricultural and food wastes to produce biochar, which is then employed for dye removal before being repurposed as dye-laden biochar for secondary use (*e.g.,* as soil conditioner), is shown in Fig. 8. This highlights the biochar's applicability to extend beyond its immediate function as a sorbent for dye removal. However, its long-term environmental behavior after employment in dye adsorption remains an area of active research. The environmental and logistical implications of reintegrating dye-laden biochar into soil or other systems must be critically evaluated. Issues like the cost of post-treatment, transport, regulatory acceptance, and potential ecological risks associated with residual dye compounds can limit the scalability of such circular approaches. Accordingly, while it is widely recognized for its high efficiency in removing dyes from aqueous systems, questions remain about the environmental fate of dye-laden biochar following disposal or secondary use, particularly in soil environments. Potential concerns include the leaching of retained dyes under fluctuating pH and moisture conditions, as well as the possible formation of toxic by-products *via* abiotic or microbial degradation [236,237]. In addition, interactions between dye-laden biochar and soil microbial communities

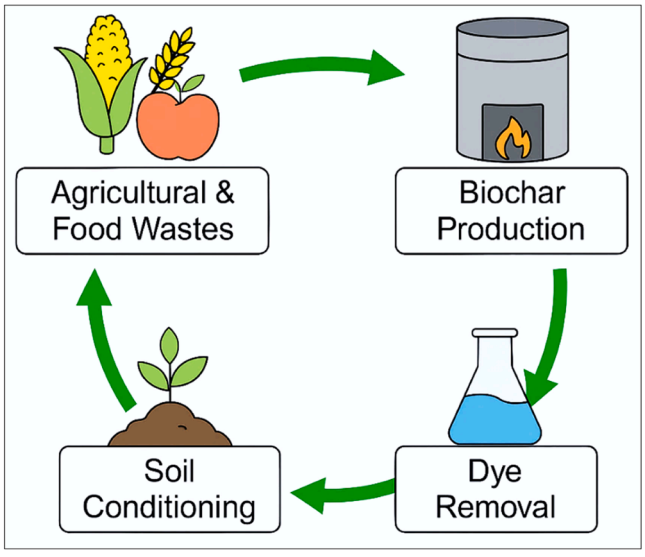

Fig. 8. Sustainable biochar loop: from waste conversion to dye removal and reuse.

are not well understood and may influence nutrient cycling, soil respiration, and overall ecosystem health [238–240]. These uncertainties underscore the need for comprehensive risk and integrated lifecycle assessments (LCAs) to ensure that the deployment of biochar for dye removal contributes positively to environmental sustainability rather than introducing new ecological risks. Furthermore, most current studies focus on short-term lab-scale evaluations under controlled conditions, leaving a critical gap in field-scale, long-term assessments required to inform regulatory policies and safe deployment practices.

6.1.1. *Carbon sequestration potential of dye-laden biochar*

As briefly highlighted previously, the essentiality of biochar in measures to mitigate climate change originates from its ability to sequester carbon in a form that is chemically stable. Its predominantly aromatic structure resists microbial and oxidative degradation, enabling long-term persistence in soils, from decades to centuries, unlike labile organic matter that decomposes rapidly and releases carbon dioxide back into the atmosphere [241,242]. Because of this characteristic, biochar is not only a valuable soil amendment but also a strategic tool for long-term carbon storage. Moreover, both labile and recalcitrant carbon fractions make up biochar. Short-term soil fertility and microbial activity can be aided by the mineralization of the labile fraction shortly after soil application, but the recalcitrant fraction is highly stable and locks away carbon in the soil matrix for extended periods [243,244]. The ratio of these fractions is significantly influenced by feedstock characteristics and pyrolysis conditions [243].

Lin *et al.* [240] have reported that the role of biochar in carbon sequestration becomes more nuanced when this material has previously been applied in dye adsorption processes. According to the authors, the adsorptive removal of dyes adds complexity to the biochar lifecycle, especially in terms of post-use environmental behavior and carbon stability. Empirical evidence consistently demonstrates that biochar does not necessarily lose its value after becoming saturated with dyes [27,46,143,144,175,237,245]. Therefore, in addition to soil amendment, it can be repurposed in applications like co-composting or encapsulated in engineered matrices. However, the way the adsorbed dye molecules affect the physical and chemical integrity of the carbon matrix determines how well dye-laden biochar can sequester carbon. Conversely, sorption of labile or weakly bound dye components could reduce the recalcitrance of the biochar matrix, undermining its carbon sequestration potential. Hence, not all dye-biochar interactions confer greater stability. Microbial access to easily degradable (labile) carbon fractions may be restricted in some cases by the formation of strong interactions between adsorbed dye molecules, especially those with large aromatic structures like crystal violet, and the surface of the biochar. In soil systems, this can effectively stabilize the carbon in the biochar by increasing its recalcitrance [246]. On the other hand, under varying pH or redox conditions, some dye classes—especially azo dyes—may undergo desorption or microbial breakdown, which would accelerate carbon mineralization and negate the sequestration effect [240,247]. Moreover, it has been found that the long-term fate of dye-laden biochar is governed not only by the properties of the biochar itself but also by environmental factors, including soil type, microbial activity, and existing levels of organic carbon [237,239,248]. For example, in nutrient-poor or acidic soils, biochar—whether pristine or dye-saturated—can increase the retention of native organic matter and decrease GHG emissions. Yet, the interaction between dye molecules and carbon structures could change these effects, necessitating a thorough understanding of both feedstock characteristics and dye chemistry. Harmonized testing frameworks, including long-term leaching assays and soil incubation studies, are necessary to assess environmental fate across diverse scenarios and to define safe thresholds for reuse of dye-laden biochar in agriculture or land restoration. To illustrate this interplay, Table 7 presents a comparative overview of how various dye-laden biochars behave in terms of carbon stability, potential degradation risks, and suitable end-of-life strategies. It includes the explanation of key considerations for practical management or further use of spent biochar, based on its specific interaction with the adsorbed dye. Moving forward, multidisciplinary collaboration will be essential in addressing the complex interplay of biochar chemistry, dye toxicity, soil health, and regulatory considerations to significantly realize the sustainability potential of biochar-based systems.

Many peer-reviewed studies (as cited) that have examined different substrate–dye combinations under various experimental and environmental conditions have contributed to the environmental stability and carbon sequestration potential summarized in Table 7. Although this synthesis offers a summary of what is currently known, there are still limited direct experimental comparisons made under controlled conditions. Therefore, to confirm and build upon these findings, more focused experimental research is encouraged. Nonetheless, as illustrated in Table 7, dye-laden biochar does not behave uniformly in the environment; therefore, it becomes difficult to treat biochar as a generic material post-use. While some feedstock-dye combinations yield stable carbon forms that are somewhat safe to apply directly to soils, others would require stabilization treatments to mitigate contaminant leaching or carbon loss [233,258]. The potential for particularly azo dyes to undergo reductive cleavage in moist or acidic soils, releasing breakdown products that might destabilize the carbon matrix, makes them problematic. However, methods including advanced oxidation (*e.g.,* Fenton reaction or electrochemical regeneration), alkaline washing, and low-temperature thermal desorption have proven effective in restoring the adsorption capacity of biochar without extensive degradation of its carbon matrix [259,260]. For example, electrochemical regeneration, especially for dyes like methyl orange (azo, anionic dye type) and methylene blue, can achieve over 80 % dye desorption efficiency over multiple cycles [261–263].

Comparative studies report that ultrasound-assisted regeneration typically consumes *ca.* 60–120 kWh per kg of dye desorbed, whereas electrochemical techniques may consume *ca.* 40–90 kWh per kg, depending on electrode material and electrolyte conditions [29]. In terms of regeneration cycles, ultrasound methods often maintain *ca.* 60–75 % adsorption efficiency over 4–6 cycles, while electrochemical

Table 7
Carbon stability and environmental fate of dye-laden biochars from various feedstocks.

