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Review

Engineering Constructed Wetland Biomass into Multifunctional Biochar Composites for Circular Water Remediation

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ABSTRACT: Constructed wetlands produce large amounts of lignocellulosic biomass due to harvesting operations, which are conventionally considered as waste. Such biomass, which is characterized by a high content of cellulose, hemicellulose, and lignin, is a renewable source of carbon material for engineered biochar production. Recent developments in thermochemical conversion processes (slow pyrolysis, hydrothermal carbonization, activation), surface functionalization (doping with heteroatoms, magnetization, composite formation), and carbon architecture engineering have made it possible to turn pure biochar into a highly efficient adsorbent that can remove both cationic and anionic dyes from industrial textile wastewater. This review adopts a feedstock-engineering-structure-performance-sustainability perspective, correlating biomass composition, conversion processes, surface chemistry, adsorption phenomena, and performance in wastewater. Reported adsorption capacities vary considerably with biomass origin, thermochemical processing, surface modification, dye characteristics, and experimental conditions. Although several engineered biochars have demonstrated promising adsorption and reuse behaviour under laboratory conditions, the available evidence remains insufficient to establish their general performance in real industrial wastewater treatment. Further research involving authentic constructed-wetland biomass, standardized adsorption protocols, long-term regeneration, contaminant-leaching assessments, and pilot-scale validation is required. Feedstock-specific life-cycle and techno-economic assessments will also be essential to determine the environmental and economic feasibility of these materials within circular water-remediation systems. Amongst the emerging possibilities are the artificial intelligence (AI)-assisted search for new materials, pilot scale continuous flow demonstrations, and the use of International Organization for Standardization (ISO) protocols for life cycle and techno-economic analysis. The convergence of materials science, environmental engineering, and sustainability policy makes engineered biochar from constructed wetland biomass a promising candidate as the foundation of a circular water treatment strategy for dye-contaminated wastewater. Literature was collected from major scientific databases including Scopus, Web of Science, and ScienceDirect, focusing on publications related to constructed wetland biomass-derived biochar for water remediation.

Keywords: Constructed wetland biomass; Engineered biochar; Macrophytes; Dye adsorption; Surface modification; Wastewater remediation; Circular economy

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1. Introduction

Unprecedented discharges of dyes have occurred due to the rapid growth of industrialization on a global scale, particularly in the textile industry, leather processing, paper production, pharmaceuticals, cosmetics, food processing, and commercial printing. Over 700,000 tonnes of dyes are produced annually, and about 10–20% (~140,000 tonnes) is lost into the effluents as a result of dye synthesis, dyeing, and finishing operations [1–3]. Dyes are extremely color-forming even at very low concentrations of <1 $mg \cdot L^{-1}$, decrease light transmission, and destroy aquatic ecosystem functioning [4,5]. Their toxic effects include mutagenic activity, carcinogenic effects, hormonal disturbances, as well as the ability to produce carcinogenic aromatic amines in anaerobic environments, which are significantly more dangerous than the initial compound itself [6–8].

Effluents from the textile industry are quite complicated in terms of their composition and contain salts (NaCl, Na_2SO_4 up to 100 $g \cdot L^{-1}$), surfactants, metals (Cr, Cu, Zn), chelating agents [9,10], and high chemical oxygen demand (COD >2000–10,000 $mg \cdot L^{-1}$) [11,12]. The multi-component nature of such effluents makes the adsorption process quite competitive and seriously complicates the operation of traditional treatment systems. Existing remediation techniques (biological, chemical, and physical) have their own operational limitations. As summarized in Table 1, Biological treatment processes such as activated sludge and anaerobic digestion are slow and incomplete, chemical oxidation processes such as advanced oxidation processes (AOPs) are efficient but expensive, physical processes such as nanofiltration (NF), reverse osmosis (RO), and ultra-filtration (UF) produce dangerous streams of concentrate, while coagulation/flocculation results in enormous amounts of sludge that needs to be disposed of.

Table 1. Conventional dye wastewater treatment technologies and limitations.

Category	Technology	Mechanism	Limitations	Source
Biological	Activated sludge, anaerobic digestion	Microbial breakdown	Slow kinetics, incomplete degradation	[13,14]
Chemical Oxidation	AOPs (Fenton, O_3/UV)	Hydroxyl radical oxidation	High cost, toxic intermediates	[15,16]
Physical Separation	NF, RO, UF	Size exclusion	Fouling, retentate disposal	[17,18]
Others	Coagulation/Flocculation	Charge neutralization	Sludge generation	[19,20]

Although AOPs have proven to be able to decolorize the solution to a high extent, the operational cost ($2.50–7.50 per cubic meter of treated water) and the amount of energy used limit their application alone [21]. Membrane separations produce the clean permeate but create the hazardous retentate streams, which form about 15–20% of the flow volume of the feed solution [22,23]. Under such conditions, adsorption seems to be the most effective, flexible, and economical approach to deal with the issue at hand. It provides high selectivity, straightforward operation, and possibilities of regeneration, decreasing the dye concentration from milligram per litre values down to sub-ppb levels with more than 99% decolorization efficiency [24–26]. As compared to oxidation or membrane technology, adsorption is immune to toxic shock loading, flexible towards batch or fixed bed operation, and devoid of secondary sludge formation [27,28].

