



Development of a Magnetic Date Seed Powder-based Nanocomposite for Sustainable Adsorptive Treatment of Safranin O-contaminated Water

N. P. Swetha Menon¹, S. Jayapriya², S. Srividhya³, V. Bhanu Rekha⁴, G. Malarvizhi⁵ and A. Jose Anand^{6*}

¹Department of Fashion Designing, SRM Institute of Science and Technology, Ramapuram, Chennai, TN, India

²Department of Costume Design and Fashion, Nehru Arts and Science College, Thirumalayampalayam, Coimbatore, TN, India

³Department of Fashion Design, STUDIO Design School, Saveetha Institute of Medical and Technical Sciences (SIMATS), Chennai, TN, India

⁴Department of Fashion Designing, SRM Institute of Science and Technology, Ramapuram, Chennai, TN, India

⁵Department of Costume Design and Fashion, KPR College of Arts Science and Research, Coimbatore, TN, India

⁶Department of Electronics and Communication Engineering, KGC College of Technology, Karapakkam, Chennai, TN, India

Received: 04.06.2026 Accepted: 10.06.2026 Published: 30.06.2026

*joseanand97@gmail.com



ABSTRACT

This study addresses the growing demand for sustainable adsorbent materials at wastewater treatment by detailing physicochemical characterization, adsorption efficacy and environmentally friendly synthesis of epichlorohydrin-crosslinked Date Seed Powder nanocomposite (ECH-DSP) for elimination of Safranin O (SO) dye from polluted aqueous systems. The novelty of this work lies in the development of an epichlorohydrin-crosslinked date seed powder nanocomposite derived from agricultural waste, providing a sustainable adsorbent with enhanced surface functionality and adsorption properties for dye-contaminated wastewater treatment. The synthesized adsorbent underwent thorough examination through Fourier transform infrared spectroscopy (FTIR), Brunauer–Emmett–Teller (BET) surface area analysis, zeta potential measurements, and X-ray diffraction (XRD) to assess its surface topology, crystalline structure, surface functionalities, suspension stability, and pore distribution. The adsorption capacity of the synthesized nanocomposite was methodically assessed by altering operational parameters, including solution pH, adsorbent concentration, ionic concentration, interaction time, and initial dye concentration. Kinetic studies established that the adsorption mechanism primarily adhered to the pseudo-second-order kinetic model, with boundary layer diffusion and intraparticle diffusion also affecting the overall adsorption process. Equilibrium investigations demonstrated that the adsorption behavior conformed most closely to the Langmuir isotherm, signifying monolayer adsorption on a uniform surface. Furthermore, Dubinin–Radushkevich isotherm analysis suggested that the adsorption process was predominantly governed by physical interactions. Moreover, treatment of real textile wastewater collected from a textile dyeing facility showed maximum color elimination effectiveness of 75.09% under optimum experimental circumstances. The evaluations of regeneration and reusability indicated that the adsorbent maintained substantial adsorption-desorption efficiency after five successive cycles, indicating acceptable regeneration performance and reusability over repeated adsorption-desorption cycles. The results demonstrate that m-ECH-DSP were viable adsorbent for dye-contaminated wastewater treatment for promising treatment of dye-contaminated industrial wastewater.

Keywords: Date seed powder nanocomposite; Safranin O adsorption; Epichlorohydrin crosslinking; Textile wastewater treatment; Adsorption kinetics.

1. INTRODUCTION

Growing environmental pollution from dye-containing industrial wastewater poses serious environmental and human health risks due to the toxic and non-biodegradable nature of synthetic dyes (Kumar *et al.* 2026). Conventional treatment methods often exhibit limitations, including high cost, sludge formation, and low removal efficiency (Chowdhury *et al.* 2026). Therefore, sustainable biomass-derived nanocomposite adsorbents have gained significant attention owing to their eco-friendly nature, low cost, high adsorption efficiency, and excellent reusability for wastewater remediation applications (Rao *et al.* 2025). Safranin O is

a cationic dye extensively used in textile, leather, biological staining, and printing industries. The discharge of Safranin O-containing effluents into aquatic environments can adversely affect water quality due to its persistence, intense coloration, and potential toxic effects on aquatic organisms. Therefore, the development of efficient and sustainable adsorbents for Safranin O removal remains an important environmental challenge. Date seed-derived materials and ZnO-based nanocomposites have recently attracted considerable attention for wastewater remediation owing to their low cost, eco-friendly nature, high adsorption efficiency, and photocatalytic performance. Date seed powder bio-adsorbent synthesized for methylene blue removal from

wastewater under optimized conditions, where the developed model showed strong agreement with experimental findings (Osman *et al.* 2022). Similarly, date seed powder bio-adsorbent synthesized for methylene blue removal exhibited a Langmuir adsorption capacity of 76.652 mg g⁻¹ and followed pseudo-second-order kinetic behavior, indicating efficient dye adsorption through electrostatic interaction and intraparticle diffusion mechanisms (Narasimharao *et al.* 2022). Despite these promising results, the practical application of unmodified date seed powder remains limited by its relatively low surface functionality, restricted number of active adsorption sites, poor mechanical stability, and difficulties associated with adsorbent recovery and reuse. These limitations necessitate suitable modification strategies to improve adsorption performance and operational applicability. Magnetic biosorbents have recently attracted considerable interest owing to their facile separation from treated water and enhanced reusability. Various magnetic biochar-, cellulose-, and agricultural waste-derived adsorbents have demonstrated efficient removal of dyes and heavy metals. However, many reported systems involve complex synthesis procedures, costly precursors, or limited regeneration performance, creating a need for sustainable and economically viable magnetic biosorbents derived from abundant agricultural residues.

The incorporation of nanomaterials into date seed-derived adsorbents has further enhanced wastewater treatment performance. In addition to biomass-derived adsorbents, nanostructured materials such as ZnO-based systems have been widely investigated for wastewater treatment applications. These studies highlight the beneficial role of nanomaterial incorporation in enhancing pollutant removal efficiency and provide useful insights for designing advanced adsorption systems. A Ni-Fe LDH/DSP composite synthesized for moxifloxacin removal achieved a maximum adsorption capacity of 251.6 mg/g with enhanced antibacterial and antifungal activities (Mahmoud *et al.* 2025).

