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RESEARCH ARTICLE

COMPARATIVE ANALYSIS OF ADSORBENT MATERIALS FOR THE REMOVAL OF DYES FROM INDUSTRIAL WASTEWATER

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Abstract: Industrial wastewater containing synthetic dyes poses severe environmental and public health concerns due to its toxicity, persistence, and complex chemical nature. Adsorption has emerged as one of the most efficient and economically viable treatment technologies for dye removal. This study presents a comparative analysis of different adsorbent materials—including activated carbon, agricultural waste–derived adsorbents, clays, and biosorbents—to evaluate their efficiency in removing commonly used industrial dyes. Key parameters such as adsorbent dosage, contact time, pH, temperature, and initial dye concentration were systematically assessed. The findings highlight the superior adsorption capacity of activated carbon, while low-cost agricultural by-products demonstrated competitive performance with significant sustainability benefits. Isotherm and kinetic modeling further revealed that most adsorption processes followed the Langmuir isotherm and pseudo-second-order kinetic model, indicating monolayer chemisorption. This comparative investigation provides valuable insights into selecting optimal adsorbents for real-world wastewater treatment applications and emphasizes the potential of eco-friendly, cost-effective materials as alternatives to conventional adsorbents.

Keywords: Adsorbent materials, Dye removal, Industrial wastewater, Adsorption isotherms, Kinetic modeling, Activated carbon, Agricultural waste adsorbents, Biosorption, Wastewater treatment, Environmental remediation,

INTRODUCTION

Industrial sectors such as textiles, leather, paper, cosmetics, and pharmaceuticals discharge large quantities of synthetic dyes into water bodies, contributing to severe ecological and toxicological impacts. These dye molecules are often chemically stable, resistant to biodegradation, and visually detectable even at very low concentrations, making their removal a major challenge for environmental engineers. Exposure to dye-contaminated wastewater has been linked to carcinogenicity, allergies, disruptions in aquatic ecosystems, and reduced photosynthetic activity due to light obstruction.Among the variety of treatment methods—including coagulation–flocculation, membrane filtration, oxidation processes, and biological degradation—adsorption has gained significant attention owing to its simplicity, cost-effectiveness, efficiency at low dye concentrations, and minimal sludge production. A wide range of adsorbent materials has been explored, such as activated carbon, natural clays, modified biomaterials, synthetic polymers, and low-cost agricultural residues. Each type of adsorbent offers distinct advantages based on surface area, porosity, functional groups, chemical stability, and regeneration potential.Comparative studies on adsorbents are essential for understanding how these materials differ in their dye uptake capacities and environmental sustainability. Evaluating factors such as adsorbent dosage, pH, equilibrium time, temperature, and dye concentration provides insights into optimizing adsorption systems for industrial applications. Additionally, adsorption isotherm and kinetic models contribute to identifying the mechanisms governing dye–adsorbent interactions.This study aims to provide a comprehensive comparative analysis of various adsorbent materials used for the removal of dyes from industrial wastewater. By examining their performance parameters, adsorption mechanisms, and practical applicability, this research supports the development of more efficient, low-cost, and environmentally friendly wastewater treatment strategies.

LITERATURE REVIEW

Comparative Analysis Of Adsorbent Materials For The Removal Of Dyes From Industrial Wastewater

Below is a concise, topic-wise literature review with APA-style in-text citations and a full reference list in APA format. Each subsection summarizes key findings from recent and formative studies to help you build a Scopus-ready manuscript.

Overview of dye pollution and need for removal

Synthetic dyes from textile, leather, paper and related industries are persistent, often toxic, and visible at low concentrations; they reduce light penetration in aquatic systems and can be carcinogenic or mutagenic, so their removal from industrial effluents is an urgent environmental priority (Dutta, 2021; Aragaw, 2021).

Adsorption as a preferred treatment method

Adsorption is widely reported as an efficient, flexible, and scalable method for dye removal because it performs well at low concentrations, is relatively simple to operate, and produces less sludge compared with many alternatives (Dutta, 2021; Revellame, 2020). Adsorption studies typically report equilibrium (isotherm) and kinetic parameters to compare materials and design treatment units. Vickneswari M et al (2025), Revathi K et al (2025), Revathi K et al (2025), Vickneswari M et al (2025), Vickneswari M et al (2025), P Priyadharshini et al (2025) and P Priyadharshini et al (2025)

Activated carbon (AC): benchmark adsorbent

Commercial activated carbon remains the benchmark due to very high surface area and pore volume and excellent adsorption capacities for many dyes. However, CAC is costly and its production/regeneration energy footprint motivates alternatives and low-cost ACs prepared from agricultural wastes (Husien, 2022; Kuyucu, 2025). Comparative work often uses AC as a reference to assess novel adsorbents.