The commercial activated carbon continues to be considered as the standard adsorbent material with a specific surface area of 800–1500 $m^2 \cdot g^{-1}$ and a capacity of adsorption between 200–600 $mg \cdot g^{-1}$ [29–31]. But fossil dependence, high manufacturing costs ($2.0–$4.5/kg), and losses of 5–10% in each regeneration cycle pose sustainability issues [32–34]. One solution is to use renewable lignocellulosic biomass, especially constructed wetlands, as feedstock for manufactured biochar [35–37]. A constructed wetland is an ecological system that uses synergies among macrophytes, soil, and microbial communities for wastewater treatment. Regular removal of macrophytes, including *Phragmites australis*, *Typha latifolia* and *Eichhornia crassipes* leads to removal of 20–60 tonnes of dry biomass/ha/year that is otherwise

discarded through land filling or burning, releasing greenhouse gases [38–40]. This biomass, consisting primarily of cellulose, hemicellulose, and lignin, is a potential source of carbon.

Pristine biochar extracted from these sources displays lower surface areas (<100 $m^2 \cdot g^{-1}$), lower pore volumes (<0.1 $cm^3 \cdot g^{-1}$), and negatively charged surfaces, which limit anionic dye adsorption [41–43]. To solve these limitations, carbon structure modification techniques are utilized. For instance carbon activation (steam, CO_2, KOH, $ZnCl_2$) creates hierarchical pores (500–1800 $m^2 \cdot g^{-1}$) [44–46], heteroatom doping (N, S, P, B) adjusts the charge distribution and π–π interactions [47,48], magnetic functionalization (Fe_3O_4, γ Fe_2O_3) facilitates quick magnetic separation in a few seconds [49] and composite engineering (LDHs, TiO_2, ZnO) creates positive charge centers and Lewis acid sites for the dual dye uptake process [50]. Through these processes, constructed wetland biomass is converted into a highly functional adsorbent that can absorb both cationic dyes such as Methylene Blue and Rhodamine B, and anionic dyes such as Congo red and Reactive Black 5.

Though substantial progress has been made, the current body of literature still suffers from fragmentation by limiting its scope to either synthesis techniques or single dye systems. Very few reviews provide systematic relationships between feedstock properties, thermal processing, surface modifications, adsorption principles, and sustainability considerations. This paper thus offers an integrated synthesis through the use of a Feedstock-Engineering-Structure-Performance-Sustainability approach, including feedstock types and conversion, surface functionalization and doping, magnetic and composite engineering, adsorption thermodynamics and kinetics, characterizations, regeneration and real-world wastewater treatment, sustainability considerations, and future prospects like AI-driven material development and pilot-scale studies.

Previous reviews have discussed biochar production, modification strategies, or dye adsorption separately. However, limited attention has been devoted specifically to constructed wetland biomass and its transformation into engineered biochar for circular water remediation. This review addresses that gap by integrating feedstock characteristics, thermochemical conversion, surface engineering, adsorption mechanisms, regeneration behaviour, real wastewater applications, and sustainability assessment within a unified feedstock-engineering-structure-performance-sustainability framework.

Literature Search Strategy

A structured literature search was undertaken using Web of Science, Scopus, ScienceDirect, and Google Scholar to identify studies on constructed-wetland biomass, aquatic macrophyte-derived biochar, biochar engineering, dye adsorption, regeneration, wastewater treatment, and sustainability assessment. The review primarily considered publications from 2010 to 2026. Search terms were combined using Boolean operators where appropriate. Studies were considered relevant when they addressed biomass conversion, material characterization, pollutant removal, adsorption mechanisms, regeneration, environmental safety, life-cycle assessment, or techno-economic performance. Research involving agricultural residues and other non-wetland feedstock were included for comparison where it helped explain material properties or adsorption mechanisms. Particular attention was given to distinguishing direct evidence from constructed-wetland biomass from findings obtained using other feedstock or adsorbent classes. The literature was critically assessed for experimental conditions, comparability of reported performance metrics, methodological limitations, and evidence of practical applicability.

2. Feedstock Characteristics and Thermochemical Conversion

The production of high-performance biochar from constructed wetlands starts with an appreciation of its inherent lignocellulosic structure. The collection of macrophytes like *Phragmites australis*, *Typha latifolia*, and *Eichhorni acrassipes* results in a yearly productivity range of 20–60 tonnes of dry weight per hectare; hence, a renewable non-food competing carbon feedstock [38–40]. The chemical constituents of this biomass

include cellulose (30–50%), hemicellulose (20–35%), and lignin (15–30%); each providing distinct contributions to the biochar creation process as illustrated in Figure 1 [51,52]. Cellulose contributes hydroxyl groups and crystallinity, while hemicellulose decomposes quickly to produce volatile materials and pores [53], and lignin, which is highly aromatic, gives rise to fixed carbon content and graphitic domains [54]. Inorganic materials like silica, calcium, and potassium that are concentrated during the process of phytoremediation are natural catalysts in the carbonization process and enhance pore formation [55,56].

Unlike conventional agricultural residues, constructed wetland macrophytes frequently accumulate metals, nutrients, pharmaceuticals, and other contaminants during wastewater treatment. Consequently, contaminants may become concentrated in the biochar ash fraction during pyrolysis. Although thermal conversion can immobilize certain contaminants, the environmental safety of wetland-derived biochar should be accessed through metal-speciation studies, standardized leaching tests, and long-term stability evaluations before large-scale deployment. Furthermore, managing regeneration effluents and ensuring environmentally sound disposal or reuse of spent biochar remain important considerations for large-scale implementation.