ZnO-based membrane and nanoparticle systems have also shown remarkable dye and heavy metal removal efficiencies. PANI/ZnO-modified polystyrene membranes demonstrated superior hydrophilicity, permeability, and antifouling behavior while achieving high dye rejection efficiencies (Sichali *et al.* 2025). ZnO nanoparticles synthesized through co-precipitation achieved 99.08% methylene blue degradation within 70 min and retained excellent recyclability after repeated cycles (Elmorsi *et al.* 2026). Biosynthesized ZnO nanoparticles prepared using *Plantago lanceolata* leaf extract exhibited strong antibacterial, antioxidant, and photocatalytic activities with excellent colloidal stability and crystalline structure (Worku, 2025). Similarly, ZnO nanoparticles synthesized using melon peel and seed extracts demonstrated effective methyl orange degradation, highlighting the suitability of agricultural

waste-derived nanomaterials for sustainable wastewater remediation (Bozkurt *et al.* 2026).

Several ZnO hybrid composites have been developed to improve adsorption performance and reusability. PPy/ZnO-NiO nanocomposites achieved a maximum Pb (II) adsorption capacity of 469.56 mg/g following the Langmuir isotherm and pseudo-second-order kinetic models (Abd Ali *et al.* 2024). ZnO nanoparticle-based biocomposites derived from algae extract and banana peel exhibited removal efficiencies above 96% for Pb (II) and Cu (II) ions with excellent regeneration stability (El-Sesy *et al.* 2026). Chitosan-biochar/ZnO hybrid composites prepared from renewable biomass sources achieved adsorption capacities up to 270.21 mg/g for methyl orange removal due to their enhanced surface area and chemisorption behavior (Prabhu *et al.* 2025). Furthermore, ZnO recovered from waste zinc-carbon batteries demonstrated sustainable dye removal performance following pseudo-second-order kinetics and Langmuir adsorption behavior (Hasan *et al.* 2024).

Green-synthesized ZnO-based adsorbents and photocatalysts have also shown significant applicability in environmental remediation. Activated carbon-loaded ZnO nanocomposites synthesized using *Averrhoa carambola* leaf extract exhibited enhanced methylene blue adsorption and photocatalytic degradation due to synergistic interactions between activated carbon and ZnO (Jebanisha and Devi, 2025). ZnO nanoparticles synthesized using *Centella asiatica* extract achieved an adsorption capacity of 152.93 mg/g for ciprofloxacin removal from wastewater (Tran *et al.* 2025). Similarly, green-synthesized ZnO nanoparticles derived from *Citrus limon* peel demonstrated a maximum adsorption capacity of 75.65 mg/g for Anionic Actas Pink dye removal through spontaneous and exothermic adsorption processes (Yousaf *et al.* 2024). Advanced nanocomposite systems integrated with predictive modeling techniques have further improved wastewater treatment efficiency. GO/CoFe₂O₄/ZnO nanocomposites synthesized for fluoride removal achieved efficiencies above 94% using response surface methodology and GRU predictive models (Noor *et al.* 2023). Although considerable progress has been achieved in the development of date seed-derived adsorbents and nanocomposite-based wastewater treatment materials, several challenges remain unresolved. Many reported adsorbents suffer from insufficient structural stability, limited regeneration capability, difficult post-treatment separation, and reduced applicability under practical wastewater conditions. Furthermore, studies focusing on magnetic epichlorohydrin-crosslinked date seed-based adsorbents for efficient Safranin O removal remain scarce, highlighting an important research gap. It was hypothesized that the combined incorporation of epichlorohydrin crosslinking and magnetic functionalization would enhance the structural stability,

adsorption efficiency, separation capability, and reusability of date seed-derived adsorbents. Therefore, the objective of this study was to synthesize and evaluate a magnetic epichlorohydrin-crosslinked date seed powder nanocomposite for the efficient removal of Safranin O from aqueous media. Compared with previously reported date seed-based adsorbents, the proposed material incorporates both epichlorohydrin crosslinking and magnetic functionalization to overcome the limitations of raw date seed powder, including poor structural integrity and difficult recovery after adsorption. This dual-modification strategy is expected to improve adsorption performance while facilitating convenient magnetic separation and repeated reuse.

This investigation introduces a novel magnetic epichlorohydrin-crosslinked Date Seed powder nanocomposite (m-ECH-DSP) developed from low-cost agricultural waste for sustainable dye remediation applications. The study uniquely integrates epichlorohydrin crosslinking and magnetic functionalization to enhance structural stability, adsorption efficiency, separation capability, and reusability of the biosorbent. Unlike conventional adsorbents, the synthesized m-ECH-DSP exhibits efficient Safranin O removal under realistic textile wastewater conditions while maintaining significant regeneration performance over multiple adsorption-desorption cycles. The combined evaluation of adsorption kinetics, diffusion mechanisms, isotherm behavior, and real wastewater applicability provides a comprehensive understanding of the adsorption process. This work demonstrates the potential of the synthesized adsorbent for wastewater remediation applications and provides a basis for future investigations on large-scale implementation and long-term operational performance.

2. MATERIALS AND METHODOLOGY

2.1 Chemicals

This study employed analytical-grade chemicals obtained from Sigma-Aldrich, comprising zinc oxide (ZnO), epichlorohydrin (ECH), chitosan, sodium hydroxide (NaOH), hydrochloric acid (HCl), Safranin O (SO) dye and acetic acid (CH₃COOH). All reagents and chemicals were utilized as obtained, without further purification, during the experimental procedures.

2.2 Apparatus

The residual concentration of Safranin O (SO) dye post-adsorption was quantitatively assessed utilizing a Shimadzu UV-1900i UV-Vis Spectrophotometer at a specific maximum absorption wavelength. High-purity deionized water, employed for the formulation of dye solutions, the washing of adsorbents, and all adsorption tests, was provided by Star Scientific equipment, Tamil Nadu, India, to guarantee experimental precision and contamination-free conditions.

2.3 Preparation of ZnO Nanoparticles

The ZnO employed at study was produced by chemical precipitation process, utilizing zinc nitrate hexahydrate (Zn(NO₃)₂·6H₂O) as the precursor and sodium hydroxide (NaOH) as the precipitating agent. A 0.1 M zinc nitrate solution was made by dissolving 2.97 g of Zn(NO₃)₂·6H₂O in 100 mL of deionized water, with continuous magnetic stirring at 400 rpm for 20 minutes to achieve homogeneity. Subsequently, 0.1 M NaOH was incrementally added to the precursor solution until the pH reached roughly 9 while maintaining steady stirring.

The mixture was agitated continuously for 2 hrs at ambient temperature, leading to the development of white precipitates that signify the synthesis of ZnO nanoparticles (Thanikodi and Solairaju, 2026). The reaction mixture was further aged for 12 h at room temperature to facilitate complete precipitation and crystal growth. The final yield of ZnO nanoparticles obtained after drying and calcination was approximately 85%. Precipitate was isolated via centrifugation at 9000 rpm for 10 minutes and subsequently washed many times with deionized water and ethanol to eliminate residual contaminants. The purified precipitate was dried in a hot-air oven at 70 °C for 8 hours and then calcined at muffle furnace at 500 °C for 4 hours to produce crystalline ZnO nanoparticles appropriate for nanocomposite synthesis and adsorption applications.