Biochar feedstock	Pyrolysis temp. (°C)	Adsorbed dye type	Influence on carbon stability	Recommended post-treatment	Environmental concern	Study
Poultry litter	450	Congo red	Unstable within aerobic soil conditions	Immobilization in low-permeability areas	Risks of dye molecule desorption and microbial degradation under variable soil pH	[249,250]
Rice husk	500	Methylene blue	Increased stability resulting from dye-surface bonding	Soil enrichment	Cationic dyes normally form strong bonds, thereby lowering biochar biodegradability	[251,252]
Corn stover	500	Crystal violet	Enhanced aromaticity and stability of the structure	Direct soil amendment	Large aromatic dyes tend to promote the recalcitrance of biochar carbon	[117,253]
Food waste	700	Malachite green	Complex behavior, prone to partial degradation	Amended into the soil with clay or bentonite	Dye often enhances the reactivity of the adsorbent surface, necessitating controlled conditions	[254,255]
Sewage sludge	300 – 900	Reactive black 5	Moderate stability; dye cleavage risk	Encapsulation in cement or biochar bricks	Azo dyes tend to degrade in acidic or reducing conditions	[256,257]

methods can retain over 80 % efficiency for up to 8 cycles before significant performance loss is observed [44]. Accordingly, this regeneration contributes to resource efficiency by extending the useable lifespan of the sorbent, lowering the demand for producing new biochar, even though it typically consumes additional energy or chemicals [261,263]. Moreover, microbial composition, moisture availability, and native organic matter all affect the rates of carbon mineralization in soils amended with dye-laden biochar [248,264,265]. Thus, it is essential to optimize pyrolysis parameters to maximize dye adsorption and ensure long-term carbon persistence in environmental applications. In essence, utilizing biochar for dye removal presents a promising dual-benefit pathway: it addresses industrial wastewater pollution and contributes to climate mitigation *via* carbon sequestration. However, this synergy can only be sustainable when post-adsorption behavior is thoroughly assessed to ensure that dye-laden biochar maintains its role as a net carbon sink throughout its lifecycle.

6.1.2. *Other post-adsorption fate and circular dynamics of biochar*

The presence of immobilized dyes typically turns biochar into a complex composite material that needs to be handled carefully to ensure maintained environmental benefits and prevented secondary contamination [13,220,237]. Modern approaches place more emphasis on expanding the use of dye-laden biochar through circular economy frameworks than on discarding it as waste [266,267]. In addition to its use soil amendment and carbon sequestration, given in the preceding sections, this section explores how the lifecycle of dye-laden biochar might be optimized for its reintegration into productive systems. The interrelated routes that define this lifecycle are depicted in Fig. 9, which emphasizes a circular model in which end-of-life decisions are guided by material reintegration rather than disposal. This potential conceptual model loops dye-laden (spent) biochar reuse through different routes into a circular economy framework.

The incorporation into engineered construction materials is one of the most promising avenues for post-use valorization of dye-laden biochar. Studies [268,269] have reported that spent biochar, particularly due to its porous structure and thermal stability, can be loaded into bricks, lightweight concrete composites, asphalt, and insulating panels. In addition to preventing leaching, this incorporation entraps the adsorbed dye compounds and gives the resultant products co-benefits, including decreased bulk density and increased thermal resistance [270,271]. Importantly, the dyes remain physically, effectively immobilized within the construction matrix, hence minimizing environmental exposure. For instance, fired clay bricks or non-structural concrete with up to 10 % dye-laden biochar loading have demonstrated compressive strengths within regulatory standards while maintaining contaminant stability [272]. This is a further example of a closed-loop strategy for converting a waste sorbent into a durable material. Nevertheless, the long-term mechanical stability of such composites, potential dye degradation under environmental exposure, and lack of standardized guidelines for construction-grade waste-based additives remain significant challenges that must be addressed through further durability testing and regulatory development.

In cases where structural reuse in construction is not feasible, controlled thermal processing of spent biochar, *via* secondary low-oxygen combustion, gasification, or catalytic cracking, offers another pathway. Importantly, the yield of energy and the breakdown of complex adsorbed dye compounds (azo and anthraquinone dyes, in particular) can lower overall environmental risk. For example, modern thermal technologies paired with emission control units can safely treat dye-saturated biochar and minimize the formation of secondary contaminants such as dioxins and polycyclic aromatic hydrocarbons [273]. Although some fixed carbon is lost in this process, the net effect can still be positive in terms of energy recovery and pollution mitigation—especially in decentralized systems seeking to valorize biomass wastes that are a burden. However, the energy consumption and partial loss of sequestered carbon during thermal treatment must be weighed against the benefits of pollutant destruction, particularly in carbon accounting or low-resource contexts. Also, the resultant biochar ash, although devoid of significant sorptive potential, may still be suitable for uses for secondary valorization in environmental infrastructure, such as permeable reactive barriers, landfill liners, geotechnical stabilization, or as aggregate material in road bases [274]. These applications are not predominantly dependent on the sorptive capacity of the biochar but utilize its physical and chemical properties to control or impede the movement of contaminants. For instance, when mixed into compacted clay material to create biochar–clay hybrid composites, dye-laden biochar has demonstrated the ability to decrease permeability and enhance cation retention [265,275].

Furthermore, dye-laden biochar can be stabilized for long-term storage or controlled release scenarios using encapsulation technologies such as polymeric binding, geopolymerization, or cementitious matrices [276–278]. By decreasing the risk of leaching, these methods

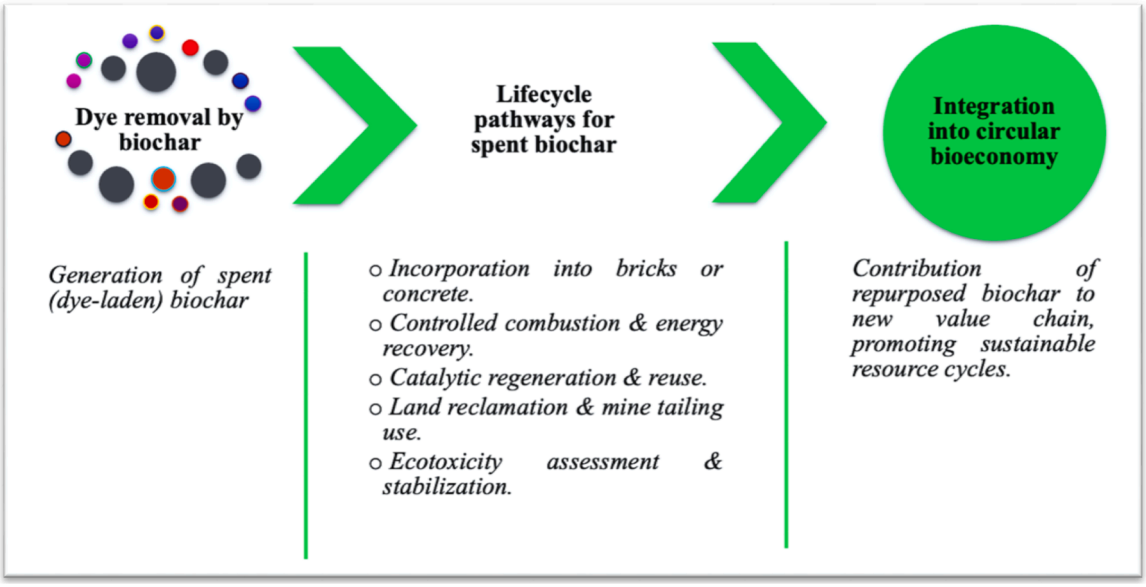

Fig. 9. Lifecycle of dye-laden biochar within a circular economy framework [268–270]. Layout created by the authors based on data compiled from the cited literature. No copyright permission required.

typically allow for safer handling and repurposing in industrial or municipal settings. Also, encapsulation creates new avenues for standardized material development by converting once-spent sorbents into fillers or building additives that are classified. Yet, many of these encapsulated forms do not fit neatly into current regulatory categories, raising questions about long-term liability, certification, and end-of-life disposal responsibilities. On the other hand, land reclamation and mine tailing stabilization are two applications for used biochar that are increasingly being explored [279,280]. In this case, biochar serves as both a structural and chemical amendment. It can immobilize residual dyes and lower the bioavailability of co-contaminants (*e.g.,* heavy metals) when applied to degraded or contaminated lands. Even spent biochar, despite being saturated with contaminants, can increase microbial respiration, support vegetation growth, and lower leaching losses when properly applied, according to field tests conducted in mine-impacted environments [281]. These benefits, however, are highly site-specific and necessitate pre-application risk assessments, as noted earlier. As a result, large-scale deployment for land reclamation should only proceed after site-specific field trials that account for the combined effects of dye chemistry, soil geochemistry, and microbial community dynamics.