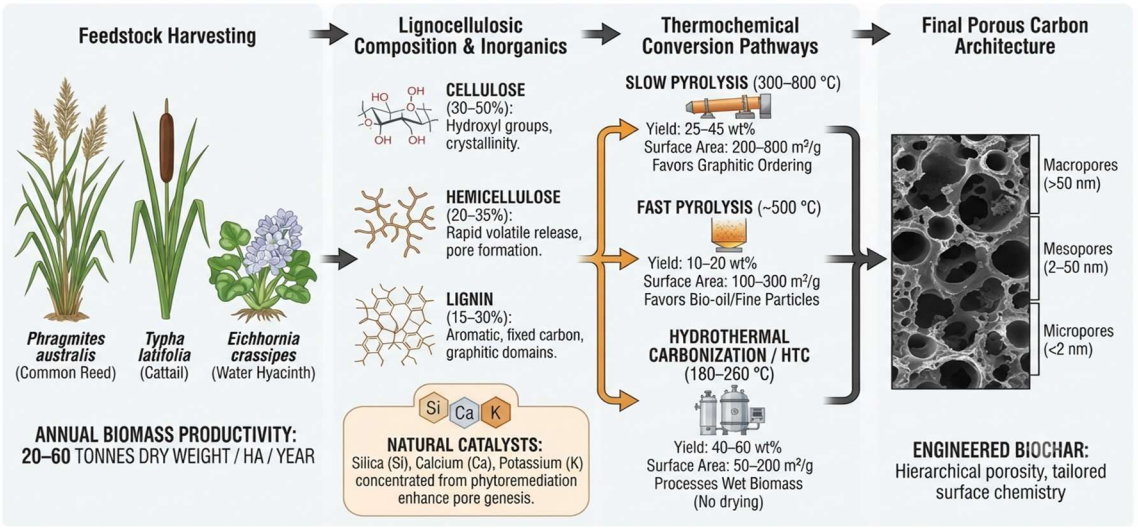

Figure 1. Conceptual illustration of the contributions of cellulose, hemicellulose, and lignin to biochar development and pore formation, synthesized from published literature and intended for explanatory purposes rather than representing direct experimental measurements [52–56].

The thermochemical reaction process determines the yield, porosity, and surface composition of the biochar. Slow pyrolysis, done at temperatures between 300 °C to 800 °C in inert atmospheres, gives high yields (25 to 45%) and biochar with surface area ranging from 200 $m^2 \cdot g^{-1}$ to 800 $m^2 \cdot g^{-1}$. Fast pyrolysis, designed for maximum production of bio-oil, results in low structural order biochar with 10% to 20% yields. Hydrothermal carbonization (HTC), conducted at 180–260 °C in subcritical water, eliminates the need for feedstock drying and typically produces oxygen-rich hydrochar with yields of approximately 40–60%. As summarized in Table 2, each pathway offers distinct advantages: slow pyrolysis favors graphitic ordering, fast pyrolysis provides fine particle sizes, and HTC enables efficient processing of wet biomass.

Table 2. Thermochemical conversion pathways.

Process	Temperature (°C)	Yield (wt%)	Surface Area ($m^2 \cdot g^{-1}$)	References
Slow Pyrolysis	300–800	25–45	200–800	[57,58]
Fast Pyrolysis	~500	10–20	100–300	[57,58]
HTC	180–260	40–60	50–200	[59]

Note: The reported surface area values should be interpreted cautiously because they may correspond to either pristine biochar or activated biochar, depending on feedstock characteristics and post-treatment methods. Direct comparison among studies therefore requires careful consideration of activation conditions and characterization protocols.

The activation methods also help to fine-tune the materials. Microporosity is achieved through physical activation by steam or CO_2 at 800–1000 °C, while surface areas of 900–1500 $m^2 \cdot g^{-1}$ are attained through chemical activation by KOH, H_3PO_4, or $ZnCl_2$ [49]. Therefore, the interaction between biomass composition and process determines the pore hierarchy, the number of surface functional groups, and, consequently, the adsorption properties of biochar.

3. Surface Functionalization and Heteroatom Doping

Pristine biochar produced from constructed wetland biomass usually displays relatively low surface area (less than 100 $m^2 \cdot g^{-1}$), pore volume (less than 0.1 $cm^3 \cdot g^{-1}$), and a negatively charged surface, which hinders their potential applications for the adsorption of anionic dyes [41–43]. To address these issues, a number of techniques have been developed to modify the surface of biochar and make it a promising material for dye removal. These techniques are activation, heteroatoms doping, magnetization, and compositing.

Among the listed techniques, activation is a widely used route for modifying biochar porosity. KOH or $ZnCl_2$ activation can produce high-surface-area materials, although the resulting properties depend on activation ratio, temperature, washing, and precursor [49]. Table 3 provides representative examples from the broader biochar adsorption literature. Reported capacities exceeding 1000 $mg \cdot g^{-1}$ are exceptional, system-specific values and should not be interpreted as typical performance. Adsorption capacity is influenced by initial dye concentration, adsorbent dosage, pH, contact time, ionic strength, temperature, and the model used to estimate the maximum capacity.

Table 3. Engineered biochar adsorption performance.

Material	Target Dye	Capacity ($mg \cdot g^{-1}$)	Surface Area ($m^2 \cdot g^{-1}$)	References
$ZnCl_2$-Activated Biochar	Methylene Blue	450–600	900–1200	[60]
KOH-activated *Myriophyllum aquaticum* biochar	Malachite Green	2570.7 *	1632.7	[61]

* Langmuir-model theoretical maximum adsorption capacity reported under optimized laboratory conditions.

