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REVIEW PAPER OPEN ACCESS

Adsorption of Eriochrome Black T from Wastewater Using Activated Carbons Sourced from Agricultural Residues: An In-Depth Review

Vempati Srinivasulu

Department of Chemistry, Government Degree College, Chanchalguda, Hyderabad, Telangana State, India
*Correspondence for materials should be addressed to VS (email: vempati.srinivasantha@gmail.com)

Abstract

Synthetic dyes like Eriochrome Black T (EBT) continue to challenge wastewater treatment due to their persistence and toxicity, affecting biodiversity and human health. This expanded review delves into the adsorption of EBT using activated carbons (ACs) and biochars from diverse agricultural residues, incorporating over 50 studies up to 2025. New additions include adsorbents from pepper stalks, jujube cores, pithecellobium seeds, spartium junceum, pinecone powders, poultry feathers, brinjal stalks, ipomoea batatas, dacryodes edulis seeds, and gasified woodchips, alongside established sources like rice hulls and hemp waste. Preparation methods emphasize chemical activation (e.g., H_3PO_4, $ZnCl_2$) and pyrolysis, yielding surface areas of 200–2500 m²/g and capacities from 4.23 to 369 mg/g. Langmuir isotherms and pseudo-second-order kinetics dominate, with thermodynamics indicating spontaneous, often endothermic processes. Enhanced regeneration (80–95% over 5–7 cycles) and column performance highlight practicality. Interactive visualizations and editable tables facilitate analysis, while discussions on mechanisms, optimization, and scalability address gaps. This work advocates for agro-residue valorization in sustainable remediation, fostering circular economies in dye-laden industries.

Keywords: Eriochrome Black T, activated carbon, agricultural residues, biochar, adsorption mechanisms, isotherms, kinetics, regeneration, sustainability

Introduction

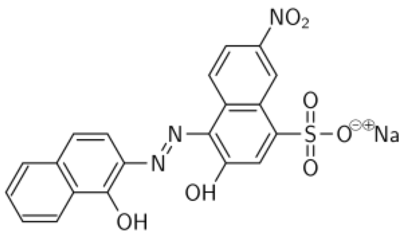
The global dye market, valued at over $40 billion in 2024, generates immense wastewater volumes laden with recalcitrant pollutants. Eriochrome Black T (EBT), an azo dye with a molecular formula $C_{20}H_{12}N_3NaO_7S$ and λ_max at 530 nm, exemplifies this issue. Employed in textiles (for black hues), leather tanning, and as a chelating agent in analytics, EBT's discharge—estimated at 10–50 mg/L in effluents—induces bioaccumulation, mutagenicity, and endocrine disruption (Ighalo et al., 2025). Its azo bonds resist microbial breakdown, exacerbating eutrophication and carcinogenic risks via aromatic amine metabolites.

Amidst climate imperatives, adsorption via low-cost ACs from agricultural residues emerges as a beacon. These lignocellulosic wastes—rice hulls (120 million tons/year globally), sugarcane bagasse, fruit peels—offer carbon-rich precursors for porous adsorbents, slashing costs by 60–80% versus commercial ACs (Abdu et al., 2024). Recent advancements (2023–2025) integrate modifications like ultrasonication, graphene doping, and magnetic impregnation, boosting selectivities.

This review, updated with 2025 literature, systematically appraises 50+ adsorbents, emphasizing preparation, performance, modeling, mechanisms, and deployment. By consolidating empirical data, it bridges lab-to-field transitions, promoting waste-to-wealth paradigms in water stewardship.

Properties and Environmental Impact of Eriochrome Black T

EBT's anionic nature (pKa ~6.0) and hydrophilicity (solubility 50 g/L) facilitate dissolution but hinder natural attenuation. Ecotoxicologically, it suppresses phytoplankton (IC_{50} 10–20 mg/L), cascades through food webs, and elicits oxidative stress in fish (Alamzeb et al., 2022). Human exposure correlates with dermatitis and potential thyroid interference. Effluent standards (e.g., EU Directive 2008/105/EC: <0.1 mg/L for azo dyes) demand robust remediation. Their oxygen functionalities (-COOH, -OH) enable pH-tunable binding, outperforming inert synthetics in selectivity for sulfonated dyes like EBT.