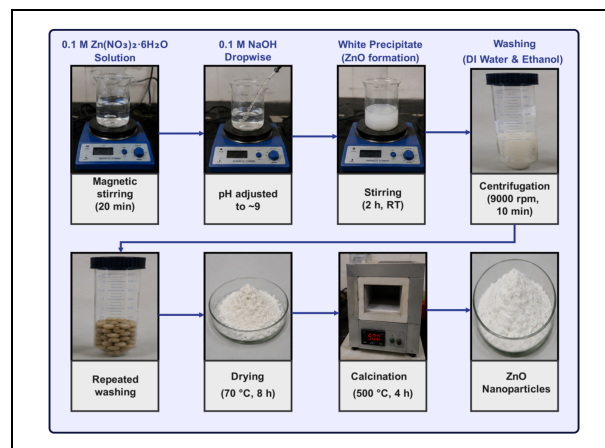


Fig. 1: Preparation of ZnO nanoparticles

2.4 Preparation of m-ECH-DSP Nanocomposite

Date Seed Powder (DSP) sourced from a local market served as the main biomass precursor for the synthesis of m-ECH-DSP nanocomposite adsorbent. The date seeds were first separated from the fruit remnants, meticulously cleaned with deionized water to eliminate surface contaminants, and subsequently dried at hot-air oven at 40 °C. Desiccated seeds were then ground with a mechanical grinder and sifted through a 150 µm screen to achieve consistent particle sizes appropriate for adsorption purposes.

To prepare ZnO-incorporated DSP particles, 0.5 g of DSP powder was dispersed in an aqueous suspension containing XX g of synthesized ZnO nanoparticles under continuous magnetic stirring at ambient temperature for 1 h to ensure uniform interaction among the biomass matrix and ZnO nanoparticles. The resultant suspension was subjected to mild alkaline treatment to improve nanoparticle incorporation onto the DSP surface. The synthesized ZnO/DSP material was thoroughly washed by deionized water until a neutral pH was attained, followed by drying at 70 °C. The dried ZnO/DSP composite powder was subsequently sieved through a 150 µm mesh to ensure uniform particle distribution.

The synthesized magnetic nanoparticles were subsequently dispersed into the ZnO/DSP suspension under continuous stirring to achieve homogeneous magnetic functionalization and uniform distribution throughout the composite matrix. Chitosan and ZnO/DSP were subsequently combined in a weight ratio of 1.5:0.5 and dispersed in 50 mL of 5% acetic acid, continuously stirred for 24 hours at ambient temperature to achieve a homogenous polymeric suspension. This ratio was selected based on preliminary optimization studies and previous reports to achieve adequate bead stability and adsorption performance. The chitosan–ZnO/DSP combination was subsequently added dropwise to 0.5 mol L⁻¹ NaOH to facilitate bead production by coagulation. The synthesized beads were thoroughly rinsed with filtered water until a neutral pH was attained. The beads were chemically crosslinked with a 1% epichlorohydrin solution in a thermostatic water bath at 40 °C for 4 hours to enhance structural stability and adsorption effectiveness. The manufactured magnetic epichlorohydrin crosslinked Date Seed powder nanocomposite (m-ECH-DSP) beads were meticulously cleaned with deionized water and subsequently dried at 30 °C prior to further characterisation and adsorption studies. Fig. 2 depicts the comprehensive fabrication process of the m-ECH-DSP nanocomposite adsorbent.

2.5 Characterization

Total pore volume, mean pore diameter, and specific surface area of the produced m-ECH-DSP nanocomposite were ascertained utilizing a Micromeritics Instrument Corporation ASAP 2020 Plus Surface Area and Porosity Analyzer. Fourier Transform Infrared Spectroscopy Bruker Tensor 27 FTIR Spectrometer was utilized to evaluate surface chemical interactions and functional groups of adsorbents before and after adsorption of Safranin O (SO) dye. FTIR spectra were recorded within the range of 4000–400 cm⁻¹ at a resolution of 4 cm⁻¹.

Crystalline properties and phase composition of the adsorbent were examined by X-ray Diffraction within a diffraction angle range of 10–80° (2θ). Additionally, zeta potential and particle size distribution of the m-

ECH-DSP nanocomposite were assessed using a Zetasizer Nano ZSP instrument to ascertain surface charge and colloidal stability characteristics of the produced adsorbent material. XRD analysis was performed using a scanning range of 10–80° (2θ) at 40 kV and 30 mA.

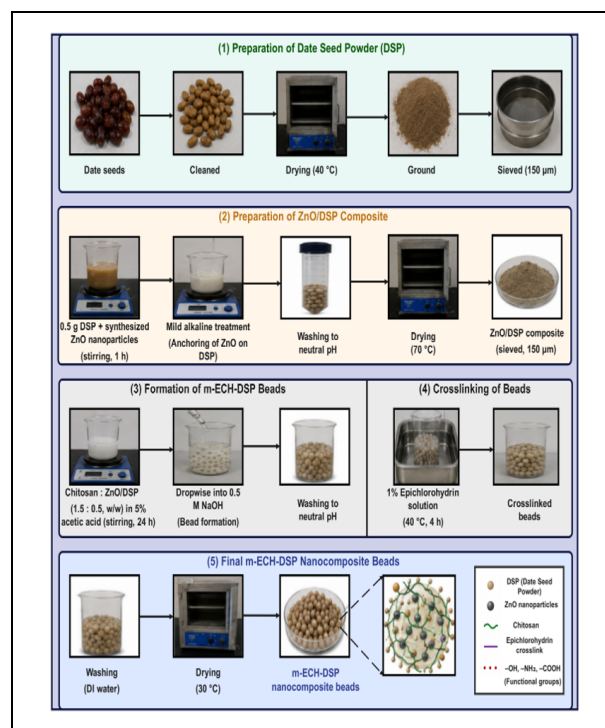


Fig. 2: Fabrication process of m-ECH-DSP nanocomposite

2.6 Adsorption Studies

Batch adsorption experiments were conducted using 100 mL dye solution at 30 ± 2 °C under continuous agitation at 150 rpm using adsorbent dosages ranging from 0.01 to 0.10 g. Adsorption efficiency of the produced m-ECH-DSP nanocomposite for the elimination of Safranin O (SO) dye was methodically assessed under batch adsorption conditions. The impact of critical operational factors includes adsorbent dose, solution pH, interaction time, initial dye concentration, adsorption-desorption reusability cycles, and ionic strength were comprehensively examined to attain optimal adsorption efficiency. The ideal experimental conditions for effective dye removal were established based on the acquired adsorption results. The efficacy of the improved adsorption system was confirmed by the use of actual textile wastewater samples to evaluate the practical performance of the designed adsorbent under realistic environmental circumstances. All adsorption experiments were performed in triplicate, and the reported values represent the mean of three independent measurements.

