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Supplementary Materials

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

Md Nashir Uddin, Abigail Samwini, Dong Hee Kang and Gbekeloluwa Babatunde Oguntimein *

Department of Civil and Environmental Engineering, Morgan State University, Baltimore, MD 21251, USA
* Correspondence: gbeke.oguntimein@morgan.edu

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Table S1. Adsorption performance of pristine biochar for dye removal from wastewater.

Feedstock/Biochar Type	Dye	Dye Class	Adsorption Capacity	Experimental System	Ref
American sycamore leaf biochar	Thiazolyl blue, BPB	Cationic/anionic	High (dye-specific)	Batch	[1]
Modified Pinus brutia biochar	Malachite green	Cationic	Enhanced vs pristine	Batch	[2]
KOH-activated spruce bark biochar	Reactive azo dyes	Azo	Very high	Batch	[3]
Sludge-derived activated biochar	Methylene blue	Cationic	High	Batch	[4]
Areca husk biochar	Anthraquinone dye	Non-ionic aromatic	Moderate–high	Batch	[5]
Palmyra fiber biochar	Malachite green	Cationic	High	Batch–CCD	[6]
Ball-milled biochar–fly ash composite	Methylene blue	Cationic	High	Batch	[7]
Biochar–hydrogel composite	Mixed dyes	Mixed	Ultra-high	Batch	[8]
Macroalgae biochar	Acid Red 88	Anionic	Moderate	Batch	[9]
Oil-cake biochar	Acid dyes (real effluent)	Anionic	Moderate–high	Real wastewater	[10]
Jamun seed biochar	Fuchsin	Cationic	Moderate	Batch	[11]
Phoenix seed biochar	Direct Red 28	Anionic	Moderate	Batch	[12]
Palm shell biochar	Mixed dyes	Mixed	High	Batch	[13]
Sewage sludge biochar	Reactive dyes	Anionic	Moderate–high	Batch	[14]
Lotus stem fiber biochar	Organic dyes	Mixed	High	Batch	[15]

Table S2. Adsorption performance of engineered and composite biochar-based adsorbents.

Engineering Strategy	Structural/Chemical Modification	Target Dye(s)	Performance Outcome	Dominant Mechanism(s)	Ref
KOH chemical activation	Increased microporosity, graphitization	Azo dyes	↑ Capacity, faster kinetics	π-π stacking, pore filling	[3]
Sludge-derived activation	Mineral-enriched surface, high SSA	Methylene blue	↑ Capacity	Electrostatic attraction, pore filling	[4]
Ball milling	Defect generation, reduced particle size	Methylene blue	↑ Adsorption rate	Shortened diffusion paths	[7]
Biochar–hydrogel composite	3D interconnected porous network	Mixed dyes	Ultra-high uptake	Multi-site adsorption synergy	[8]
$ZnCl_2$ impregnation	Lewis acid sites, mesopore formation	Organic dyes	↑ Anionic dye uptake	Surface complexation	[16]
Fe(III)-treated biochar	Positively charged metal sites	Crystal violet	↑ Capacity & selectivity	Electrostatic attraction, coordination	[17]
Magnetic modification	Fe_3O_4 incorporation	Cationic dyes	Stable performance, easy recovery	Magnetic separation, surface binding	[18]
Alginate immobilization	Structural stabilization	Eosin yellow	Improved reusability	Reduced leaching, diffusion control	[19]
Palmyra fiber optimization	Pyrolysis + CCD optimization	Malachite green	↑ Capacity	Surface charge tuning	[6]
Areca husk biochar tailoring	Controlled pyrolysis temperature	Anthraquinone dye	↑ Performance	Aromatic stacking	[5]
Macroalgae biochar modification	Optimized pore hierarchy	Acid Red 88	Moderate–high removal	Intraparticle diffusion	[9]

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Table S2. *Cont.*

Engineering Strategy	Structural/Chemical Modification	Target Dye(s)	Performance Outcome	Dominant Mechanism(s)	Ref
Sewage sludge activation	Green chemical activation	Reactive dyes	↑ Capacity	Mineral-assisted adsorption	[14]
Palm-shell biochar engineering	Thermal activation	Mixed dyes	High removal efficiency	Electrostatic + pore filling	[13]
Jamun seed biochar optimization	Non-activated feedstock control	Fuchsin dye	Moderate performance	Diffusion + surface adsorption	[11]
Lotus stem fiber biochar	Low-cost pyrolysis	Organic dyes	High capacity	Porosity-driven adsorption	[15]

Table S3. Kinetic, isotherm, and thermodynamic models applied to dye adsorption on biochar-based adsorbents.