The studies summarized in Table 3 show that very high capacities can occur in selected adsorbent–dye systems, but these values are not directly transferable to constructed-wetland biomass. For example, Zhang et al. [61] reported Langmuir-model maximum capacities of 1772.3 $mg \cdot g^{-1}$ for pristine *Myriophyllum aquaticum* biochar and 2570.7 $mg \cdot g^{-1}$ for its KOH-activated counterpart. These are model-derived values obtained under defined laboratory conditions; they should not be interpreted as guaranteed working capacities in real wastewater. Comparisons should therefore consider the experimental concentration range, adsorbent dose, pH, equilibrium time, matrix composition, and whether the reported value is an observed equilibrium uptake or an isotherm-derived q_{max}.

Table 3 presents representative examples from the wider biochar adsorption literature, including materials prepared from non-wetland feedstocks. Table 4 focuses on selected biochars prepared from wetland-associated or aquatic macrophytes, including *Phragmites australis*, *Cyperus papyrus*, *Eichhornia crassipes*, and *Myriophyllum aquaticum*. The source studies do not all describe biomass harvested from operational constructed wetlands; some involve naturally growing aquatic plants or phytoremediation biomass. The table should therefore be read as evidence for the broader potential of aquatic macrophyte-derived biochar, rather than as a uniform dataset of constructed-wetland-derived materials.

Table 4. Comparative dye-removal performance of biochar derived from wetland-associated macrophytes and their relevance for constructed-wetland biomass valorization.

Wetland Biomass/Feedstock	Preparation/Modification	Target Dye	BET Surface Area ($m^2 \cdot g^{-1}$)	Adsorption Capacity ($mg \cdot g^{-1}$)	Regeneration Performance	References
Phragmites australis (common reed)	Fe_3O_4-modified magnetic biochar	Methylene Blue	94.2	353.4	4 cycles using 0.1 M HCl	[62]
Phragmites australis (phytoremediation biomass)	Biochar	Methylene Blue	NR	79.35 *	NR	[63]
Cyperus papyrus (phytoremediation biomass)	Biochar	Methylene Blue	NR	128.21 *	NR	[63]
Eichhornia crassipes (water hyacinth)	Citric-acid-modified biochar	Methylene Blue	NR	395.0 *	Regeneration evaluated	[64]
Eichhornia crassipes (leaf biomass)	$ZnCl_2$-activated biochar	Methylene Blue	1195	322.58 *	NR	[65]
Eichhornia crassipes (stem biomass)	$ZnCl_2$-activated biochar	Methylene Blue	1121	285.71 *	NR	[65]
Eichhornia crassipes	Water-hyacinth/molasses composite biochar	Methylene Blue	0.89	44.13	NR	[66]
Myriophyllum aquaticum	Pristine biochar (700 °C)	Malachite Green	7.65	1772.3 *	5 cycles tested	[61]
Myriophyllum aquaticum	KOH-activated biochar (700 °C)	Malachite Green	1632.7	2570.7 *	5 cycles tested	[61]
Eichhornia crassipes	Slow-pyrolysis biochar	Reactive Yellow 176	211.3	19.68 *	Not evaluated	[67]

Note: Reported adsorption capacities are not directly comparable because the experimental conditions and capacity definitions differ. Most feedstocks were wetland-associated or aquatic macrophytes; several were collected from natural aquatic systems or phytoremediation sites rather than confirmed operational constructed wetlands. NR = not reported in the cited source summary. * Langmuir-model theoretical maximum adsorption capacity; these values are model-derived and should be distinguished from measured equilibrium uptake.

Key operating conditions reported in the primary studies: Methylene Blue (MB) removal was optimized at pH 8.0, 1.0 $g \cdot L^{-1}$ dosage and 30 min contact time; the isotherm experiments covered 5–200 $mg \cdot L^{-1}$ initial MB, while the study used 0.1 M HCl for regeneration. The study examined contact time, dosage, temperature, initial dye concentration, and pH; the specific numerical settings associated with the listed maximum capacities are not stated in the accessible abstract and are therefore recorded as NR here [62,63]. More than 90% MB removal was reported within the first 60 min; initial concentration and pH affected removal, but the abstract does not provide the full numerical settings for dosage and pH (NR) [64]. The MB experiments used 700 $mg \cdot L^{-1}$ dye solution, 50 mg adsorbent in 20 mL (2.5 $g \cdot L^{-1}$), pH values of 4, 7, and 10, and a 24 h contact period for the pH/isotherm experiments; kinetic experiments were followed for 4 h [65]. The reported optimum conditions were pH 8, 0.8 g adsorbent, and 50 $mg \cdot L^{-1}$ initial MB [66]; the contact time is NR in the accessible report. The Malachite Green (MG) study used an initial concentration range of 100–400 $mg \cdot L^{-1}$ and pH 7 for subsequent experiments; equilibrium was approached at about 240 min [61]. The dosage was varied in the batch tests and is not represented here as a single universal value. The reported conditions for Reactive Yellow 176 were 10–200 $mg \cdot L^{-1}$ initial concentration, pH 7, 0.3 $g \cdot L^{-1}$ dosage, 300 min contact time, and 30 °C. Where a value is not supplied above, it should not be inferred from another study [67].

The studies in Table 4 show substantial variation in the adsorption performance of wetland-associated macrophyte biochar. Modification can improve performance in particular systems, but the magnitude and direction of the effect depend on feedstock, treatment, pollutant, and test conditions. Direct comparison is especially difficult when some studies report measured equilibrium uptake, and others report isotherm-derived q_{max} values. As shown by the operating conditions summarized in Table 4 below, initial concentration, pH, dosage, contact time, and temperature differ among investigations. In addition, several feedstocks were obtained from natural aquatic ecosystems or phytoremediation sites rather than documented constructed wetlands. The current literature therefore supports further investigation of aquatic macrophyte biomass as a biochar precursor, while leaving a clear need for standardized testing of biomass harvested from operational constructed wetlands and for validation in real wastewater matrices.