The adsorption uptake capacity was calculated by the following equation (1):

$$q = \frac{(c_i - c_f)V}{W} \quad \dots (1)$$

Percentage removal efficiency of dye was estimated using equation (2):

$$\% \text{ Removal} = \frac{(c_i - c_f)}{c_i} \times 100 \quad \dots (2)$$

Where:

- q : Equilibrium adsorption capacity (mg g^{-1})
- C_i : Initial adsorbate concentration (mg L^{-1})
- C_f : Final/equilibrium adsorbate concentration (mg L^{-1})
- V : Volume of dye solution (L)
- W : Mass of adsorbent material (g)

The adsorption kinetics of Safranin O dye onto the produced m-ECH-DSP were examined by intraparticle diffusion and pseudo-first-second-order models to identify the adsorption mechanism and rate-controlling processes involved in the process. The equilibrium adsorption behavior was assessed using the Freundlich, Langmuir, and Dubinin–Radushkevich (D–R) isotherm models to analyze adsorption capacity, surface properties, and interaction dynamics between the adsorbent and dye molecules.

The adsorption kinetics were interpreted using the following kinetic equations:
Pseudo-first-order kinetic equation:

$$q_t = q_e(1 - e^{-k_1 t}) \quad \dots (3)$$

Pseudo-second order kinetic equation:

$$q_t = \frac{q_e^2 k_2 t}{1 + q_e k_2 t} \quad \dots (4)$$

Intraparticle diffusion model:

$$q_t = k_i t^{1/2} + C \quad \dots (5)$$

The adsorption equilibrium behavior was evaluated using the following isotherm equations:

Langmuir isotherm equation:

$$q_e = \frac{q_{\max} K_L C_e}{1 + K_L C_e} \quad \dots (6)$$

Freundlich isotherm equation:

$$q_e = K_F C_e^{1/n} \quad \dots (7)$$

The Dubinin–Radushkevich isotherm model was additionally employed to estimate the adsorption

energy and distinguish between physical and chemical adsorption mechanisms. Dubinin–Radushkevich (D–R) isotherm equation (Basumatary *et al.* 2026):

$$q_e = q_{\max} e^{-\beta \varepsilon^2} \quad \dots (8)$$

Here, q_e represents the equilibrium adsorption capacity of Safranin O dye onto the m-ECH-DSP nanocomposite in mg g^{-1} ; $q_{\max}$ defines the highest monolayer adsorption in mg g^{-1} ; and qt shows the dye adsorbed at a certain contact time t in mg g^{-1} . The kinetic constants, k_1 represents the pseudo-first-order rate constant, whereas k_2 represents the pseudo-second-order rate constant.

The Freundlich adsorption constant, denoted as K_F , is measured in L mg^{-1} . K_L represents the Langmuir adsorption equilibrium constant, which pertains to the affinity between adsorbent and adsorbate molecules. Intraparticle diffusion rate constants were shown by k_p ($\text{mg g}^{-1} \text{ min}^{-1}$). The term n denotes the Freundlich intensity factor related to adsorption preference and surface heterogeneity, whereas C signifies the boundary layer thickness constant in the intraparticle diffusion model.

Furthermore, C_e represents the equilibrium concentration of Safranin O dye remaining in the aqueous solution post-adsorption (mg L^{-1}), and t signifies the length of adsorption contact (min). In the Dubinin–Radushkevich isotherm model, β denotes the adsorption energy constant ($\text{L}^2 \cdot \text{mol}^{-2}$), while ε signifies the Polanyi potential. Real textile wastewater was collected from the XX textile industry located at XX. The collected wastewater was filtered to remove suspended solids and stored at 4 °C prior to adsorption experiments. Following adsorption, the spent adsorbent was treated with 0.1 M NaOH solution for 60 min, washed thoroughly with deionized water until neutral pH, dried at 60 °C, and reused for subsequent adsorption cycles.

3. RESULTS AND DISCUSSION

3.1 Physicochemical Properties of m-ECH-DSP Adsorbent

An m-ECH-DSP adsorbent was thoroughly characterized through multiple physicochemical and morphological analysis techniques, including Brunauer–Emmett–Teller (BET) surface area analysis, Fourier Transform Infrared Spectroscopy (FTIR), zeta potential measurements, and X-ray Diffraction (XRD), to assess its surface properties, functional groups, crystalline structure, pore characteristics, and colloidal stability.

3.1.1 BET Surface of m-ECH-DSP Adsorbent

The BET analysis of the synthesized m-ECH-DSP adsorbent provided a specific surface area of 4.92

m²/g before adsorption, which decreased markedly to 0.11 m²/g after SO dye adsorption. This reduction confirms that the available active surface sites of the adsorbent were effectively occupied by Safranin O dye molecules during the adsorption process.

Total pore volume decreased from 0.110 cm³/g before adsorption to 0.00715 cm³/g after adsorption, indicating that SO dye molecules entered and filled the pores of the m-ECH-DSP adsorbent. The substantial increase in average pore radius after adsorption should be interpreted cautiously. This apparent increase is likely associated with the blockage or complete filling of smaller mesopores by Safranin O molecules during adsorption, resulting in their exclusion from nitrogen adsorption measurements. Consequently, only larger residual pores remained accessible for BET characterization, leading to an apparently higher calculated average pore radius. Similar behavior has been reported for dye-loaded bioadsorbents, where pore filling alters the measurable pore size distribution (Tran *et al.* 2017).

These results confirm the adsorption of Safranin O dye onto the m-ECH-DSP surface and support the effective pore-filling and surface-interaction mechanism of the developed adsorbent. Although the measured BET surface area of m-ECH-DSP (4.92 m² g⁻¹) is relatively modest compared with certain porous adsorbents, its adsorption performance can be attributed primarily to the abundance of chemically active functional groups present on chitosan and date seed powder surfaces. Hydroxyl (–OH), amino (–NH₂), and oxygen-containing functional groups provide numerous binding sites for Safranin O molecules through electrostatic attraction, hydrogen bonding, and surface complexation. Therefore, adsorption efficiency is governed not only by surface area but also by surface chemistry and accessibility of active adsorption sites. Previous scholarly works state that the BET analysis revealed that the synthesized CS-AC/ZnO bio-composite possessed a mesoporous surface with a specific surface area of 20.54 m² g⁻¹, providing abundant active sites for Cd²⁺ adsorption. The enhanced surface texture and pore distribution contributed

significantly to the high adsorption efficiency and improved contaminant removal performance (Makhlouf *et al.* 2025).