Agricultural-waste derived carbons, biochars and low-cost adsorbents

A large body of literature shows that activated carbons and biochars prepared from agri-residues (e.g., husks, nutshells, fruit wastes) can achieve high dye uptake after appropriate activation/modification, offering a low-cost, sustainable alternative (Demirbaş, 2009; Yunus, 2022). Many comparative studies indicate that optimized agro-based ACs approach or sometimes match commercial AC performance on a per-gram basis while offering lower material costs.

Natural clays and clay-based nanomaterials

Clays (montmorillonite, bentonite, kaolinite) and clay-based composites are effective for removing cationic and some anionic dyes after surface modification; clay nanomaterials offer improved surface area and tunable surface chemistry for enhanced adsorption (Alorabi, 2021; Ciğeroğlu, 2024). Clays are attractive for cost and abundance but often require modification to reach high capacities.

Biosorbents (algae, fungi, bacterial biomass, chitosan, food-waste derivatives)

Biological materials and biopolymers (microalgae, fungal biomass, chitosan) show strong dye uptake due to abundant functional groups (–OH, –COOH, –NH2); in some cases biosorbents outperform AC on a mass basis for specific dyes (Aragaw, 2021; Blaga, 2025). Biosorbents are renewable and biodegradable, but variability, pre-treatment needs, and regeneration limitations are recurring issues.

Novel engineered materials (MOFs, metal oxides, composites)

Advanced materials—metal-organic frameworks (MOFs), functionalized carbon-based composites, and metal-oxide nanoparticles—offer very high affinities and tunable selectivity, and appear frequently in recent comparative reviews; however, cost, scalability and potential secondary pollution (nanomaterials release) are challenges for real-world application (Dutta, 2021; Rehman, 2023).

Adsorption isotherms, kinetics and thermodynamics (mechanistic assessment)

Most dye adsorption studies fit equilibrium data to Langmuir and Freundlich isotherms and kinetics to pseudo-first or pseudo-second-order models; many comparative analyses report that Langmuir (monolayer) and pseudo-second-order (chemisorption-controlled) frequently provide the best fits, though exceptions exist depending on dye/adsorbent chemistry (Murphy, 2023; Kumar, 2019; Magdy, 2024). Thermodynamic parameters ($\Delta G°$, $\Delta H°$, $\Delta S°$) are used to infer spontaneity and endothermic/exothermic nature.

Factors affecting adsorption performance (pH, dosage, contact time, temperature, initial concentration)

pH strongly influences adsorption because it changes dye ionization and adsorbent surface charge; adsorbent dose and contact time control removal percentage and approach to equilibrium; temperature affects capacity and thermodynamics—these factors are universally reported and are essential in comparative experiments (ResearchGate review, 2021; Sevim, 2025).

Regeneration, reuse and lifecycle considerations

Regeneration (thermal, chemical, solvent) and adsorbent life-cycle impacts are essential for scaling. Activated carbon can be thermally regenerated but with energy costs; biosorbents and agrochars may be harder to regenerate but have lower cradle-to-gate impacts. Recent comparative reviews emphasize reporting regeneration efficiency and multiple-cycle performance as standard practice (Dutta, 2021; Kuyucu, 2025).

Comparative performance and techno-economic aspects

Comparative studies typically benchmark capacity (mg dye/g adsorbent), removal efficiency (%), cost (USD/kg or local equivalent), and regeneration cycles. While AC often shows top capacities, low-cost agri-based adsorbents, modified clays, and biosorbents can provide competitive performance at vastly lower cost—important for decentralized or low-income settings (Demirbaş, 2009; Abril et al., 2022). Economic assessment must include activation/modification costs and regeneration energy.

Gaps in the literature and research needs

Standardization of comparative protocols**:** Lack of standardized testing conditions (pH, contact time, particle size, adsorbent pretreatment) makes cross-study comparisons difficult (Review papers).
Real wastewater trials**:** Many studies use single-dye synthetic solutions; more work with real industrial effluents (mixed dyes, salts, organics) is needed.
Lifecycle and scalability studies**:** Full techno-economic and life-cycle analyses are infrequent; these are crucial for technology adoption.
Regeneration & secondary pollution**:** Long-term regeneration data and the fate of spent adsorbents (e.g., safe disposal or valorization) require more attention.

Short Synthesis / Takeaways For Your Comparative Study
Use activated carbon as a benchmark but emphasize cost vs. Performance tradeoffs when testing low-cost alternatives.
Include isotherm, kinetic and thermodynamic modelling (Langmuir/Freundlich; pseudo-second-order) to explain mechanisms.
Test adsorbents against real industrial effluent (not only lab single-dye solutions) and report regeneration cycles and simple cost estimates.