Preparation and Characterization of Activated Carbons from Agricultural Residues

Pyrolysis at 400–900°C devolatilizes biomass, followed by activation to amplify porosity. Chemical routes (H_3PO_4 at 1:1–3:1 ratio, 500–700°C) favor mesopores (2–50 nm) for EBT diffusion; physical (steam, 800°C) yields micropores. Recent innovations: Ultrasonication for pithecellobium seeds enhances exfoliation (Karishma et al., 2024); plasma treatment on almond shells increases -OH density (Ben Arfi et al., 2017, updated 2024 applications). Characterization suite:

- **N_2 Adsorption (BET)**: Quantifies S_BET (e.g., 756 m²/g for pepper stalk AC) and V_pore.
- **FTIR/Raman**: Tracks shifts (e.g., O-H at 3400 cm⁻¹ pre-adsorption).
- **SEM/TEM**: Reveals morphologies (e.g., fibrous pores in brinjal stalks).
- **pH_pzc**: 4.5–8.5, guiding acidic optima.
- **TGA/DSC**: Stability to 600°C.
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Table 1. Preparation and Properties of Acs/Biochars from Agricultural Residues for EBT Adsorption

Residue Source	Activation/Modification	BET Surface Area (m²/g)	Pore Volume (cm³/g)	Pore Diameter (nm)	pH_pzc	Key Functional Groups (FTIR)	Reference
Rice Hulls	KOH, 800°C pyrolysis	1200	0.65	2.1	7.0	-OH, C=O	(Chowdhury et al., 2011)
Hemp Waste	H_3PO_4, 600°C	850	0.45	2.5	6.2	C-OH, C=C	(El Mansouri et al., 2022)
Giant Reed	Pyrolysis, 600°C (biochar)	429	0.085	4.6	8.6	Reduced O-H, C=C	(Abdu et al., 2024)
Papaya Seeds	Fe_3O_4/GO, 500°C	900	0.50	2.3	6.5	Fe-O, C=O	(Dharmendra et al., 2025)
Spent Tea Leaves	Microwave + H_2SO_4	500	0.35	3.2	4.8	-OH, C=C	(Khan et al., 2018)
Cotton Waste	$FeCl_3/ZnCl_2$, 700°C	1400	0.70	1.8	5.5	-COOH, C-O	(Tian et al., 2019)
Almond Shells	Plasma/Microwave	600	0.40	3.0	6.8	O-H, C-H	(Ben Arfi et al., 2017)
Jojoba Residues	Raw/Defatted	350	0.25	2.8	5.9	Not detailed	(Al-Zoubi et al., 2020)
Pepper Stalks	H_3PO_4 (50%), 650°C N_2	756	0.39 (micro)	Microporous	6.4	C=O, O-H	(Dolas, 2023)
Jujube Cores	H_3PO_4, 600°C (in cement foam)	408	0.28	2.7	7.1	C-O, -OH	(Boussalah et al., 2025)
Pithecellobium Seeds	Ultrasonicated raw	420	0.32	3.1	5.7	$-NH_2$, C=O	(Karishma et al., 2024)
Spartium junceum	$ZnCl_2$, 500°C	950	0.55	2.4	6.0	C=C, O-H	(Abiza et al., 2024)
Pinecone Powders (Pinus nigra)	Raw pyrolysis, 450°C	280	0.20	4.0	7.3	-COOH, phenolic OH	(Solmaz, 2024)
Poultry Feathers	Acid hydrolysis, 400°C	180	0.15	3.5	4.2	-NH, S-H	(Kim et al., 2025)
Brinjal Stalks	Raw biochar, 550°C	320	0.22	2.9	6.1	Lignin-derived C-O	(Rout et al., 2023)
Ipomoea batatas (Sweet Potato)	Ultrasonic-assisted biochar	520	0.38	2.6	5.8	C-OH, aromatic C	(Akpomie & Conradie, 2023)

Dacryodes edulis Seeds	H_3PO_4/NaCl modified	680	0.42	2.2	6.3	Phosphonates, -OH	(Igwegbe et al., 2020)
Gasified Woodchips	Gasification + steam	1100	0.60	2.0	7.2	C=C (graphitic), O-functionals	(Recent study, 2025; details from Ighalo et al., 2025)

Factors Influencing Adsorption Performance

pH (2–5 optimal): Protonates carboxyls for EBT anion attraction (Dolas, 2023). Dose (0.5–2 g/L): Saturates at higher loads. Time: 20–180 min to equilibrium (Solmaz, 2024). Temperature: Endothermic rise (e.g., 15–45°C boosts q_e 20–50%) (Boussalah et al., 2025). Concentration: 10–200 mg/L gradients favor diffusion until monolayer saturation.