Table 1. BET surface of the m-ECH-DSP adsorbent

Investigation	Before	After
BET surface area (m ² /g)	4.92	0.11
Total pore volume (cm ³ /g)	0.110	0.00715
Average pore radius (Å)	29.11	411.11

3.1.2 FTIR Spectra of m-ECH-DSP Adsorbent

Fig. 3 depicts FTIR spectra of the produced m-ECH-DSP nanocomposite prior to adsorption (a) and subsequent to Safranin O (SO) dye adsorption (b). The main functional groups associated with chitosan, Date Seed Powder (DSP), epichlorohydrin, and ZnO, including nanocomposite, along with their related peak assignments and spectrum alterations post-dye adsorption were encapsulated in Table 2.

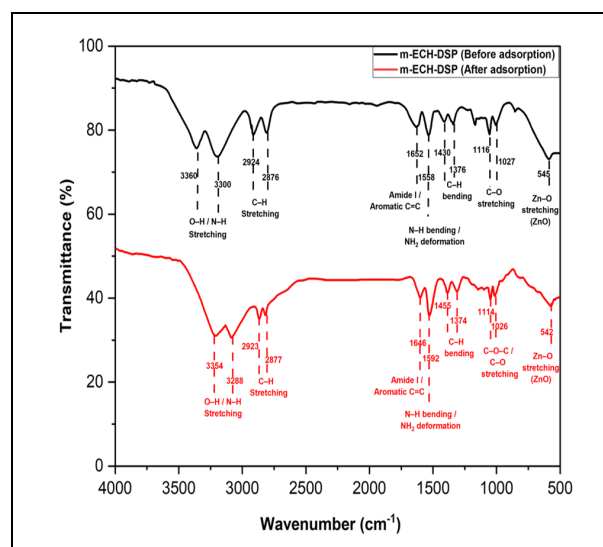


Fig. 3: FTIR spectral analysis of m-ECH-DSP

Table 2. FTIR peak assignments of m-ECH-DSP before and after SO adsorption

Nanocomposite	O–H / N–H Stretching (cm ⁻¹)	C–H Stretching (cm ⁻¹)	Amide I / Aromatic C = C (cm ⁻¹)	N–H Bending / NH ₂ Deformation (cm ⁻¹)	C–H Bending (cm ⁻¹)	C–O/C–O–C Stretching (cm ⁻¹)	Zn–O Stretching (cm ⁻¹)
m-ECH-DSP	3360	2924	1652	1558	1430	1116	545
	3300	2876	-	-	1376	1027	-
m-ECH-DSP+SO	3354	2923	1646	1592	1455	1114	542
	3288	2877	-	-	1374	1026	-

The FTIR spectrum of m-ECH-DSP exhibits broad absorption bands at approximately 3360 and 3300 cm^{-1} due to overlapping N–H and O–H stretching vibrations. An N–H stretching vibration manifests as a weak shoulder peak, resulting from its overlap with the broader and more intense O–H absorption band.

Following the adsorption of Safranin O dye, minor peak shifts were noted at 3354 cm^{-1} and 3288 cm^{-1} , along with additional peak shifts at 1646, 1592, 1455, 1374, 1114, 1026, and 542 cm^{-1} , signifying the interaction among dye molecules and the adsorbent surface. Similar FTIR assignments have been reported for chitosan-based composites and lignocellulosic biomass materials (Coates, 2000). The observed FTIR peak shifts, together with zeta potential and adsorption studies, suggest that electrostatic attraction, hydrogen bonding, and possible π – π interactions may contribute to the adsorption process (Crini and Badot, 2008). Although the proposed mechanism is supported by indirect experimental evidence, additional advanced analyses such as XPS or solid-state NMR would be required for definitive confirmation of individual interaction pathways. The detected peak fluctuations validate the effective adsorption of Safranin O dye onto the m-ECH-DSP surface (Fig. 4).

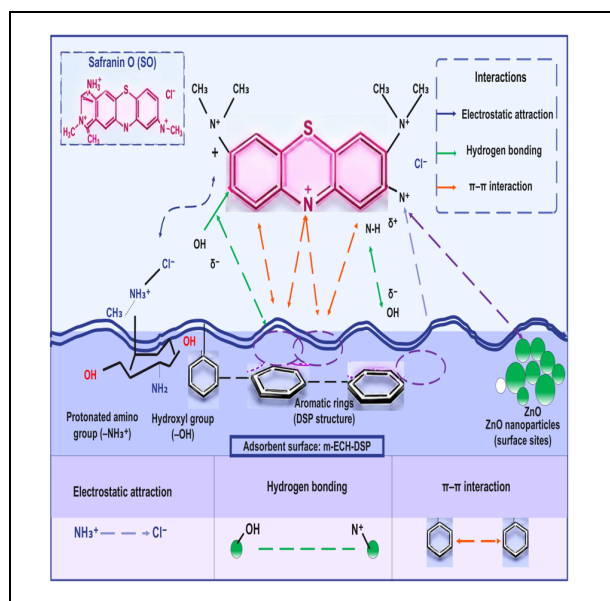


Fig. 4: Proposed adsorption mechanism of SO dye

The aromatic C=C / Amide I vibration at 1652 cm^{-1} before adsorption shifted to 1646 cm^{-1} after adsorption, confirming interaction between Safranin O dye molecules and the adsorbent surface through π – π interaction and hydrogen bonding.

Correspondingly, the N–H bending / NH_2 deformation peak shifted from 1558 cm^{-1} to 1592 cm^{-1} after adsorption, accompanied by a significant decrease in peak strength. The spectral alterations signify robust

intermolecular interactions, especially electrostatic attraction and hydrogen bonding among functional groups of the adsorbent surface and SO dye molecules, thereby validating a successful adsorption process.

Furthermore, C–H bending peaks at 1430 and 1376 cm^{-1} shifted to 1455 and 1374 cm^{-1} , while C–O stretching peaks at 1116 and 1027 cm^{-1} shifted to 1114 and 1026 cm^{-1} after adsorption. The characteristic Zn–O vibrations observed at 545 cm^{-1} before adsorption and 542 cm^{-1} after adsorption confirmed the successful addition of ZnO nanoparticles within the m-ECH-DSP nanocomposite structure. In previous studies, FTIR analysis confirmed the presence of functional groups such as hydroxyl, carbonyl, and aromatic carbon structures on both date seed powder (DSP) and CDSP surfaces, which actively contributed to naphthalene adsorption (Foo and Hameed, 2010), (Akinpelu *et al.* 2021).