Biochar System/Feedstock	Target Dye	Dominant Kinetic Model	Isotherm Model	Thermodynamic Characteristics	Mechanistic Interpretation	Ref
American sycamore leaf biochar	Thiazolyl blue, BPB	Pseudo-second-order (PSO)	Freundlich	ΔG° < 0; endothermic	Heterogeneous surface adsorption	[1]
Pinus brutia modified biochar	Malachite green	PSO	Langmuir	Spontaneous	Monolayer adsorption on engineered sites	[2]
KOH-activated spruce bark biochar	Azo dyes	PSO	Langmuir	Endothermic	Surface-controlled adsorption, pore filling	[3]
Sludge-derived activated biochar	Methylene blue	PSO	Langmuir	ΔG° < 0	Chemisorption-dominated uptake	[4]
Areca catechu husk biochar	Anthraquinone dye	PSO	Langmuir	Spontaneous	Strong dye–surface affinity	[5]
Palmyra fiber biochar (CCD-optimized)	Malachite green	PSO	Langmuir	Spontaneous, endothermic	Optimized active site utilization	[6]
Ball-milled biochar–fly ash composite	Methylene blue	PSO	Langmuir–Freundlich	ΔG° < 0	Synergistic composite adsorption	[7]
Biochar–hydrogel composite	Mixed dyes	PSO	Langmuir	Endothermic	Multi-site adsorption network	[8]
Macroalgae-derived biochar	Acid Red 88	PSO + IPD	Freundlich	Spontaneous	Diffusion-limited adsorption	[9]
Oil-cake biochar	Acid dyes (real effluent)	PSO	Freundlich	ΔG° < 0	Competitive adsorption in complex matrix	[10]
Jamun seed biochar	Fuchsin	Multi-stage (IPD)	Freundlich	Spontaneous	Intraparticle diffusion dominance	[11]
Phoenix seed biochar	Direct Red 28	PSO	Langmuir	Endothermic	Electrostatic + pore filling	[12]
Palm-shell biochar	Mixed dyes	PSO	Langmuir	Spontaneous	Surface-controlled adsorption	[13]
Sewage-sludge activated carbon	Reactive dyes	PSO	Langmuir	ΔG° < 0	High-energy adsorption sites	[14]
Super-adsorbent engineered biochar	Mixed dyes	PSO	Langmuir	Endothermic	High-affinity active sites	[20]
Lotus stem fiber biochar	Organic dyes	PSO	Langmuir	Spontaneous	Porosity-driven adsorption	[15]
Fe(III)-treated pine needle biochar	Crystal violet	PSO	Langmuir	ΔG° < 0	Electrostatic + coordination bonding	[17]
Algal biochar	Congo red	PSO	Langmuir	Endothermic	Anionic dye–surface interactions	[21]

EDA = electron donor–acceptor; IPD = intraparticle diffusion; MW = molecular weight.

Table S4. Regeneration, reusability, and end-of-life management of dye-loaded biochar-based adsorbents.

Biochar System	Dye/Matrix	Regeneration Method	Cycles Tested	Capacity Retention (%)	Key Stability Observation	Ref
Modified Pinus brutia biochar	Malachite green	Ethanol washing	5	~82% after 5 cycles	Minimal structural degradation; adsorption governed by reversible interactions	[2]
Okara biochar immobilized in Ca–alginate beads	Eosin yellow	Desorption–re-adsorption	6	~85% after 6 cycles	Immobilization prevented biochar loss and improved mechanical stability	[19]
KOH-activated spruce bark biochar	Azo dyes	Ethanol/NaOH washing	5	~80% after 5 cycles	Activated structure retained pore integrity	[3]
Sludge-derived activated biochar	Methylene blue	Thermal + chemical regeneration	5	~88% after 5 cycles	Mineral-assisted adsorption sites remained stable	[4]
Ball-milled biochar–fly ash composite	Methylene blue	Solvent regeneration	4	~78% after 4 cycles	Slight loss attributed to irreversible pore filling	[7]
Biochar–hydrogel composite	Mixed dyes	Desorption–re-adsorption	5	>90% after 5 cycles	Polymer network protected adsorption sites	[8]
Palmyra fiber biochar (optimized)	Malachite green	Ethanol washing	4	~83% after 4 cycles	Optimized surface chemistry enabled reversible adsorption	[6]
Areca catechu husk biochar	Anthraquinone dye	Regeneration via solvent washing	4	~80% after 4 cycles	Stable aromatic framework favored reuse	[5]

Table S4. *Cont.*

Biochar System	Dye/Matrix	Regeneration Method	Cycles Tested	Capacity Retention (%)	Key Stability Observation	Ref
Macroalgae-derived biochar	Acid Red 88	Chemical desorption	4	~76% after 4 cycles	Diffusion-limited desorption reduced recovery	[9]
Oil-cake biochar (real effluent)	Acid dyes (real wastewater)	Regeneration washing	3	~70% after 3 cycles	Competitive adsorption reduced regeneration efficiency	[10]
Fixed-bed biochar column	Reactive Blue 5G (industrial wastewater)	Column regeneration	Multiple	Stable breakthrough behavior	Demonstrated operational stability under continuous flow	[22]
Magnetic activated carbon/biochar	Mixed dyes	Magnetic recovery + washing	6	~90% after 6 cycles	Magnetic separation enabled rapid reuse	[18]

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