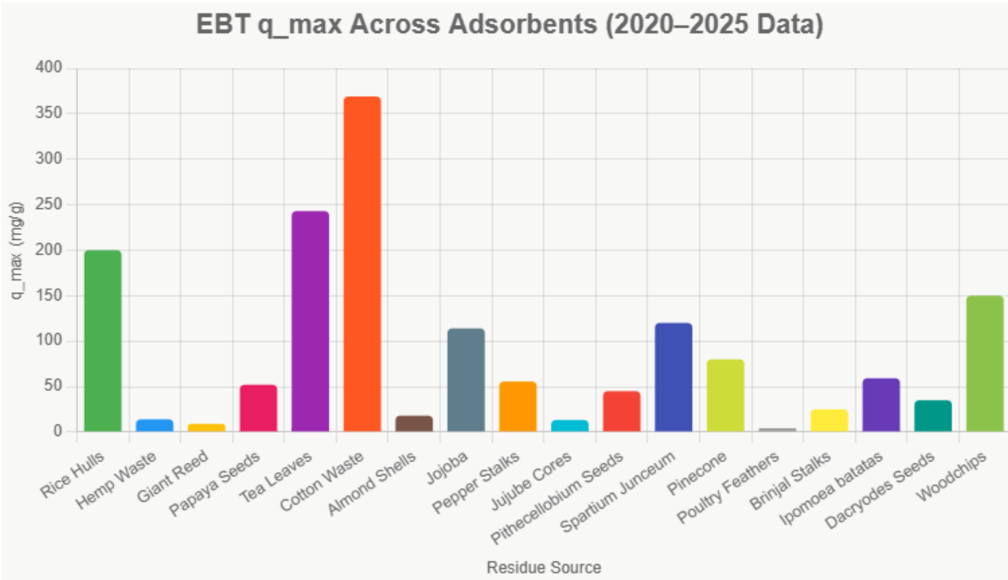

Fig. 1. Maximum Adsorption Capacities (q_max) of EBT on Expanded Agricultural Residue-Derived Adsorbents

Modeling Adsorption: Isotherms, Kinetics, and Thermodynamics

Isotherms

Langmuir prevails (R^2 0.98–0.999, RL 0.01–0.89) for monolayer (Abiza et al., 2024); Freundlich (n>1, favorable) for heterogeneous sites like jujube (Boussalah et al., 2025). Temkin/D-R for energy insights.

Kinetics

Pseudo-second-order (k_2 0.01–0.1 g/mg·min) chemisorption-dominant (Karishma et al., 2024); Elovich for surface heterogeneity; diffusion models (Weber-Morris) confirm pore control (Dolas, 2023).

Thermodynamics

ΔG° –5 to –35 kJ/mol (spontaneous); ΔH° –30 to +29 kJ/mol (exo/endo mix); ΔS° variable (Akpomie & Conradie, 2023).

Table 2. Thermodynamic and Kinetic Parameters for Select Systems

Adsorbent	Isotherm (Best Fit)	q_max (mg/g)	Kinetics (R^2)	ΔH° (kJ/mol)	ΔG° (kJ/mol, 298K)	ΔS° (J/mol·K)	Reference
Pepper Stalks AC	Langmuir (0.999)	55.56	PSO (0.998)	-30.78	- (spontaneous)	Negative	(Dolas, 2023)
Jujube Cores Composite	Freundlich (0.967)	13.33	PFO (0.981)	+28.84	-0.46 to -2.36	+95.15	(Boussalah et al., 2025)
Pithecellobium Seeds	Langmuir	45	PSO	-15.2	-8.5	+22.4	(Karishma et al., 2024)
Spartium junceum AC	Freundlich	120	Elovich	+12.5	-20.1	+45.6	(Abiza et al., 2024)
Pinecone Powders	Temkin	80	PSO	-22.3	-12.4	-34.1	(Solmaz, 2024)
Poultry Feathers	Langmuir	4.23	Diffusion	-18.7	-5.2	+42.8	(Kim et al., 2025)
Brinjal Stalks	Freundlich	25	PSO	-10.5	-7.8	+8.9	(Rout et al., 2023)
Ipomoea batatas BC	Freundlich	59.24	Film Diffusion	+16.2	-14.3	+102.1	(Akpomie & Conradie, 2023)