3.1.3 XRD Analysis of m-ECH-DSP

Fig. 5 shows X-ray diffraction (XRD) of the produced m-ECH-DSP nanocomposite prior to and subsequent to the adsorption of the SO dye. A specific diffraction peak identified at $2\theta = 20.2^\circ$ relates to the semi-crystalline structure of chitosan within the composite matrix. The diffraction reflections centered at $2\theta = 31.7^\circ$, 34.4° , and 36.2° confirm the inclusion of ZnO particles inside the nanocomposite structure. The diffraction peaks observed at 31.7° , 34.4° , and 36.2° correspond to the (100), (002), and (101) crystallographic planes of hexagonal wurtzite ZnO, respectively, which are consistent with the standard JCPDS card No. 36-1451. The absence of additional impurity peaks indicates successful incorporation of ZnO nanoparticles within the composite matrix without detectable secondary crystalline phases.

The lack of prominent high-intensity ZnO peaks at elevated diffraction angles was attributed to the amorphous carbonaceous matrix of Date Seed Powder (DSP), which partially attenuates and broadens the diffraction signals of ZnO particles. After the adsorption of Safranin O dye, a significant decrease in peak intensity and minor peak shifts were seen in the XRD patterns. Following adsorption of Safranin O dye, slight shifts in diffraction peak positions together with reduced peak intensities were observed. These changes may be attributed to interactions between dye molecules and surface functional groups of the composite, resulting in local lattice distortion, partial coverage of crystalline domains, and increased amorphous character of the adsorbent surface. The reduction in peak intensity further suggests successful deposition of dye molecules onto the adsorbent matrix, which partially masks the crystalline ZnO reflections. These changes signify structural interactions between the adsorbent surface and dye molecules, leading to partial rupture of the crystalline

structure and an enhancement in the amorphous characteristics of the composite material. Prior studies indicate that the XRD analysis confirmed the successful synthesis of highly crystalline ZnO nanoparticles with a hexagonal wurtzite crystal structure and well-defined diffraction peaks corresponding to pure ZnO phases. The absence of secondary impurity peaks indicated high phase purity, while the sharp and intense reflections demonstrated good crystallinity and stable nanoparticle formation (Bouaziz *et al.* 2025).

The obtained diffraction pattern validates the successful integration of ZnO into the *m*-ECH-DSP nanocomposite and further illustrates the effective interaction between Safranin O dye molecules and the adsorbent surface during the adsorption process.

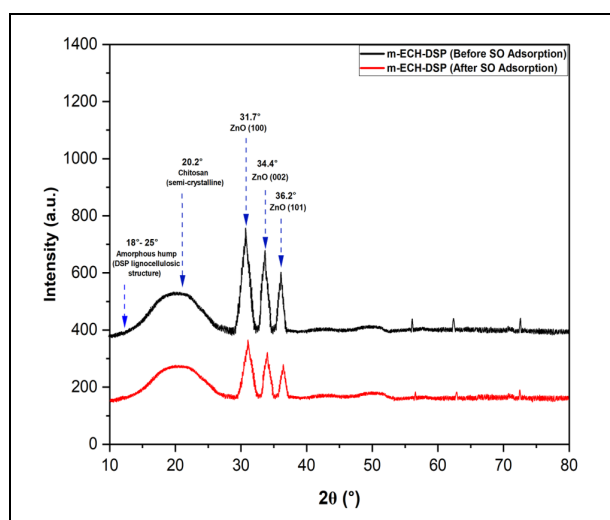


Fig. 5: Comparative XRD analysis before and after adsorption of *m*-ECH-DSP

3.1.4 Zeta Potential

Surface charge properties and particle size distribution of the produced *m*-ECH-DSP nanocomposite, prior to and during Safranin O (SO) dye adsorption, were assessed using zeta potential and particle size studies as depicted in Fig. 6. Before adsorption, the *m*-ECH-DSP nanocomposite had a zeta potential of -21.6 mV, signifying a negatively charged adsorbent surface with good colloidal stability.

Upon adsorption of the cationic SO dye, the zeta potential shifted to -3.2 mV, indicating partial neutralization of the negatively charged groups at the adsorbent surface. This change was because of electrostatic interactions among positively charged SO dye molecules and hydroxyl ($-\text{OH}$) and amino ($-\text{NH}_2$) functional groups present at the *m*-ECH-DSP surface. The shift of zeta potential from -21.6 mV to -3.2 mV confirms the effective adsorption of positively charged Safranin O dye molecules onto the *m*-ECH-DSP surface through electrostatic interaction. However, determination

of the point of zero charge (pHpzc) would provide a more comprehensive understanding of surface charge behavior across different pH conditions and could further validate the proposed adsorption mechanism.

Particle size analysis indicated that the mean particle diameter of the *m*-ECH-DSP nanocomposite before adsorption was approximately 841.1 nm with a polydispersity index of 0.111, indicating relatively uniform particle distribution and good dispersion stability. After adsorption of Safranin O (SO) dye, the average particle size increased to 1133 nm, while the PDI value increased to 0.811. The increase in particle size and PDI after adsorption may be attributed not only to the attachment of Safranin O molecules onto the adsorbent surface but also to particle aggregation induced by reduced electrostatic repulsion following dye adsorption. The substantial increase in PDI from 0.111 to 0.811 suggests a broader particle size distribution and possible agglomeration of adsorbent particles after interaction with dye molecules. Such aggregation behavior is commonly observed when surface charge neutralization decreases colloidal stability. Bimetallic Ag/ZnO nanoparticles synthesized by *Plectranthus amboinicus* leaf extract were employed for photocatalytic degradation. The nanocatalyst achieved a degradation efficiency of 94% at optimized conditions and exhibited excellent colloidal stability with a zeta potential of -16.4 mV. Comparative studies confirmed superior degradation performance over bacterial decolorization methods (Ranjini *et al.* 2025).

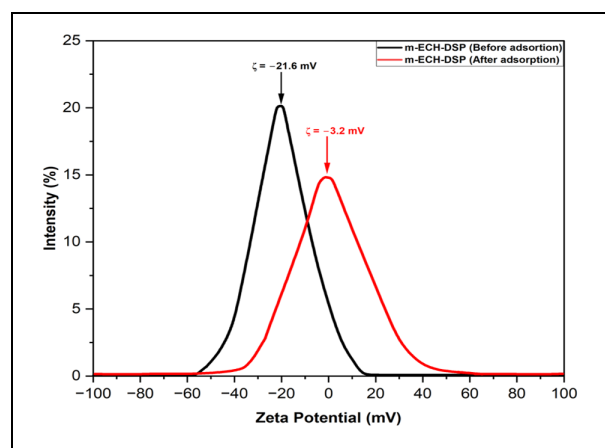


Fig. 6: Zeta potential analysis before and after adsorption of *m*-ECH-DSP

Although BET, FTIR, XRD, and zeta potential analyses provided valuable information regarding the physicochemical properties of the synthesized adsorbent, direct morphological characterization using SEM or TEM was not conducted in the present study. Such analyses would enable visualization of surface texture, particle morphology, and ZnO nanoparticle distribution within the composite matrix and should be considered in future investigations.