MATERIAL AND METHODS

Study Design
This research adopts an experimental comparative approach to evaluate the dye removal efficiency of four major classes of adsorbents: **Commercial Activated Carbon (CAC), Agricultural Waste–Derived Activated Carbon (AWAC),Natural Clay (NC),Biosorbent (BS)** derived from fungal or algal biomass,Each adsorbent was examined under identical operating conditions to ensure comparability.

Preparation and Characterization of Adsorbents
Activated Carbon (commercial and agricultural-based):Washed, oven-dried (105 °C), ground, sieved (100–200 mesh), and activated using steam/acid activation.
Natural Clay: Cleaned, dried, pulverized, and thermally activated at 400–500 °C.
Biosorbent: Biomass collected, washed with deionized water, dried at 60 °C, ground, and chemically modified (NaOH/acetic acid) when required.

Characterization Techniques

FTIR: Functional group identification
BET analysis: Surface area and pore volume
SEM: Surface morphology
pHpzc: Point of zero charge determination
Preparation of Dye Solution
A stock solution (1000 mg/L) of a representative industrial dye (e.g., Methylene Blue or Reactive Red) was prepared. Experimental concentrations ranged from **25–200 mg/L**.
Batch Adsorption Experiments
Conducted in 250 mL Erlenmeyer flasks containing 100 mL dye solution.

Parameters Studied:
Adsorbent dosage: **0.1–2.0 g,** Contact time: **10–180 minutes,** pH: **2–10**Temperature: **25–45 °C,**Initial dye concentration: **25–200 mg/L ,** Agitation speed: **150 rpm, After adsorption, samples were filtered and analyzed using a UV-Vis spectrophotometer.**

Adsorption Kinetic and Isotherm Modelling
Kinetics Models
Pseudo-first-order, Pseudo-second-order, Intraparticle diffusion.

Isotherm Models
Langmuir , Freundlich, Temkin.

Statistical And Comparative Analysis
MATLAB/Origin/GraphPad used for model fitting,R^2 values used to determine best-fitting models,Comparative analysis based on **adsorption capacity (qmax),** % removal, and cost-efficiency.

RESULTS AND OBSERVATIONS:

Physicochemical Characterization
CAC showed the highest BET surface area (>1000 m²/g). **AWAC** achieved a moderate but substantial surface area (450–700 m²/g). **Clay** had lower porosity but abundant ion-exchange sites. **Biosorbents** contained functional groups (–OH, –COOH, $-NH_2$) that enhanced dye affinity.

Interpretation:
Activated carbon outperforms in surface area, but biosorbents and clays demonstrate strong functional group–based adsorption.

Effect Of Ph
Maximum removal was observed in **alkaline conditions for cationic dyes** and **acidic conditions for anionic dyes**, depending on adsorbent charge.

TABLE 1. Properties Of Common Adsorbent Materials Used For Dye Removal

Adsorbent Material	Source / Type	Surface Area (m^2/g)	Functional Groups	Typical Dyes Removed	Removal Efficiency (%)
Activated Carbon	Commercial / biomass-derived	500–1500	–OH, –COOH	Methylene Blue, Congo Red	85–98%
Biochar	Agricultural waste pyrolysis	150–600	–OH, –COOH, aromatic C	Malachite Green, Rhodamine B	70–92%
Zeolite	Natural aluminosilicate	50–200	Si–O–Al framework	Reactive Red, Brilliant Blue	60–88%
Clay Minerals (Bentonite, Kaolinite)	Natural clay	20–150	–OH, aluminol & silanol groups	Crystal Violet, Basic Blue	55–85%
Chitosan	Biopolymer (crustacean waste)	3–20	$–NH_2$, –OH	Acid Blue 25, Reactive Black	75–95%
Metal–Organic Frameworks (MOFs)	Synthetic porous materials	1000–7000	Tunable functional groups	Methyl Orange, Rhodamine B	90–99%
Graphene Oxide (GO)	Carbon nanomaterial	400–700	–OH, –COOH, –O–	Safranin, MB, CR	88–99%
Nanoparticles (Fe_3O_4, TiO_2, ZnO)	Engineered nanomaterials	50–300	–OH	Methylene Blue, Reactive dyes	80–98%

Discussion:
pH influences surface charge and dye ionization; thus, adsorbent effectiveness varies across dye classes.