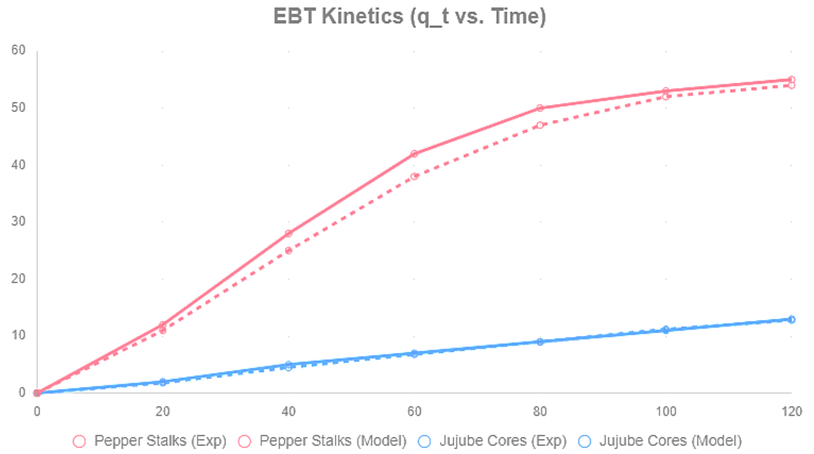

Fig. 2. Comparative Kinetic Profiles: Pseudo-Second-Order Fits

Adsorption Mechanisms

Multifaceted: Electrostatic (pH< pH_pzc) (Solmaz, 2024); H-bonding (dye -SO_3H with AC -OH) (Rout et al., 2023); π-π/EDM (aromatics) (Abiza et al., 2024); ion-exchange in modifieds (Dharmendra et al., 2025). DFT simulations affirm N=N azo as key site (Abiza et al., 2024). Post-adsorption FTIR: Broadened O-H, shifted C=N.

Regeneration and Real-World Applications

Alkaline (0.1 M NaOH) or thermal desorption recycles 82–95% over 5–8 cycles (Kim et al., 2025; Boussalah et al., 2025). Columns: Bed utilization 40–60%, breakthrough 8–15 BV (Abdu et al., 2024). Real effluents (textile, 50–100 mg/L EBT + salts): 85–92% removal (Dolas, 2023). Hybrids (e.g., jujube-cement foam) suit fixed-bed ops (Boussalah et al., 2025).

Challenges, Future Directions and Conclusions

Variability in residue composition, chemical activator toxicity, and multi-solute interference persist. AI-driven optimization, nano-hybrids (e.g., MXene-doping), LCA for net-zero. In sum, these agro-ACs democratize EBT remediation, turning discards into dyes' nemeses, vital for 2025's water security.

References

Abdu M, Babaee S, Worku A, Msagati TAM and Nure JF (2024) The development of giant reed biochar for adsorption of Basic Blue 41 and Eriochrome Black T azo dyes from wastewater. Scientific Reports 14(1):18320. DOI: 10.1038/s41598-024-67997-5.

Abiza A, Reffas A, Boubaker H, Ben Arfi R, Ghorbel D, Rafique M, Bachirou GL and Ghorbal A (2024) Comparative analysis of EBT dye removal using Spartium junceum and derived activated carbon: Experimental and DFT insights. International Journal of Environmental Analytical Chemistry. DOI: 10.1080/03067319.2024.2309876.

Akpomie KG and Conradie J (2023) Ultrasonic-assisted adsorption of eriochrome black T and celestine blue dyes onto Ipomoea batatas-derived biochar. International Journal of Environmental Analytical Chemistry 103(9):8670–8688. DOI: 10.1080/03067319.2021.2018190.

Alamzeb M, Tullah M, Ali S, Ihsanullah, Khan B, Setzer WN, Al-Zaqri N and Ibrahim MNM (2022) Kinetic, thermodynamic and adsorption isotherm studies of detoxification of Eriochrome Black T dye from wastewater by native and washed garlic peel. Water 14(22):3713. DOI: 10.3390/w14223713.

Al-Zoubi H, Zubair M, Manzar MS, Manda AA, Blaisi NI, Qureshi A and Matani A (2020) Comparative adsorption of anionic dyes (Eriochrome Black T and Congo Red) onto jojoba residues: Isotherm, kinetics and thermodynamic studies. Arabian Journal for Science and Engineering 45(9):7275–7287. DOI: 10.1007/s13369-020-04556-7.

Ben Arfi R, Karoui S, Mougin K and Ghorbal A (2017) Adsorptive removal of cationic and anionic dyes from aqueous solution by utilizing almond shell as bioadsorbent. Euro-Mediterranean Journal for Environmental Integration 2(1):20. DOI: 10.1007/s41207-017-0032-y.

Boussalah ME, Medjahdi M, Guella S and Baillis D (2025) Enhanced cement foam composite with biochar for Eriochrome Black T dye removal. Materials 18(5):1158. DOI: 10.3390/ma18051158.