Interestingly, the environmental behavior of dye-laden biochar under variable conditions appears to be a key factor in all reuse strategies. The nature of adsorbed dyes, soil pH, redox potential, and microbial activity can all affect how stable the carbon matrix is. For example, certain dyes may effectively increase the permanence of biochar in soil by preventing microorganisms from accessing labile carbon sites [282, 283]. Conversely, under specific conditions, other dye types may be desorbed or function as redox catalysts, which could accelerate leaching or degradation [284,285]. These dynamics highlight the necessity of comprehensive risk assessment and ecotoxicological evaluation before deploying dye-laden biochar in open environments, including land-based applications. Currently, the absence of standardized ecotoxicological protocols hinders consistent evaluation. Interdisciplinary frameworks involving ecotoxicology, soil science, and environmental engineering would be necessary to guide safe reuse approaches. It is necessary to conduct empirical tests to determine the mobility of adsorbed dyes, possible degradation products, and their effects on microbial and plant systems. To ensure that reusing dye-laden biochar does not inadvertently introduce new environmental hazards, factors like phytotoxicity, microbial community shifts, and dye leaching potential must be evaluated. Essentially, LCAs and techno-economic analyses are important for assessing the environmental value of these lifecycle strategies. Such models aid in the quantification of net carbon savings, energy return on investment, and economic viability [74,286]. For instance, compared to landfilling or incineration alone, the use of dye-laden biochar in construction applications or as a soil cap in contaminated lands appears to offer improved climatic performance and cost efficiency, according to preliminary LCA data [258,287]. However, many LCAs rely on simplified assumptions or laboratory-scale data, which may not completely capture environmental trade-offs or operational complexities at scale. Robust sensitivity analyses and field validation are essential to ensure accurate sustainability claims. These findings reinforce the premise that, with careful oversight, dye-laden biochar can continue delivering environmental benefits beyond its initial use in wastewater remediation.

6.2. Economic outline of raw vs. modified adsorbing materials

The economic performance of biochar is typically associated with operational flexibility. Adoption of biochar-based filters or packed beds, for instance, necessitates minimal capital expenditure and can be easily integrated into both upstream and downstream segments of existing wastewater treatment setups [26,288]. This allows dye removal either as a pre-treatment step or as a polishing technique, without interfering with operations in small-scale textile units or dyeing workshops in low- and middle-income countries [288]. Particularly in situations where centralized wastewater treatment is impractical from a logistical or economic standpoint, this modularity provides a competitive edge. In addition, on-site pyrolysis and local feedstock sourcing lower transportation costs while establishing regional value chains that stimulate rural bioeconomies, as stated by Berazneva *et al.* [289].

Moreover, biochar producers have learnt to meticulously assess the surface modification procedures of the material to balance the effectiveness and cost. This carbon-rich material offers a competitive edge over conventional adsorbents like activated carbon due to the abundance of its raw materials and much cheaper operational (manufacturing and modification) costs [44,290]. Importantly, techno-economic analyses suggest that process optimization—including ideal pyrolysis conditions, batch *vs.* continuous reactors, and modular plant designs—can reduce costs by up to 30 % compared to early-generation systems [291–293]. For instance, biochars produced at higher pyrolysis temperatures generally incur greater costs, and modifications further raise their production and commercial price. Uzun *et al.* [294] have recently suggested that these costs can be typically reduced using locally available biomass feedstocks and by optimizing pyrolysis conditions to balance performance with affordability.

Co-benefits such as partial energy recovery during pyrolysis also reduce net operational expenses [295]. Furthermore, modified biochars, such as those doped with iron, magnetite, acid, or amine-functional groups, have demonstrated enhanced affinity for anionic and cationic dyes, enabling their use in dynamic column systems or batch reactors [237,296]. On the other hand, activated carbon—both modified and unmodified—tends to be more expensive due to the intensive energy and chemical inputs required for their production and regeneration. There have been instances where modified biochars—*i.e.,* those that have demonstrated efficacy in improving selectivity and adsorption kinetics for specific dye profiles—perform better than standard activated carbon at a lower cost [137,297,298]. For example, it has been found that aminated biochars can adsorb certain cationic and reactive dyes (*e.g.,* azo or anthraquinone dyes) up to four times better than standard activated carbon, and the former is much cheaper than the latter—-specifically, aminated biochar costs just 12.5 % of what activated carbon costs [299–301]. Importantly, modified biochars facilitate easier separation, recovery, regeneration, and reuse, thereby extending service life, meaning that these materials are reusable across multiple cycles, adding to their long-term economic viability [29,234]. However, according to some researchers [30, 302–304], the fact remains that the biochar functionalization increases production and final costs and reduces environmental compatibility. Even so, the increased adsorption efficiency decreases the volume of sorbent needed per treatment cycle, ultimately lowering net treatment costs [301,305,306]. Also, biochar can reduce operating costs and increase overall dye removal efficiency when used in hybrid treatment systems, like in conjunction with membrane filtration or biological treatment.

Table 8 illustrates the variability in biochar costs based on raw material feedstock and treatment conditions. Sludge-derived biochars, as the lowest-cost category (ranging from $0.56 – $1.00/kg), present a particularly appealing option for industrial wastewater treatment due to their dual function in waste mitigation and adsorbent generation. Conversely, tree branch- and virgin wood-based biochars are the most expensive, costing up to $11.00/kg and $17.80/kg, respectively, largely due to higher pyrolysis energy demands and the opportunity cost of the feedstock. Among modified biochars, HCl-magnetic and amine-magnetic biochars show a favorable cost-to-performance balance, costing $0.69/kg and $2.60/kg, respectively, while retaining significant dye adsorption augmentations. In contrast, Fe_3O_4 –MnO_2 magnetic biochar, although highly functionalized, is priced at $10.00/kg, which limits its economic appeal for routine use. These comparisons suggest that not all modifications yield proportional returns in adsorption performance and must be thoroughly analyzed through a cost-benefit lens.

Additionally, because magnetic modifications (such as FeO_4-MnO_2

Table 8
Comparative material costs: raw biochar *vs.* modified biochar *vs.* activated carbon.