Recent studies have further demonstrated that adsorption performance is strongly influenced by the interplay between feedstock characteristics, surface chemistry, pore architecture, and modification strategy. Advanced biochar engineering approaches involving chemical activation, metal-oxide incorporation, and composite formation have been shown to enhance pollutant affinity, adsorption kinetics, and regeneration potential. Importantly, these studies emphasize that adsorption performance cannot be explained solely by surface area; because surface functionality and pollutant-specific interactions frequently govern adsorption efficiency under practical conditions [68–70].

Apart from activation, heteroatom doping involves the incorporation of nitrogen, sulfur, or phosphorus within the structure of the carbon matrix by changing the electronic charge and altering the point of zero charge (pHpzc). For instance, N-doping creates pyridinic and graphitic N that improves π–π donor–acceptor properties and anionic dye adsorption. Some studies of nitrogen-functionalized biochar have reported enhanced adsorption of anionic dyes, including Congo Red. However, the magnitude of improvement depends on feedstock, surface chemistry, solution conditions, and experimental methodology; comparisons across independent studies should therefore be interpreted cautiously [71,72]. In addition to adsorption selectivity, this strategy increases the range of pH values under which biochar operates. This allows the creation of biochar capable of trapping both cationic and anionic dyes and thus filling a gap in multifunctional wastewater treatment technology.

4. Magnetic Modification and Composite Engineering

Whereas activation and heteroatom doping considerably improve adsorption efficiency, these methods fail to solve the problem of adsorbent separation after treating contaminated water. To tackle this issue, scientists have found another way—magnetic modification of the material. Magnetic functionalization can facilitate adsorbent recovery using an external magnetic field. The efficiency and speed of separation depend on magnetic loading, particle size, dispersion, solution composition, and separation conditions. Likewise, the performance of metal-oxide and layered-double-hydroxide composites under saline conditions requires validation using the specific material and wastewater matrix [49]. Combining biochar with superparamagnetic iron oxide nanoparticles enables efficient separation via external magnetic fields (Figure 2a), while composite engineering introduces Lewis acid sites for dual dye uptake (Figure 2b).

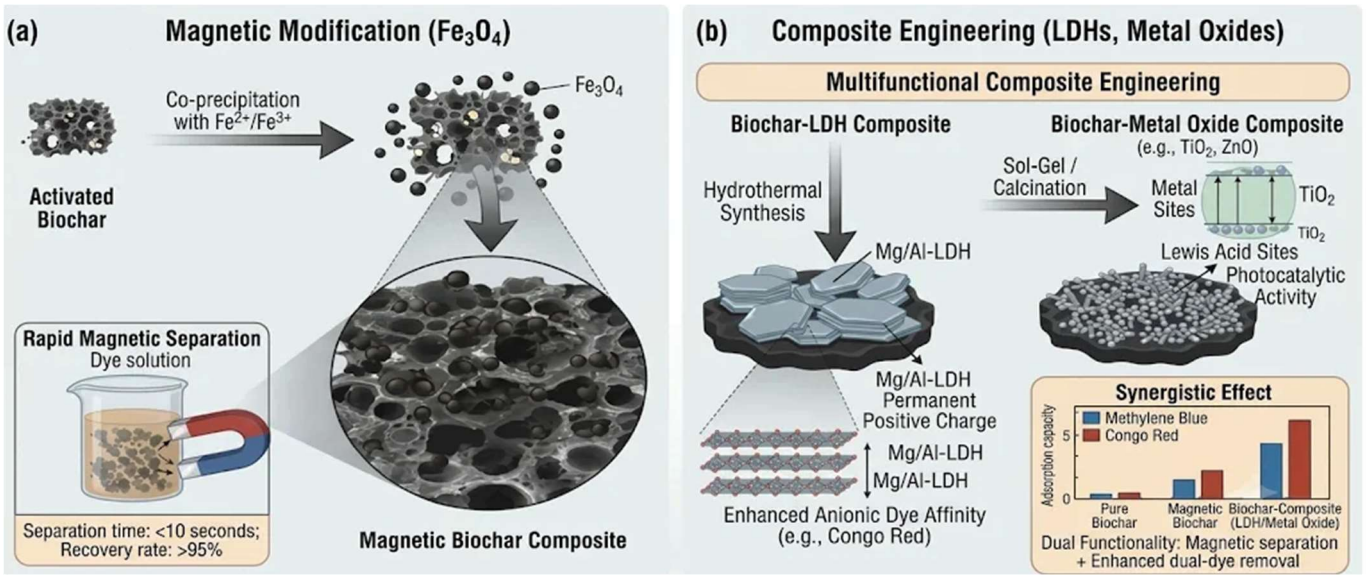

Figure 2. Conceptual representation of magnetic-functionalization and composite-engineering approaches for biochar enhancement: (**a**) magnetic modification of activated biochar via Fe^{2+}/Fe^{3+} co-precipitation to form a magnetic biochar composite (Fe_3O_4) enabling rapid magnetic separation and recovery from dye solutions; (**b**) multifunctional composite engineering combining layered double hydroxides (e.g., Mg/Al-LDH via hydrothermal synthesis for enhanced anionic dye affinity such as Congo Red) and metal oxides (e.g., TiO_2, ZnO via sol-gel/calcination providing metal/Lewis acid sites and photocatalytic activity), alongside synergistic dual-dye removal and magnetic recovery. The figure summarizes mechanisms reported in the literature and does not represent quantitative experimental results [49,50].