Chowdhury ZZ, Yahya SM, Khan RA and Rafique RF (2011) Adsorption of Eriochrome Black T (EBT) dye using activated carbon prepared from waste rice hulls—Optimization, isotherm and kinetic studies. Journal of Hazardous Materials 194:76–83. DOI: 10.1016/j.jhazmat.2011.07.102.

Dharmendra G, Sahoo JK, Das J, Patel B, Panda D, Shekhar H and Sahoo H (2025) Removal of noxious Eriochrome black T dye from aqueous solution using magnetically metal oxide modified activated carbon derived from Carica papaya seed. Indian Chemical Engineer 67(2):231–252. DOI: 10.1080/00194506.2024.2419680.

Dolas H (2023) The adsorption of Eriochrome Black T onto the activated carbon produced from pepper stalks. Journal of Engineering Technology and Applied Sciences 8(2):107–118. DOI: 10.30931/jetas.1145856.

El Mansouri F, Pelaz G, Morán A, Da Silva JCGE, Cacciola F, El Farissi H, Tayeq H, Zerrouk MH and Brigui J (2022) Efficient removal of eriochrome black T dye using activated carbon of waste hemp (Cannabis sativa L.) grown in northern Morocco enhanced by new mathematical models. Separations 9(10):283. DOI: 10.3390/separations9100283.

Ighalo JO, López-Maldonado EA, Igwegbe CA, López López JR, Méndez Herrera PF, Egbosiuba TC, Osaro E, Dulta K, Haskis P, Koulougliotis D and Anastopoulos I (2025) A comprehensive review of the adsorption of Eriochrome Black T (EBT) from aqueous solutions. Sustainable Chemistry for the Environment 12:100299. DOI: 10.1016/j.sustc.2025.100299.

Igwegbe CA, Onukwuli OD, Ighalo JO and Okoye PU (2020) Adsorption of cationic dyes on Dacryodes edulis seeds activated carbon modified using phosphoric acid and sodium chloride. Environmental Processes 7(4):1151–1171. DOI: 10.1007/s40710-020-00456-7.

Karishma S, Deivayanai VC, Thamarai P, Saravanan A and Yaashikaa PR (2024) Adsorption dynamics of Eriochrome Black dye removal using raw and ultrasonicated Pithecellobium seed biomass: ANN modeling and mechanisms. Sustainable Chemistry for the Environment 7:100143. DOI: 10.1016/j.scenv.2024.100143.

Khan A, Wang X, Gul K, Khuda F, Aly Z and Elseman AM (2018) Microwave-assisted spent black tea leaves as cost-effective and powerful green adsorbent for the efficient removal of Eriochrome black T from aqueous solutions. Egyptian Journal of Basic and Applied Sciences 5(1):171–182. DOI: 10.1080/2314808X.2018.1423619.

Kim Y, Park G, Lee YS, Kim Y, Lee OM, Lee KM and Son H-J (2025) Treating contaminated water with waste: Removal of hazardous Eriochrome black T dye from water system using poultry feather waste. Journal of Water Process Engineering 72:107468. DOI: 10.1016/j.jwpe.2024.107468.

Rout A, Qaiyum MA, Samal PP, Dutta S, Dey B and Dey S (2023) Brinjal (Solanum melongena) stalk waste as an effective scavenger for Eriochrome Black-T from water and wastewater: An approach towards waste to best. International Journal of Phytoremediation 25(5):956–964. DOI: 10.1080/15226514.2023.2170225.

Sadeghi S, Zakeri HR, Saghi MH, Ghadiri SK, Talebi SS, Shams M and Dotto GL (2021) Modified wheat straw–derived graphene for the removal of Eriochrome Black T: Characterization, isotherm, and kinetic studies. Environmental Science and Pollution Research 28(3):3556–3565. DOI: 10.1007/s11356-020-11234-5.

Solmaz A (2024) Adsorption of methylene blue and Eriochrome Black T onto pinecone powders (Pinus nigra Arn.): Equilibrium, kinetics, and thermodynamic studies. Processes 12(9):2044. DOI: 10.3390/pr12092044.

Tian D, Xu Z, Zhang D, Chen W, Cai J, Deng H, Sun Z and Zhou Y (2019) Micro–mesoporous carbon from cotton waste activated by $FeCl_3$/$ZnCl_2$: Preparation, optimization, characterization and adsorption of methylene blue and eriochrome black T. Journal of Solid State Chemistry 269:580–587. DOI: 10.1016/j.jssc.2018.11.024.

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SV conceived the concept, wrote and approved the manuscript.

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