Specific source-dependent material	Temp. (°C)	Price ($/kg)	Study
Oiltea camellia shell biochar	500	0.67	[308]
Water oak wood biochar	400	0.77	[309]
Coconut shell biochar	-	0.80	[310]
Chicken manure biochar	450	1.30	[301]
Switchgrass biochar	800	5.49	[309]
Tree branch biochar	-	11.00	[310]
Virgin wood feedstock biochar	-	17.80	[310]
Sludge derived biochar	400	0.70	[311]
Sludge derived biochar	550	0.90	[311]
Sludge derived biochar	700	1.00	[311]
Sludge derived biochar	-	0.56	[312]
HCl-magnetic biochar	550	0.69	[307]
Si-modified biochar	500	1.44	[308]
Amine- magnetic biochar	450	2.60	[301]
Fe_3O_4 –MnO_2 magnetic biochar	350	10.00	[313]
Commercial oxidized with **HNO_3** activated carbon	-	1.40	[310]
Coconut shell activated carbon	-	1.50 – 3.00	[310]
Granular activated carbon	-	6.40	[310]
Chitosan activated carbon	-	15.40	[314]
Commercial activated carbon	-	21.00	[315]
Filtrasorb –400 activated carbon	-	20.00 – 22.00	[314]

composites) improve surface polarity and active site availability, they greatly improve the removal of both cationic and anionic dyes. Nonetheless, these improvements are less practical for large-scale or low-resource applications because they are frequently outweighed by the high costs of reagents and synthesis steps. On the other hand, when focusing on particular dye types like azo or anthraquinone dyes, simpler modifications like HCl treatment or amination frequently result in significant performance gains at significantly lower costs. The physicochemical characteristics of the dyes (*e.g.,* molecular weight, charge, and hydrophobicity), the surface chemistry and porosity of the modified biochar, and the operating conditions (*e.g.,* pH, temperature, and ionic strength) under which adsorption has been tested are the three main factors that frequently interact to cause discrepancies between studies. For example, because of their improved hydrogen bonding and electrostatic attraction, aminated biochars are generally better at eliminating acidic or reactive dyes than other types. However, this same modification might not work as well for non-polar dye structures or in settings with high ionic competition. Furthermore, dual modifications—such as combining magnetic particles with acid or amine groups—introduce synergistic effects that enhance both kinetics and selectivity, which is why some biochars show strong adsorption. Such strategies, however, could make regeneration more difficult and increase the chance of long-term modifier leaching, which would lessen the sustainability of the environment. The choice of modifier should therefore be closely linked to the particular application and wastewater context, even though surface modification is typically advantageous. To maintain economic and environmental viability, the trade-off between cost and performance gain must be systematically evaluated, particularly in environments with limited resources. To increase cross-study reliability and industrial relevance, future comparative studies should use standardized testing conditions and report performance per cycle or per unit cost.

In contrast, activated carbon variants show even greater variability. Common options like coconut shell activated carbon cost between $1.50 – $3.00/kg, but more specialized versions like Filtrasorb –400 and chitosan-activated carbon reach $20.00 – $22.00/kg and $15.40/kg, respectively. The cost gap between biochar and activated carbon strengthens the case for biochar as a scalable and affordable solution, especially in developing regions with limited wastewater treatment budgets. Also, this biochar cost advantage is even more pronounced when it is sourced from waste streams, which would otherwise incur disposal costs. Moreover, the presented cost ranges are not merely academic; they translate into tangible operational differences in treatment systems. For instance, biochars with moderate functionalization, such as HCl-modified variants, offer excellent adsorption performance at a fraction of the activated carbon cost [307]. Although some modified biochars, like those functionalized with Fe_3O_4 –MnO_2 nanoparticles, are more expensive, their high adsorption capacity can offset the initial expense by decreasing the quantity of material needed per treatment cycle and enabling potential reuse [307].

Nevertheless, it is still critical to develop a methodology for evaluating the efficacy of biochar surface modification, considering both modification cost and efficiency, which would consequently impact the cost of large-scale application. Accordingly, rather than relying on a circular economy narrative alone, the economic case for biochars should focus on affordability, scalability, and industrial compatibility—factors that are crucial for their transition from lab-scale innovation to commercial wastewater treatment solutions. For instance, despite the encouraging findings regarding biochar for dye adsorption, scalability remains challenged by factors such as clogging, regeneration inefficiency, and the complexity of real-world wastewater matrices. Also, the higher costs of modified biochars need to be addressed for them to become cornerstone materials in sustainable wastewater treatment at various scales. This is especially important in dye-intensive sectors such as textiles and paper manufacturing. Ultimately, to deliver high performance at low cost within a circular production framework, the economic viability of biochar must be improved.

7. Prospects for biochar in dye remediation and beyond

The scalability and reliability of biochar for dye removal are still constrained by a number of unaddressed questions, despite significant progress. One key gap is the lack of mechanistic data under complex matrices, like dye removal in the presence of competing ions, surfactants, or organic co-contaminants at scale. Although important factors like pH sensitivity, surface area influence, and isotherm behavior have been clarified by batch experiments, real-world scenarios remain underexplored. The regeneration and repurposing of dye-laden biochar is another pressing issue. Existing methods, such as solvent extraction and thermal reactivation, are energy-intensive (typically, > 400 °C) or depend on toxic solvents, which may compromise sustainability [316, 317]. New low-temperature techniques such as microwave-assisted regeneration (typically, < 150 °C) or ultrasound-based desorption shows potential for retaining structural integrity while reducing energy consumption.

Lifecycle modeling and cost prediction of biochar further depend on understanding how > 5 reuse cycles affect sorption efficiency and dye stability [29,44,117,143]. Although biochar is often labeled “eco-beneficial”, limited studies have quantified net GHG emissions or ecotoxicological risks across its entire lifecycle, such as the source of feedstock, carbonization, and post-adsorption disposal. Similarly, which is another critical concern, the environmental fate of dye-laden biochar during reuse or disposal remains poorly understood. The risk of dyes desorbing or the generation of hazardous metabolites under different environmental conditions is still not well recognized, even though construction integration, land application, and soil conditioning are suggested dye-laden biochar reuse paths. This can lead to re-pollution of water or soil, negating the advantages of the original adsorption process. Hence, to ensure ecological safety, studies assessing the long-term behavior of dye-saturated biochar in soil and aquatic environments, particularly concerning its interactions with microbes, organic matter, and heavy metals, will be essential. This means that advanced modeling and empirical studies incorporating lifecycle analyses will be vital for validating the overall use of biochar for dye removal as an environmentally sound solution.

Also, the development of advanced composites—by integrating carbonaceous matrix with nanomaterials, metal oxides, clays, or polymers—has demonstrated promise in terms of increasing dye selectivity, adsorption rate, mechanical strength, and ease of recovery by overcoming adsorption limitations, thereby creating avenues for long-term reuse and field deployment [16,318,319]. For example, hybrid biochar composites integrating graphene oxide, TiO_2, Fe_3O_4, montmorillonite, or biopolymers (such as chitosan) have shown enhancements in dye selectivity, adsorption kinetics, and recyclability. These materials, however, need to be assessed for environmental compatibility and economic viability in addition to performance. Rigorous eco-safety assessments of these innovations are especially necessary if the dye-bound biochar is intended for agricultural reuse or landfilling.

In addition to lifecycle assessments, there are limited techno-economic evaluations tailored to dye removal applications. Although the eco-revenue and general cost of biochar have been outlined earlier, benchmarking cost-per-m^3 dye-treated against commercial alternatives such as activated carbon across different feedstocks and operational scales is necessary to inform decision-making and policy frameworks. Furthermore, several strategic directions merit attention in order to scale biochar-based dye removal systems beyond experimental or niche contexts. Firstly, it is essential to develop biochar functionalization methods that are not only eco-conscious but also cost-effective and scalable. As highlighted earlier, current methods for biochar surface modification often rely on corrosive agents or energy-intensive processes that consequently negate the environment and raise the cost of materials. Similar to the case with dye-laden biochar, utilization of these chemical agents is one of many factors that pose strong barriers to the commercial adoption of functionalized biochar for dye removal due to risks of desorption of chemicals under environmental stress [237,268]. The functionalization process based on enzymes, plant-based and agricultural extracts, bio-based acids, or plasma activation is a clear example of green chemistry alternatives that can enhance adsorption without significantly increasing costs or environmental burdens [235,320]. Secondly, protocols for adsorbent regeneration and reuse need to be revisited and optimized to become more suitable for real-world use cycles and energy-efficient. Although thermal regeneration is common, there is a chance that it will degrade the less thermally stable biochar matrix, increase carbon emissions, and release contaminants that have already been absorbed [118,320]. Also, it may not be economically viable for low-income regions. Promising avenues include non-thermal regeneration strategies like electrochemical regeneration and pH-switch desorption, which minimize structural damage and chemical demands [35,302]. Thirdly, feedstock valorization offers a significant chance to reduce expenses and expand supply chains [321,322]. Using invasive plants, food wastes, or tannery sludge can decrease raw material costs and foster localized circular economies. It is possible to mitigate disposal costs and generate new value streams by diverting currently underutilized or novel biomass resources, such as textile sludge, invasive plant species, hybrid organic wastes, food processing wastes, or even tannery waste, into dye-specific biochar production streams. Co-locating the production of biochar with industrial zones could decentralize and de-risk operations in various regions that have significant dye wastewater burdens, particularly because of their large textile industries [235,323]. This establishment of regional pyrolysis units that source from local biomass can help build a circular micro-economy centered around biochar, reducing both production and transportation costs. Finally, policy alignment and certification systems are anticipated to play a pivotal role. If biochar is to compete with conventional adsorbents, especially in industrial wastewater treatment, the subsidies, carbon credits, and water quality incentives could tip the scale in favor of biochar adoption. Of particular note, inconsistent biochar quality standards and a lack of knowledge about how biochar behaves in diverse operational and environmental settings are also factors that prevent the long-term feasibility or commercial adoption of biochar systems for real-world wastewater remediation [44,259,268].