In addition to magnetic modification, composite engineering provides numerous opportunities to increase biochar functionality. By decorating the framework of biochar with various transition metal oxides like TiO_2, ZnO, or MnO_2, scientists obtain materials with Lewis acid sites and photocatalytic activity allowing for adsorption and decomposition of dyes at once. Analogically, biochar-LDHs composites provide permanent positive charge centers and thus promote electrostatic interaction between biochar and anionic dyes, e.g., Congo Red. These composites are characterized by excellent adsorption selectivity and improved stability in solutions with high salt content typical of real industrial effluents [50].

These approaches may improve adsorption performance or facilitate adsorbent recovery in selected laboratory systems. However, performance in complex wastewater matrices cannot be inferred solely from tests using single-dye solutions. The effects of dissolved organic matter, salts, suspended solids, competing pollutants, and leaching from metal-containing composites require direct evaluation. Pilot-scale and continuous-flow evidence remains necessary before industrial applicability can be claimed.

5. Adsorption Isotherms, Kinetics, and Multiscale Interactions

A comprehensive understanding of adsorption requires linking equilibrium models, kinetic behavior, and surface interactions. Langmuir and Freundlich models are frequently used to describe dye adsorption, but a good statistical fit does not by itself prove a particular surface structure or mechanism. For example, Langmuir fitting is consistent with a finite-capacity model under its assumptions; it does not establish that all adsorption sites are identical in a heterogeneous biochar. Likewise, model preference may change with the concentration range and fitting procedure [73,74]. Mechanistic interpretation should therefore be supported by complementary surface characterization, pH-dependent experiments, and appropriate spectroscopic or thermodynamic evidence.

Kinetic data for dye adsorption are often fitted using pseudo-first-order or pseudo-second-order equations [75–80]. A pseudo-second-order fit alone is not definitive evidence of chemisorption, just as a pseudo-first-order fit does not independently establish physisorption. Equilibrium time and apparent rate

constants depend on the dye, particle size, agitation, solution composition, adsorbent dosage, and reactor configuration. Accordingly, kinetic-model parameters should be interpreted as empirical descriptions of the measured data unless corroborated by independent mechanistic evidence.

Potential interactions between dyes and biochar include electrostatic attraction or repulsion, π–π interactions with aromatic carbon domains, hydrogen bonding, pore filling, and ion exchange [81–86]. Their relative contributions are material and pollutant-specific. Evidence for a proposed mechanism should be drawn from the relevant pH response, surface charge, spectroscopic changes, pore characteristics, and competitive adsorption behavior. The presence of a particular functional group or a high BET surface area alone is insufficient to establish the dominant mechanism. This qualification is particularly important when extrapolating from model dye solutions to multi-component wastewater.

6. Advanced Characterization Techniques

For a complete understanding of adsorption properties and structural changes in engineered biochar, modern characterization tools are essential. Different methods provide unique information about physicochemical properties controlling the process of dye removal from water. With Fourier-transform infrared spectroscopy (FTIR) analysis, it is possible to identify functional groups, such as hydroxyl, carboxyl, and carbonyl groups, that participate in the formation of hydrogen bonds and electrostatic interactions between dye molecules and the surface.

The use of X-ray Photoelectron Spectroscopy (XPS) provides information about elemental composition and their chemical states of the biochar surface. This technique helps to determine heteroatom doping by means of identifying nitrogen in pyridinic or graphitic states or sulfur in thiophenic states. Thus, this method can be used to check how the surface electronic state is changed due to heteroatom doping.

With the help of Raman spectroscopy, one can get information about structural properties of the biochar, such as graphitization level and structural defects. The ratio of intensities between the D and G bands (ID/IG) indicates the level of disorder and aromatic condensation, reflecting the strength of π–π stacking interactions between dye molecules and the carbon matrix. Biochar created through engineering usually has an altered I_D/I_G ratio.

Lastly, Brunauer-Emmett-Teller (BET) estimates specific surface area, while pore-size distribution and pore volume require appropriate analysis of adsorption data and suitable models. Activated biochars normally have surface areas of 900–1500 $m^2 \cdot g^{-1}$ with hierarchical micro-mesoporous structures that minimize the mass transfer effect. This information makes BET analysis a useful tool for quantifying the relationship between structure and adsorption performance.

These techniques form the basis for understanding the relationship between structural engineering and adsorption performance. From the analysis of the FTIR, XPS, Raman, and BET results, it is possible to link the structural changes to adsorption performance, making the design evidence-based [86–88].

In addition to FTIR, XPS, Raman spectroscopy, and BET analysis, characterization techniques such as point of zero charge (pHpzc), zeta potential measurements, and standardized leaching tests provide valuable information regarding surface charge behavior, adsorption mechanisms, and environmental safety. These parameters are particularly important for engineered biochar intended for practical wastewater treatment applications.

7. Regeneration and Real Wastewater Applications

Regeneration and reuse are important to the practical assessment of engineered biochar. The available studies show that performance after regeneration depends on feedstock, surface modification, target pollutant, eluent, regeneration protocol, and the number of adsorption–desorption cycles. The evidence does not support a general ranking in which pristine, activated, and magnetic biochars retain fixed percentages over fixed numbers of cycles. Table 5 therefore presents selected study-specific examples,

including the regeneration agent and reported cycle outcome where available. These examples are not directly comparable because the adsorbates, materials, and test protocols differ.