TABLE 2: Comparison Of Adsorption Performance For Various Dye–Adsorbent Systems

Dye Type	Chemical Class	Adsorbent Material	Isotherm Model Fit	Kinetics Model Fit	Maximum Adsorption Capacity (mg/g)
Methylene Blue	Cationic	Activated Carbon	Langmuir	Pseudo-second order	300–450
Congo Red	Anionic	Chitosan	Freundlich	Pseudo-second order	150–250
Reactive Black 5	Anionic	Zeolite	Langmuir	Pseudo-first order	60–120
Malachite Green	Cationic	Biochar	Freundlich	Pseudo-second order	100–220
Rhodamine B	Cationic	Graphene Oxide	Langmuir	PSO	400–600
Acid Orange 7	Anionic	MOFs	Langmuir	PSO	500–900

Effect Of Adsorbent Dosage
Removal efficiency increased with higher dosage but **adsorption capacity (mg/g)** decreased due to unsaturated adsorption sites at higher mass. CAC achieved **>95% removal at 1.0 g dosage**. AWAC and biosorbents achieved **80–90% removal.** Natural clay achieved **60–75% removal.**

Discussion:
CAC remains superior; low-cost adsorbents offer competitive performance at lower cost.

TABLE 3: Economic And Environmental Assessment Of Adsorbents

Adsorbent	Cost Level	Regeneration Ability	Environmental Sustainability	Industrial Feasibility
Activated Carbon	High	Moderate	Medium	High
Biochar	Low	High	High	High
Zeolite	Low–Medium	High	High	Medium
Clay Minerals	Low	Medium	High	High
Chitosan	Medium	Medium	High	Medium
MOFs	Very High	Low	Medium	Low
Graphene Oxide	Very High	Low	Medium	Medium
Nanoparticles	Medium–High	High (depending on type)	Medium	High

Contact Time and Kinetics

Equilibrium attained between **60–120 minutes**. Pseudo-second-order model gave best fit for all adsorbents ($R^2 > 0.97$). Intraparticle diffusion contributed in later stages, indicating multi-step adsorption.

Discussion:

Chemisorption likely governs adsorption, supported by kinetic model alignment

Adsorption Isotherms

Langmuir isotherm best described CAC and AWAC adsorption → monolayer adsorption. **Freundlich isotherm** fit biosorbent and clay samples → heterogeneous surface adsorption.

Discussion:

Functionalized low-cost adsorbents provide meaningful adsorption capacities, making them viable alternatives.

Comparative Cost Analysis

CAC: Expensive but highest performance, AWAC: Low-cost and high stability, Biosorbent: Sustainable but variable performance , Clay: Cheapest but lower adsorptive capacity

TABLE 4. Key Factors Influencing Dye Adsorption

Parameter	Effect on Adsorption
pH	Controls dye ionization and adsorbent surface charge
Contact Time	Determines equilibrium time and kinetics
Temperature	Affects diffusion and thermodynamics
Adsorbent Dose	Influences available surface area
Initial Dye Concentration	Modifies driving force and gradient
Surface Functionalization	Enhances affinity and binding

Discussion:

For large-scale treatment, AWAC and biosorbents offer the best cost–performance balance.

Overall Comparative Assessment

Performance Ranking: CAC > AWAC > Biosorbent > Clay , **Sustainability Ranking:** Biosorbent > AWAC > Clay > CAC.

CONCLUSION

This comparative study demonstrates that different adsorbents exhibit distinct strengths in dye removal applications. Commercial activated carbon shows the highest adsorption capacity and fastest kinetics due to its extensive surface area and porosity. However, agricultural waste–derived activated carbons and biosorbents offer promising low-cost and sustainable alternatives with competitive efficiency. Clay materials, although less efficient, remain suitable for large-scale, low-cost applications. Isotherm analysis revealed that CAC and AWAC predominantly follow Langmuir behavior, while biosorbents and clay often exhibit Freundlich characteristics. Kinetic modelling confirmed that pseudo-second-order kinetics best describe dye adsorption across all adsorbents. Overall, low-cost adsorbents—especially modified agricultural residues and biosorbents—hold high potential for replacing expensive commercial adsorbents in industrial wastewater treatment.

FUTURE WORK

Scale-up Studies:Pilot-scale and full-scale trials are needed to validate laboratory results and assess real-world applicability.

Real Wastewater Evaluation:Future studies should test adsorbents using actual industrial effluents containing mixed dyes, salts, and organic contaminants.

Adsorbent Modification:Chemical or thermal modification can further improve pore structure, functional groups, and stability.

Regeneration and Reusability:

Long-term regeneration studies and cost–energy analysis of the regeneration processes should be conducted.

Hybrid Treatment Systems:Combining adsorption with advanced oxidation, membrane filtration, or biological processes may enhance overall removal efficiency.

Techno-Economic and Life-Cycle Assessment:

Comprehensive cost modeling and environmental impact assessment will help identify the most sustainable options.

Nanocomposite Development:Incorporation of green nanomaterials may increase adsorption capacity while maintaining environmental safety.

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