Adoption of biochar quality certification framework (such as International Biochar Initiative (IBI) or European Biochar Certificate (EBC) standards) and performance validation under ISO-like protocols can enhance investor confidence and guarantee regulatory compliance. Therefore, regulatory standardization in testing and product quality, as well as performance benchmarking, could further encourage commercial trust and investment. Similarly, biochar integration into national waste-to-resource strategies and climate action plans could improve investment and foster market maturity. When taken as a whole, these strategic directions make clear the path for future studies: *i.e.,* closing the gap between lab performance and field dependability, enhancing environmental protections, and creating biochar systems tailored for specific dye classes and industrial settings. With these targeted advancements, biochar can transform from a promising lab material into a robust and eco-feasible solution for dye-saturated wastewater treatment.

Recently, ML and artificial intelligence (AI) have emerged as transformative tools in adsorption science, allowing predictive modeling, mechanism elucidation, and process optimization. Employed for biochar-based dye removal, ML models, including decision trees, RF, SVM, and ANN, can precisely predict adsorption capacity, equilibrium time, and removal efficiency based on various factors such as dye structure, biochar surface chemistry, operational conditions, and environmental parameters. These data-driven models could largely decrease experimental workloads by identifying optimal conditions across wide parameter spaces and anticipating system performance in complex industrial matrices. Furthermore, hybrid approaches that couple ML with mechanistic models (for example, kinetic or isotherm models) can offer deeper insights into adsorption routes. For example, ML frameworks could predict the impact of competitive ions, pH fluctuations, or dye mixtures, which are scenarios that are typically experimentally expensive and time-consuming. The development of harmonized adsorption datasets, model transparency, as well as integration of ML into lifecycle and techno-economic assessments, should be the focus of the future research. Integrating such tools would not only accelerate discovery but could also support the scalability and tailoring of biochar systems for diverse practical wastewater contexts. A brief bibliometric analysis has been included in the following section to support this trajectory by identifying existing research gaps and highlighting promising directions for future research.

7.1. *Bibliometric analysis*

Bibliometrics studies have increasingly been used to trace research trends through the analysis of bibliographic and citation output of research published on a subject matter [324]. Bibliometric techniques allow connections to be made through citations as links that point one publication to another [325]. A very key aspect of bibliometrics is to explore the growth of a particular research area [326]. As such, this bibliometric study will present a podium to explore the evolution and growth of the use of biochar in dye remediation from waters. The bibliometrics analysis will be guided by the following objectives:

- Examine the trends and patterns of research on dye removal using biochar, *via* related bibliometric indicators such as:

  i. publication output count,
  ii. citedness,
  iii. authorship,
  iv. keyword analysis,
  v. journal analysis.

- Determine the relationship among authors, funders, and affiliation.
- Examine the influence of research output in terms of collaboration.

Insights on global research around dye removal using biochar were obtained through the utilisation of Elsevier's SciVal analytical tool,

which relies on Scopus, one of the world's largest databases, for obtaining bibliographic and citation data. The use of these tools is evident in cutting-edge academic research on bibliometric studies [327]. In order to capture the current research trends and identify existing research gaps, relevant data were extracted, subject to specific inclusion and exclusion criteria and query strings. As the topic of dye removal using biochar is a growing phenomenon, it is classified as a rapidly evolving research area, which poses a challenge regarding the time frame of articles considered in the bibliometric analysis. Thus, the study focused on publications released over a period covering the last decade, *i.e.,* between 2015 and 2025. In terms of article type, the inclusion criteria incorporated peer-reviewed articles, review papers, conference papers, and book chapter publications, as in the science domain, these are regarded as key sources, especially conference papers.

A simple search on Scopus using the keywords "biochar" and "adsorption" returned 130,153 documents, indicating that there is extensive research currently being undertaken. Upon further refinement of the search syntax to capture studies focusing on "nano biochar", the search returned 1049 documents. Also, a search syntax to capture studies that focused on the life cycle assessment of biochar adsorbents returned 1056 documents. These simple searches revealed that there is extensive research on the general topic of adsorption using biochar; however, other aspects, such as nano biochar, life cycle assessment, and cost-benefit analysis, lack sufficient research attention. For an in-depth analysis, the exclusion criteria were applied using Boolean operators such that studies irrelevant to this review paper were eliminated, *e.g.,* the adsorption of heavy metals using biochar. Specifically, documents focusing on notes, conference reviews, letters, and editorial were excluded. Consequently, the query strings were composed of the following multi-faceted search strategy, which was built with precision through testing it against independent sets of known relevant papers, thus validating the exercise:

{"biochar" AND "adsorption" AND "mechanism" AND NOT "Cu" AND NOT "copper" AND NOT "Ni" AND NOT "nickel" AND NOT "Cd" AND NOT "cadmium" AND NOT "Mg" AND NOT "magnesium" AND NOT "Pd" AND NOT "lead" AND NOT "Hg" AND NOT "mercury" AND NOT "Ar" AND NOT "arsenic" AND NOT "Cr" AND NOT "chromium" AND NOT "Zn" AND NOT "zinc" AND NOT "Mn" AND NOT "manganese" AND NOT "Al" AND NOT "aluminium" AND NOT "Fe" AND NOT "iron" AND NOT "Co" AND NOT "cobalt"}

Upon obtaining relevant articles through the aforementioned search query string, the search query syntax was enhanced to focus on publications attained between 2015 and 2025, as well as limiting the focus documents to English documents only by eliminating any other language. As such, the final search query string read as follows:

"biochar" AND "adsorption" AND "mechanism" AND NOT "Cu" AND NOT "copper" AND NOT "Ni" AND NOT "nickel" AND NOT "Cd" AND NOT "cadmium" AND NOT "Mg" AND NOT "magnesium" AND NOT "Pd" AND NOT "lead" AND NOT "Hg" AND NOT "mercury" AND NOT "Ar" AND NOT "arsenic" AND NOT "Cr" AND NOT "chromium" AND NOT "Zn" AND NOT "zinc" AND NOT "Mn" AND NOT "manganese" AND NOT "Al" AND NOT "aluminium" AND NOT "Fe" AND NOT "iron" AND NOT "Co" AND NOT "cobalt" AND PUBYEAR > 2015 AND PUBYEAR < 2026 AND (EXCLUDE (DOCTYPE,"no") OR EXCLUDE (DOCTYPE,"cr") OR EXCLUDE (DOCTYPE,"le") OR EXCLUDE (DOCTYPE,"ed")) AND (LIMIT-TO (PUBYEAR,2015) OR LIMIT-TO (PUBYEAR,2016) OR LIMIT-TO (PUBYEAR,2017) OR LIMIT-TO (PUBYEAR,2018) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO (PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2021) OR LIMIT-TO (PUBYEAR,2022) OR LIMIT-TO (PUBYEAR,2023) OR LIMIT-TO (PUBYEAR,2024) OR LIMIT-TO (PUBYEAR,2025)) AND (EXCLUDE (LANGUAGE,"Chinese") OR EXCLUDE (LANGUAGE,"Russian") OR EXCLUDE (LANGUAGE,"French") OR EXCLUDE (LANGUAGE,"Persian"))