For common-reed magnetic biochar, four reuse cycles were reported following desorption with 0.1 M HCl; the adsorption performance declined by approximately 25% by the fifth cycle [62]. For *Myriophyllum aquaticum* biochar, five regeneration cycles were tested using a 1:1 ethanol–acetic acid eluent with 30 min sonication, and appreciable adsorption capacity remained after the fifth cycle [61]. A separate study using logging-residue-derived biochars reported approximately 60–67% removal capacity after seven cycles for boron- or sulfur-modified materials, compared with about 35% for the control; this is a non-wetland feedstock and is included only as contextual evidence [89]. These results illustrate why regeneration claims should be tied to the individual material and procedure rather than generalized by material category.

Common regeneration strategies include alkaline (NaOH), acidic (HCl), ethanol, and thermal treatments. Regeneration efficiency depends on adsorbent structure, dye type, desorption conditions, and possible pore blockage or surface oxidation occurring during repeated cycles. The management of spent regeneration solutions containing concentrated pollutants should be considered when evaluating the environmental sustainability of biochar reuse [90,91].

Table 5. Selected study-specific regeneration outcomes for aquatic macrophyte-derived and comparison biochar.

Material/Feedstock	Regeneration Procedure	Reported Reuse Outcome	References
Phragmites australis magnetic biochar	0.1 M HCl elution	Four reuse cycles reported; adsorption performance declined by approximately 25% by the fifth cycle	[62]
Myriophyllum aquaticum pristine and KOH-activated biochars	Ethanol:acetic acid (1:1); sonication for 30 min	Five cycles tested; appreciable MG adsorption capacity remained after the fifth cycle	[61]
Logging-residue-derived control, boron-modified, and sulfur-modified biochars (non-wetland comparison)	Regeneration protocol as reported in the source study	After seven cycles, removal capacity was approximately 35% for the control and 60–67% for modified biochars	[89]
Eichhornia crassipes citric-acid-modified biochar	Regeneration evaluated; exact eluent and cycle protocol not stated in the accessible abstract.	The authors report retained adsorption performance after multiple cycles; no numerical retention value is quoted here	[64]

Note: The table distinguishes the number of cycles tested from the percentage of adsorption capacity retained. These are not interchangeable measures.

Most of the adsorption studies considered in this review used synthetic dye solutions under controlled batch conditions. Actual textile wastewater contains salts, surfactants, dissolved organic matter, suspended solids, and mixtures of dyes and other contaminants, all of which may alter adsorption and separation performance. Capacities obtained from single-solute systems should therefore not be treated as expected treatment capacities for industrial effluents. One water-hyacinth-derived citric-acid-modified biochar study also examined actual dye wastewater [64], but this isolated result does not establish general performance across constructed-wetland-derived biochar. Future work should report wastewater composition, treatment targets, competing solutes, regeneration performance, and contaminant leaching, and should progress from batch tests to pilot-scale continuous-flow studies [92].

Surface engineering can improve adsorption performance and, in selected systems, facilitate regeneration or adsorbent separation. However, durability and economic benefits depend on the material, regeneration procedure, pollutant, and wastewater matrix. The present evidence is strongest for laboratory-scale batch adsorption; evidence from real wastewater and pilot-scale operation is limited and should be described on a study-by-study basis. In particular, results from naturally growing aquatic macrophytes or phytoremediation biomass should not be presented as direct validation of biochar produced from operational constructed wetlands.

The difference between synthetic-solution tests and real industrial effluents is a central limitation in assessing practical performance. Competing ions dissolved organic matter, surfactants, suspended solids, and variable pH may reduce removal or alter regeneration requirements. Consequently, laboratory adsorption capacities provide a basis for screening and mechanistic study, not by themselves proof of industrial treatment effectiveness.

8. Sustainability Assessment

In addition to adsorption efficiency, long-term sustainability of engineered biochar depends on its environmental performance and economic feasibility. Life-cycle assessment (LCA) provides a framework for evaluating environmental impacts associated with biomass harvesting, transportation, drying, thermochemical conversion, chemical activation, adsorbent use, regeneration, and end-of-life management. Previous studies have demonstrated that biochar-based treatment systems may offer environmental advantages under specific operating conditions and system boundaries [93–96]. For example, Taslakyan et al. investigated a biochar-integrated reactive filtration system and reported potentially favorable environmental outcomes [94]. However, such results cannot be directly generalized to engineered biochar derived from constructed-wetland biomass because environmental impacts depend on feedstock characteristics, energy sources, treatment configuration, functional units, and assumptions regarding carbon storage and avoided emissions. Therefore, comparative sustainability claims should be based on equivalent treatment objectives and clearly defined life-cycle boundaries.

Techno-economic assessment (TEA) is equally important for evaluating the feasibility of engineered biochar in wastewater treatment. The economic performance of biochar-based systems depends on biomass collection and transportation costs, moisture content, drying requirements, pyrolysis technology, chemical activation, adsorbent dosage, regeneration efficiency, and the management of spent materials. Although favorable treatment costs have been reported for specific biochar-integrated wastewater-treatment systems [94], these values should not be interpreted as universally applicable to constructed-wetland biomass-derived biochar. In particular, economic comparisons with commercial activated carbon require consistent treatment capacities, pollutant-removal targets, operating conditions, and cost-accounting assumptions. Further feedstock-specific techno-economic investigations are therefore necessary to establish whether engineered wetland-derived biochar can provide a cost-effective alternative under practical operating conditions.