3.2 Effect of pH on SO Adsorption

This section aimed to identify optimal operational parameters for the adsorption of (SO) dye at the produced m-ECH-DSP nanocomposite adsorbent. Systematic batch adsorption studies were performed to assess the impact of critical experimental factors, including contact time, initial dye concentration, adsorbent dosage, ionic strength, and solution pH, on the adsorption effectiveness of the synthesized adsorbent.

The pH of the solution significantly influences surface charge properties of ionization and adsorbent behavior of dye molecules, consequently directly impacting adsorption efficacy. This study examined the adsorption characteristics of m-ECH-DSP for SO dye across a pH range of 2 to 8. Fig. 7 demonstrates that the adsorption capacity increased gradually as pH rose from 2 to 6, attributed to augmented electrostatic interaction between cationic dye molecules and the adsorbent surface. At acidic pH values, excess H^+ ions compete with cationic Safranin O molecules for available adsorption sites, thereby reducing adsorption efficiency. Furthermore, protonation of amino groups on chitosan decreases the availability of negatively charged adsorption sites. As pH increases toward neutral conditions, surface functional groups become less protonated, enhancing electrostatic attraction between the adsorbent and cationic dye molecules. Safranin O predominantly exists as a positively charged species throughout the investigated pH range; therefore, adsorption behavior is largely governed by variations in adsorbent surface charge rather than changes in dye speciation. Beyond pH 6, only marginal variations in adsorption capacity were observed, with adsorption values remaining nearly stable at approximately $6.8\text{--}6.9\text{ mg g}^{-1}$.

Optimum adsorption conditions were observed at pH 6, which is near the optimal adsorption condition; hence, this pH was chosen for all subsequent adsorption studies without further adjustment.

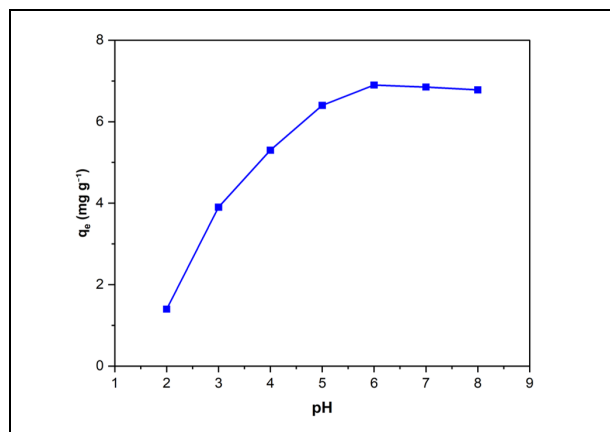


Fig. 7: Effect of pH solution on SO adsorption

The effect of adsorbent dosage at removal effectiveness of Safranin O dye was examined by adjusting the quantity of m-ECH-DSP nanocomposite at 0.05 to 0.20 g under batch adsorption conditions. The experimental outcomes obtained were illustrated in Fig. 8. Increasing the dosage of the m-ECH-DSP adsorbent from 0.04 g to 0.14 g markedly enhanced dye elimination efficiency from 38.4% to 93.2%. Nevertheless, beyond 0.14 g, only marginal variations in adsorption efficiency were observed, with removal efficiency remaining nearly stable at approximately 92.8–93.4%.

The improvement in dye removal efficacy with elevated adsorbent dosage was because of increased surface area and a quantity of active adsorption sites for interaction with Safranin O dye molecules. The elevated adsorbent concentration promotes superior adsorption by augmenting surface binding and dye absorption capacity. According to the data obtained, 0.14 g of m-ECH-DSP was determined to be the optimal dosage and was consequently chosen for all further adsorption studies. Although removal efficiency increased with adsorbent dosage, adsorption capacity per unit mass generally decreases at higher dosages owing to unsaturated adsorption sites and particle aggregation effects. Therefore, adsorption capacity should be considered together with removal efficiency when evaluating optimal dosage conditions.

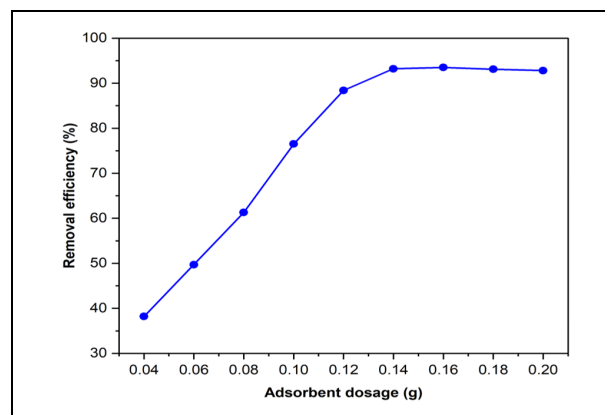


Fig. 8: Variation of SO removal efficiency with adsorbent dosage

Impact of salt content on the adsorption efficacy of the m-ECH-DSP nanocomposite for the elimination of SO dye was thoroughly examined, considering the intricate ionic composition of actual textile effluent. Dissolved salts can markedly influence adsorption behavior by modifying the solution's ionic strength and affecting electrostatic interactions, ion-exchange processes, and surface complexation among dye molecules and the adsorbent.

Adsorption experiments performed at different salt concentrations revealed the influence of ionic species on the dye removal efficacy of the synthesized adsorbent,

with the findings illustrated in Fig. 9. These data offer significant insight into the usability and durability of m-ECH-DSP nanocomposite under actual wastewater treatment conditions.

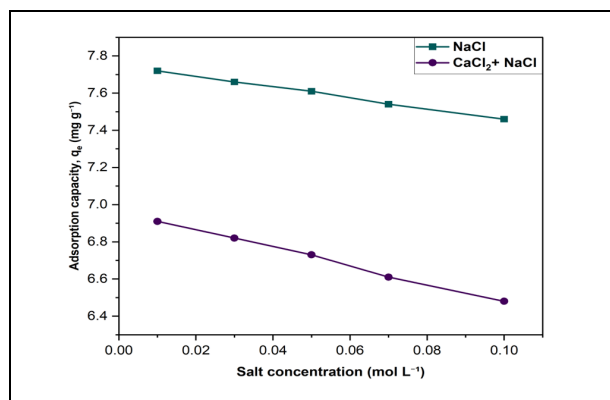


Fig. 9: Salt concentration effect on adsorption performance

In the presence of NaCl concentrations between 0.01 and 0.10 mol L⁻¹, the adsorption of m-ECH-DSP for SO exhibited a negligible decrease, remaining relatively stable within the range of 7.46–7.72 mg g⁻¹. When a combined salt medium consisting of CaCl₂ and NaCl was utilized within the same concentration range, the adsorption capacity decreased to approximately 6.48–6.91 mg g⁻¹, representing a reduction of approximately 10–13% relative to the NaCl-only system. The decline became further evident at elevated ionic concentrations.