The bibliometric workflow followed a PRISMA-style approach in order to ensure transparency and reproducibility. After initial search queries were conducted in Scopus *via* SciVal, 1352 records were identified. Duplicates (n = 121) and non-English publications (n = 79) were removed. Subsequently, inclusion criteria (peer-reviewed articles, reviews, conference papers, and book chapters published from 2015 to 2025 on dye removal using biochar) and exclusion criteria (studies on heavy metals, letters, notes, editorials, and unrelated adsorption studies) were applied, resulting in a final set of 697 records. Furthermore, the aforementioned search string returned 697 research publications. The smaller number of publications strongly supports the claims made herein. The bibliometrics analysis was comprised of a collection of 697 documents, which were composed of 633 (90.8 %) articles, 38 (5.5 %) conference papers, 13 (1.9 %) review papers, 11 (1.6 %) book chapters, and 2 (0.3 %) books. The analysis revealed that research on dye removal using biochar gained traction in 2015, with a steady increase in research attention as shown in Fig. 10. It is interesting to note that at the time of conducting the present study (May 2025), the research output for the current year had already attained 56 documents (8 %), doubling the amount attained in the whole year of 2015.

Fig. 11 presents some insights on citation and publication count, aiding the investigation to make a connection between the two. In this analysis, the researchers purposely adjusted the period to 2010 to May 2025 in order to reveal and buttress the view that research on dye removal using biochar commenced around the year 2015. It is clear that there is no evidence of prior publications indexed by Scopus. The 697 documents attained an overall total of 17,014 citations, giving an average of 24 citations per document. In correspondence with the publication trend, the citation analysis pictures a sharp increase in citations from 2015 to 2024, as shown in Fig. 11.

The study further examined the most influential publications amongst the 697 documents, in terms of the top 20 cited publications. These were analysed over 18 days to trace the general growth and influence the publications have, as well as to pick up, in real time, publications that continue to influence research trends. It is worth noting that the initial search had revealed 689 documents, and the final search, 18 days later (22 May 2025), revealed a total of 697 documents. Thus, the 8 additional documents over the search period depict continued growth and influence of research on the adsorption of dyes using biochars. The colour code green was used to depict the positive changes in terms of the number of citations over the 18-day period, while those articles whose citations remained unchanged also maintained the colour code, as shown in Table 9. Furthermore, Table 9 reveals that the top-cited article attracted a total of 557 citations. The publication recorded an increase of 10 citations during the analysis period. The high citations could be attributed to the nature of the paper, being a review paper, thus informing a wider range of scholars investigating this phenomenon. Additionally, the top-cited article was published in the *Science of the Total Environment* journal, which has a CiteScore of 17.6 and an Impact Factor of 8.2 and has been captured on Mendeley 1004 times. Thus, while the article has received 557 citations, its effect likely extends to at least 447 additional scholars who may have engaged with the work without yet publishing or formally citing it. An article metrics analysis reveals that the paper possesses 3 Policy Citations as depicted in Fig. 12. Additionally, the article goes beyond academic impact to attain high levels of societal impact through influencing the three policies made by UNESCO, the Government Publishing Office, and the National Renewable Energy Laboratory. As such, its influence on dye removal using biochar is realised.

In relation to the journals captured in Table 9 against their corresponding top-cited articles, it was imperative that the present study further look into journals that contributed to the highest-cited articles. Overall, the top 20 journals that have contributed to the 697 publications are depicted in Table 10. While the *Science of the Total Environment* hosts the highest cited article and has 12 out of the 697 publications, the analysis revealed that the Chemosphere journal has the highest number of documents, being 27 out of the 697 publications, followed by the

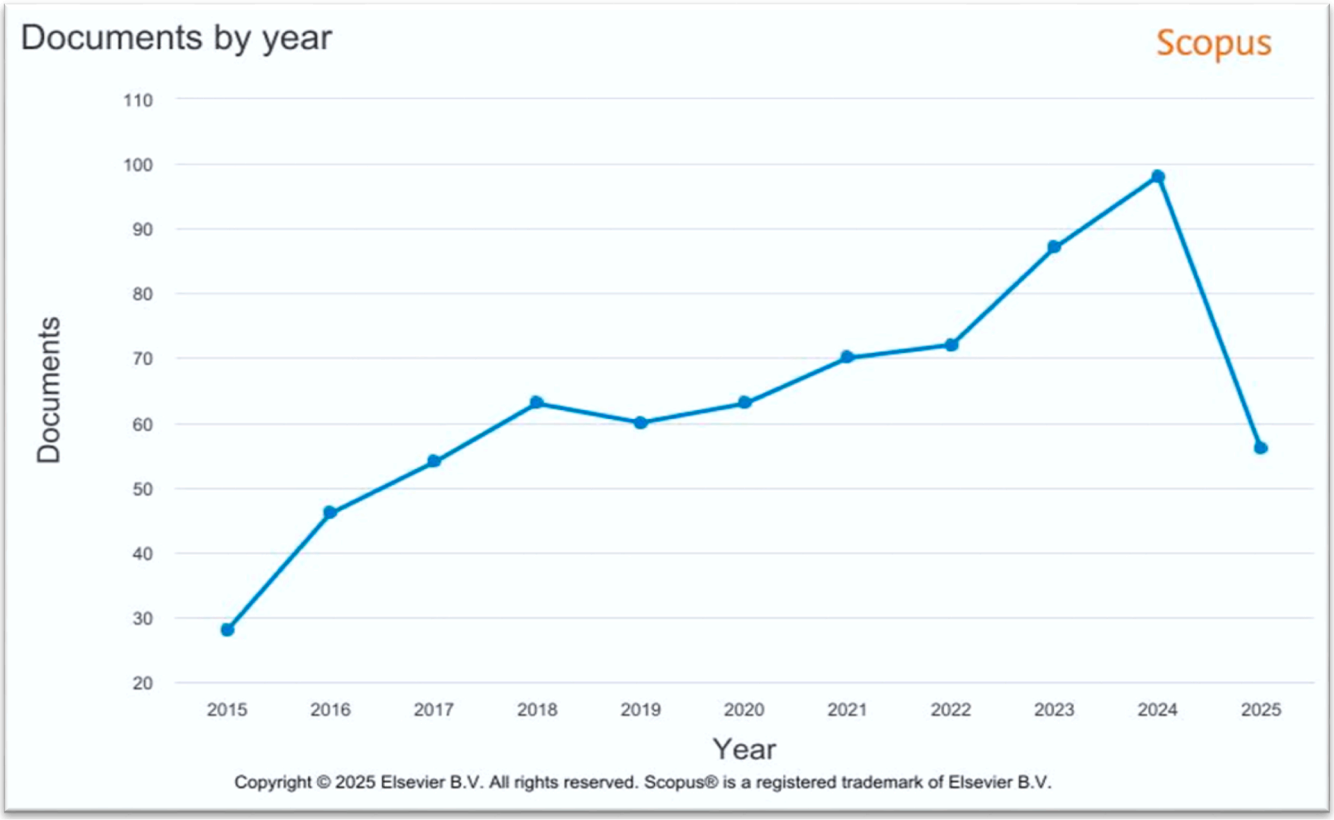

Fig. 10. Number of publications for the period 2015 to May 2025 (Source: Research Data).