As summarized in Table 6, engineered biochar derived from constructed-wetland biomass offers potential opportunities for resource recovery and circular wastewater management. Nevertheless, its environmental and economic advantages cannot be established solely from adsorption capacity, feedstock availability, or results reported for other biochar-based systems. Comprehensive assessments should incorporate material production, energy and chemical consumption, treatment performance, regeneration, contaminant leaching, and spent-adsorbent disposal. Integrating these considerations with Safe and Sustainable by Design (SSbD) principles may help identify conditions under which wetland-derived engineered biochar can provide measurable sustainability benefits.

Table 6. Key sustainability considerations for commercial activated carbon and engineered biochar derived from constructed-wetland biomass.

Parameter	Commercial Activated Carbon	Wetland-Derived Engineered Biochar
Feedstock	Coal, coconut shells, wood, and other carbonaceous precursors	Harvested aquatic macrophytes
Production	Carbonization and/or activation, depending on precursor	Pyrolysis or hydrothermal carbonization, with optional activation
Energy requirements	Depend on precursor and production technology	Depend on moisture content, drying, conversion, and modification

Regeneration	Depends on adsorbent, pollutant, and regeneration process	Depends on biochar properties, pollutant, and regeneration process
Environmental impacts	Require life-cycle assessment	Require feedstock-specific life-cycle assessment
Treatment cost	Depends on production, dosage, and operating conditions	Depends on harvesting, processing, dosage, regeneration, and scale
End-of-life management	Regeneration, disposal, or other appropriate treatment	Leaching assessment, regeneration-waste management, and safe disposal
Circular-economy potential	Depends on precursor and material recovery	Potential valorization of harvested wetland biomass

Note: This table presents qualitative considerations rather than directly comparable numerical results. Quantitative comparisons require consistent functional units, treatment objectives, and system boundaries.

9. Emerging Opportunities and Future Roadmap

The progress in biochar technology should not be limited to optimizing adsorption performance alone. It is equally important to integrate emerging technologies and standardized assessment frameworks to accelerate industrial implementation. One of the most promising developments is AI-assisted materials discovery. Machine learning algorithms can predict adsorption capacities and parameters for optimal production conditions with high precision. By correlating feedstock composition, pyrolysis parameters, and surface modification strategies, AI can help reduce experimental effort and guide the design of biochar with enhanced dye-removal performance [97]. Despite its promise, AI-assisted materials discovery remains constrained by the availability of high-quality experimental datasets, limited standardization among studies, and uncertainties associated with model transferability.

Continuous-flow studies provide an important bridge between batch adsorption experiments and practical treatment systems. Because breakthrough behavior depends strongly on reactor dimensions, bed depth, hydraulic loading rate, influent concentration, and breakthrough criteria, direct comparison among studies should be undertaken cautiously. Therefore, system performance should be evaluated using clearly reported reactor dimensions, hydraulic conditions, influent composition, breakthrough criteria, regeneration procedures, and long-term operational data. Evidence from other biochar feedstocks should not be assumed to demonstrate equivalent performance for constructed-wetland biomass-derived materials. Scaling up these systems for industrial application will require optimized reactor design, robust regeneration protocols, and seamless integration with existing wastewater-treatment infrastructure [98].

Future studies should use relevant existing ISO standards and established LCA and techno-economic assessment methods wherever applicable, while developing harmonized protocols for biochar-specific performance and safety testing where gaps remain. Relevant standards can improve reproducibility and comparability of results, regulatory certainty, and allow for comparison to traditional adsorbents, such as activated carbon. Integrating Safe and Sustainable by Design (SSbD) principles will allow biochar to align even further with policy and circular economy goals.

Moving forward, the convergence of materials science, artificial intelligence, and sustainability frameworks makes engineered biochar from constructed wetland biomass the key component of the next generation of water purification. As an example of turning a disposal problem into a climate-positive solution, biochar represents the way in which renewables can be used to sustain both nature and industry.

10. Conclusions and Perspectives

Conversion of constructed wetland biomass into engineered biochar represents a promising approach for wastewater treatment. Harvested macrophyte biomass, once regarded primarily as a waste material requiring disposal, has emerged as a renewable, non-food-competing carbon source that can support circular water-treatment strategies. Through thermochemical conversion, activation, heteroatom doping,

magnetic functionalization, and composite engineering, biochar can be transformed into a multifunctional adsorbent capable of removing both cationic and anionic dyes.

Available studies indicate that adsorption capacities vary widely depending on feedstock type, modification strategy, and experimental conditions. Sustainability assessments further suggest potential environmental benefits under specific life-cycle assessment (LCA) assumptions. Nevertheless, further pilot-scale validation, long-term stability assessment, contaminant-leaching studies, and standardized sustainability evaluations remain necessary before widespread implementation can be achieved.

Future progress will depend on integrating AI-assisted material discovery with reproducible experiments, pilot-scale continuous-flow validation, and rigorous environmental and economic assessment. Particular attention should be given to the transferability of results from other biomass feedstocks to constructed-wetland macrophytes, as well as to contaminant leaching, regeneration waste, and spent-adsorbent management. With these limitations addressed, engineered biochar derived from constructed wetland biomass could contribute to circular water-remediation systems. Its practical value will ultimately depend not only on adsorption performance but also on safety, durability, resource requirements, and verified environmental and economic benefits.

Statement of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist with language improvement, grammar correction, manuscript organization, and refinement of scientific writing. After using this tool, the authors critically reviewed, edited, and verified all content and accept full responsibility for the accuracy, integrity, and originality of the published work

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Author Contributions

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