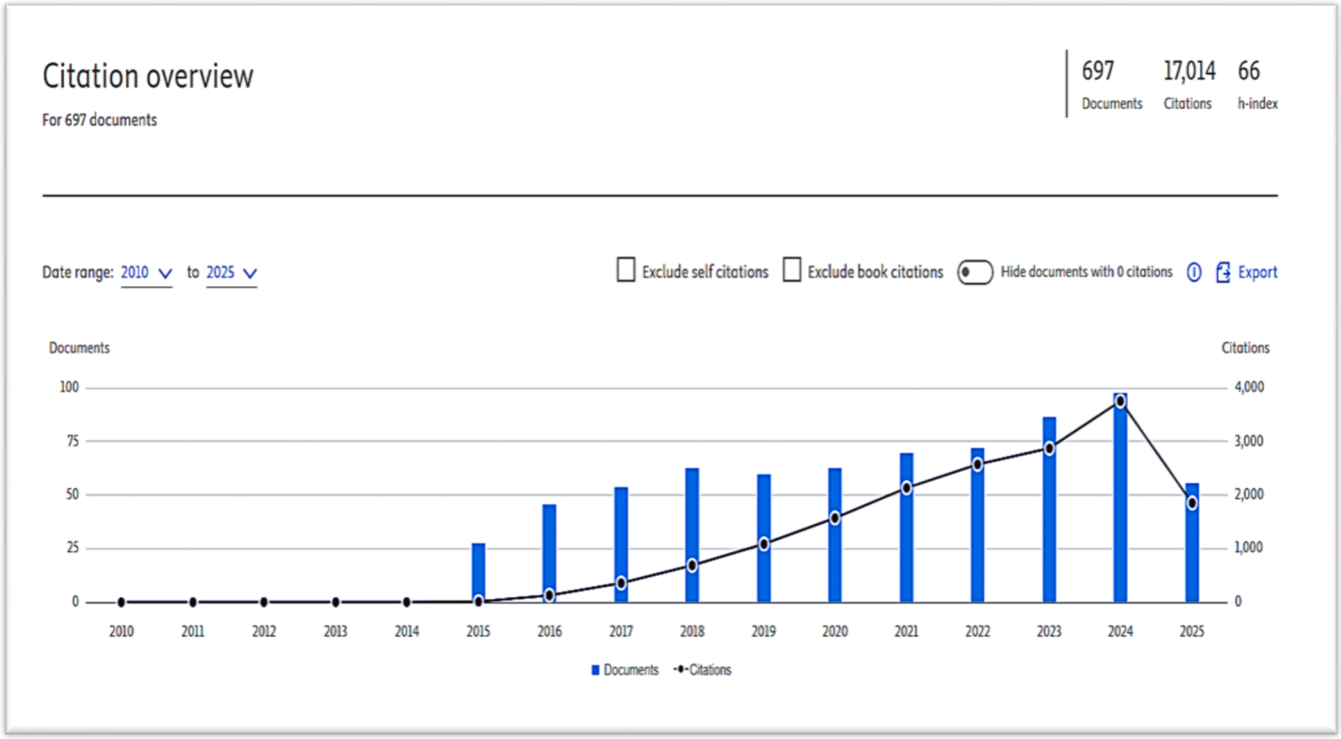

Fig. 11. Number of publications and their citations for the period 2010 to May 2025 (Source: Research Data).

Table 9
Top 20 highest-cited documents extracted from a set of 697 documents observed from 4 May 2025–22 May 2025.

Rank	Pub Year	Document Title	Journal Title	Citations 04/05/25	Citations 22/05/25
1	2021	Treatment technologies for emerging contaminants in wastewater treatment plants: A review	Science of the Total Environment	547	557
2	2017	Bacterial wilt in China: History, current status, and future perspectives	Frontiers in Plant Science	282	284
3	2016	Adsorption of Antibiotics on Graphene and Biochar in Aqueous Solutions Induced by $\pi-\pi$ Interactions	Scientific Reports	280	284
4	2017	Viruses in Soil Ecosystems: An Unknown Quantity Within an Unexplored Territory	Annual Review of Virology	281	282
5	2015	Adsorption and desorption of ammonium by maple wood biochar as a function of oxidation and pH	Chemosphere	250	251
6	2016	Hierarchical Carbon Nanotubes with a Thick Microporous Wall and Inner Channel as Efficient Scaffolds for Lithium-Sulfur Batteries	Advanced Functional Materials	187	187
7	2015	Anion exchange capacity of biochar	Green Chemistry	179	182
8	2017	Bio- and hydrochars from rice straw and pig manure: Inter-comparison	Bioresource Technology	172	172
9	2016	New evidence for high sorption capacity of hydrochar for hydrophobic organic pollutants	Environmental Science and Technology	171	171
10	2018	Porous PVdF/GO Nanofibrous Membranes for Selective Separation and Recycling of Charged Organic Dyes from Water	Environmental Science and Technology	166	168
11	2017	Effects of pyrolysis temperature and residence time on physicochemical properties of different biochar types	Acta Agriculturae Scandinavica Section B: Soil and Plant Science	159	166
12	2015	Biochar characteristics relate to its utility as an alternative soil inoculum carrier to peat and vermiculite	Soil Biology and Biochemistry	160	161
13	2019	Transfer of PCBs from Microplastics under Simulated Gut Fluid Conditions Is Biphasic and Reversible	Environmental Science and Technology	149	149
14	2017	Improved antioxidant activity and physicochemical properties of curcumin by adding ovalbumin and its structural characterization	Food Hydrocolloids	143	144
15	2019	Adsorption of selected organic micro-pollutants on sewage sludge biochar	Chemosphere	140	141
16	2018	Sorption of hydrophobic organic contaminants on functionalized biochar: Protagonist role of Î -Î electron-donor-acceptor interactions and hydrogen bonds	Journal of Hazardous Materials	134	138
17	2020	Biochar phosphorus fertilizer effects on soil phosphorus availability	Chemosphere	137	137
18	2018	Pesticide fate in soil-sediment-water environment in relation to contamination preventing actions	Current Opinion in Environmental Science and Health	136	138
19	2017	Shift in Mass Transfer of Wastewater Contaminants from Microplastics in the Presence of Dissolved Substances	Environmental Science and Technology	135	136
20	2015	Adsorptive removal of pharmaceuticals from water by commercial and waste-based carbons	Journal of Environmental Management	135	135

Bioresource Technology journal with 17 publications.

7.2. Funding, subject area, and country analysis

A focused bibliometric overview was conducted to identify key funding sources, research themes, and national contributions driving the

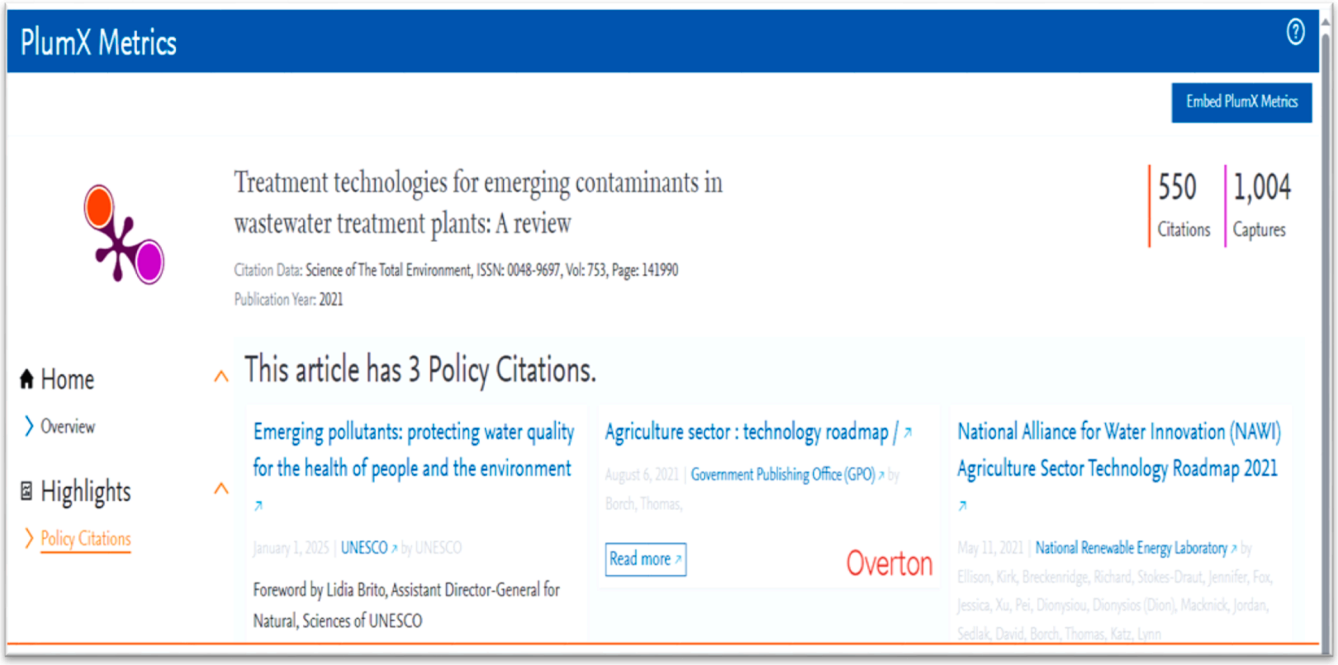

Fig. 12. Policy citations for the top-cited article (Source: PlumX Metrics).

Table 10
Top 20 journals in which dye removal using biochar research was published in, 2015–2025 (Source: Research Data).

Rank	Journal	Publication count	Proportion (%)
1	Chemosphere	27	3.9
2	Bioresource Technology	17	2.4
3	Environmental Science and Pollution Research	16	2.3
4	Environmental Science and Technology	16	2.3
5	Journal of Environmental Management	16	2.3
6	Environmental Pollution	13	1.9
7	Science of the Total Environment	12	1.7
8	Journal of Hazardous Materials	11	1.6
9	Bioresources	8	1.1
10	Environmental Science Processes and Impacts	8	1.1
11	IOP Conference Series Earth and Environmental Science	8	1.1
12	Energy and Fuels	7	1.0
13	Journal of Analytical and Applied Pyrolysis	7	1.0
14	Scientific Reports	7	1.0
15	Water Air & Soil Pollution	7	1.0
16	Desalination and Water Treatment	6	0.9
17	Fuel	6	0.9
18	Journal of Water Process Engineering	6	0.9
19	Biomass and Bioenergy	5	0.7
20	Chemical Engineering Journal	5	0.7

field of synthetic dye removal using biochar. The findings (*see* Supplementary Table S1) reveal that China overwhelmingly dominates this research landscape, with the National Natural Science Foundation of China and the Ministry of Science and Technology collectively funding over 300 publications. This reflects a strong national commitment to environmental innovation and research funding coordination. In terms of subject area (Supplementary Figure S1), Environmental Science leads with 25.4 % of the research output, followed by Chemistry (12.7 %) and Chemical Engineering (10.7 %). These areas underpin the material science, reactivity, and application efficacy of biochar in dye removal. Country-level contributions (Supplementary Figure S2) mirror the funding trends, with China contributing over 300 publications, more than triple the USA, the next-highest contributor. Other countries, including India, Iran, and several European nations, show modest output, each contributing fewer than 30 articles. This disparity emphasizes China's leading role in shaping global research on biochar for water remediation.

7.3. Insights and implications

The funding analysis highlights China's dominance in this area. The *National Natural Science Foundation of China* alone funded 187 studies, while the *Ministry of Science and Technology* sponsored another 121. This investment correlates with China's leading output—309 publications—far ahead of the second-highest contributor, the USA, with just 90. This demonstrates China's strategic focus on environmental innovation. In terms of subject areas, *Environmental Science* is the most heavily researched field (25.4 % of publications), followed by *Chemistry* (12.7 %) and *Chemical Engineering* (10.7 %). These areas are essential because they underpin the development and testing of biochar materials, their chemical properties, and their applications in wastewater treatment. The alignment between funding priorities, research focus, and national leadership in output suggests a coordinated and well-funded research ecosystem—especially within China—that is driving the global advancement of sustainable dye removal technologies.

Biochar-based dye removal has clear cost advantages in terms of economic viability. While similar commercial activated carbons often cost 5–10 times more, recent studies have reported operating costs ranging from *ca.* $0.05 to *ca.* $0.50 per gram of biochar, depending on feedstock and activation method [328,329]. Moreover, biochar can be made from agricultural waste, which lowers disposal costs and supports regional economies. According to a basic cost-benefit analysis, biochar-based systems have the potential to save up to 70 % on dye removal treatment costs, particularly in small-scale or decentralized wastewater treatment facilities [330,331]. These figures highlight the value of biochar as an affordable, scalable alternative with economic implications for municipal water systems as well as industry. Apart from economic feasibility, the implications of the findings from the

bibliometric study on dye removal using biochar can be divided into academic, policy, and strategic dimensions. High-impact review papers play a crucial role in shaping scholarly understanding and guiding future research. The fact that the top-cited article is a review suggests a demand for comprehensive, synthesized knowledge in this field. The concentration of publications in a few high-impact journals highlights the importance of targeting specific journals for visibility and scholarly engagement. The dominance of certain journals indicates where academic training, curriculum development, and postgraduate research can be focused to meet growing interest in sustainable water treatment solutions. The presence of policy citations confirms that research in this area is informing real-world decision-making, notably by institutions such as UNESCO and the U.S. Government Publishing Office. This underscores the societal relevance of academic work on biochar and its potential to influence environmental policy. With water pollution and textile dye contamination being critical issues in developing nations, findings suggest that encouraging the uptake of such research into local environmental regulations could lead to more sustainable waste management practices.

The overwhelming contribution from China, both in publications and funding, shows a clear strategic prioritization of green technologies and environmental research that China is taking. This could position China as a global leader in low-cost, sustainable wastewater treatment innovations. The relatively lower contribution from other countries suggests potential research gaps or underinvestment in this area elsewhere. Developing nations, in particular, could benefit from investing more in this research, especially given the affordability and accessibility of biochar-based solutions. The analysis helps stakeholders identify key funding agencies (*e.g.,* National Natural Science Foundation of China) and active journals, offering direction for researchers seeking collaborations, funding, or dissemination channels. Overall, the findings reveal a vibrant and policy-relevant field with uneven global participation, highlighting opportunities for expanded international collaboration, capacity building, and integration of research into environmental policies.

8. Conclusion

Biochar presents a compelling alternative to traditional adsorbents for dye-contaminated wastewater due to its sustainable production, tunable properties, and broad applicability. Its adsorption effectiveness depends on factors such as feedstock selection, pyrolysis conditions, and surface functionalization, which govern key mechanisms including electrostatic interactions, hydrogen bonding, and $\pi-\pi$ stacking. These physicochemical interactions enable biochar to remove diverse dye types under varied wastewater conditions. Isotherm and kinetic models have provided further insights into equilibrium behavior and rate-limiting steps, supporting better process design and optimization. The findings highlight that although many studies demonstrate promising results at the lab scale, the challenges such as real wastewater complexity, regeneration efficiency, and long-term stability, remain barriers to full-scale application. Moreover, bibliometric insights reveal research gaps in lifecycle management, post-adsorption valorization, and regulatory frameworks. Recent work suggests that dye-laden biochar can be incorporated into circular economy strategies, including carbon sequestration, construction materials, and soil amendment, if eco-safety and environmental stability are ensured. Looking forward, research should focus on the development of low-cost feedstocks, standardized testing, and the integration of biochar systems into existing wastewater infrastructure. Progress in these areas could help transition biochar from a lab solution to a scalable, circular technology for industrial dye removal and beyond.

Declaration of Competing Interest

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

Acknowledgements

The National Research Foundation (NRF) is acknowledged for financial support. We acknowledge the funding received from the National Research Foundation.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nxmate.2025.100974.

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