The consistently constant adsorption performance noted in NaCl medium shows that electrostatic attraction was not the exclusive mechanism driving the adsorption of SO onto the m-ECH-DSP surface. Besides electrostatic interactions, additional adsorption mechanisms, including hydrophobic attraction, van der Waals forces, hydrogen bonding, and surface complexation, substantially influence the total adsorption process.

The inclusion of divalent Ca²⁺ ions in the NaCl + CaCl₂ system augmented the ionic strength of the solution and resulted in compression of the electrical double layer around the adsorbent surface. This mechanism diminished electrostatic contact among negatively charged functional groups and cationic dye molecules of the adsorbent. Furthermore, Ca²⁺ ions may contend with dye molecules for active adsorption sites or temporarily neutralize negatively charged surface areas, thereby diminishing the number of accessible binding sites and restricting dye diffusion towards the adsorbent surface. The adsorption ability of m-ECH-DSP was relatively diminished at mixed salt medium.

The influence of contact duration at adsorption of Safranin O (SO) dye utilizing the produced m-ECH-DSP was examined over a mixing period of 15 to 90 minutes. Experimental outcomes (Fig. 10) demonstrate

that the adsorption capacity progressively augmented with prolonged contact time throughout the initial phases of the adsorption process. This pattern is mostly ascribed to the abundance of unoccupied active adsorption sites in the adsorbent surface at the initial phase of adsorption. With the extension of contact time, the adsorption process gradually neared equilibrium, and a fairly stable adsorption capacity was noted after 60 minutes, signifying saturation of accessible binding sites at the adsorbent surface. Consequently, 60 minutes was deemed the optimal equilibrium contact duration for efficient elimination of Safranin O dye. Although the maximum adsorption capacity of m-ECH-DSP is moderate compared with certain engineered adsorbents reported in the literature, the synthesized material offers advantages, including low-cost precursor materials, eco-friendly preparation, facile regeneration, and incorporation of renewable agricultural waste. Therefore, its practical applicability should be evaluated not only based on adsorption capacity but also on sustainability, availability, and operational simplicity.

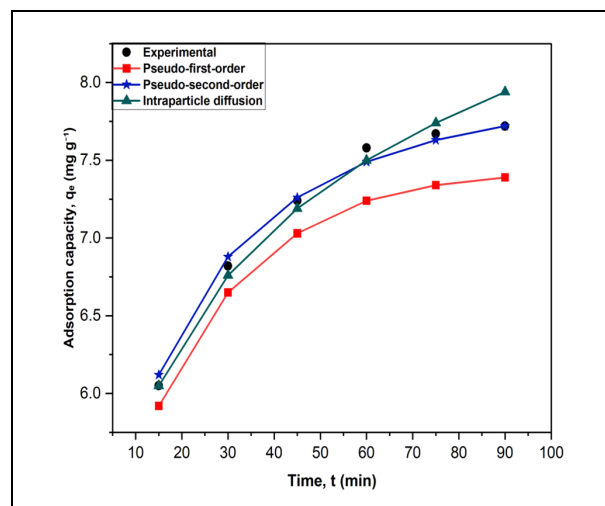


Fig. 10: Kinetic modeling of SO adsorption onto m-ECH-DSP

The effect of initial dye concentration at adsorption effectiveness of m-ECH-DSP nanocomposite was systematically assessed with the results depicted in Fig. 11. Adsorption capacity augmented with initial Safranin O concentration, attributed to intensified concentration gradient among dye solution and the adsorbent surface, thereby facilitating mass transfer and adsorption interactions. However, below a specific concentration threshold, the adsorption process progressively attained saturation because of finite accessible active sites at the adsorbent surface. The adsorption capacity remained rather stable after reaching the maximum adsorption threshold of the synthesized m-ECH-DSP nanocomposite. Adsorption isotherm experiments were conducted using initial Safranin O concentrations ranging from 10 to 100 mg L⁻¹ while maintaining optimum pH, adsorbent dosage, and contact time conditions.

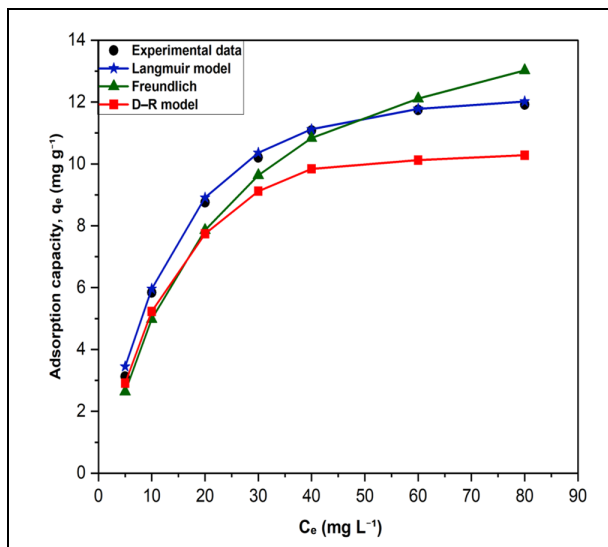


Fig. 11: Adsorption isotherm models for SO removal

3.3 Kinetic Modeling of SO Dye Adsorption

Experimental adsorption data from the contact time experiments were analyzed using chosen kinetic models. The appropriateness and precision of the suggested kinetic equations were assessed by nonlinear regression analysis, with the resultant fitting outcomes displayed in Fig. 10 and Table 3.

Table 3. Kinetic model fitting parameters for SO adsorption

Pseudo-first-order	$K_{ads1} (\text{min}^{-1})$	$q_e (\text{mg g}^{-1})$	R^2	χ^2
	0.146	7.39	0.942	0.039
Pseudo-second-order	$K_{ads2} (\text{g mg}^{-1} \text{min}^{-1})$	$q_e (\text{mg g}^{-1})$	R^2	χ^2
	0.0456	7.78	0.988	0.011
Intraparticle diffusion	$K_p (\text{mg g}^{-1} \text{min}^{-1/2})$	$C (\text{mg g}^{-1})$	R^2	χ^2
	0.186	6.05	0.991	0.006

Intraparticle diffusion and Pseudo-first- second-order kinetic models were used to examine the adsorption characteristics of the SO dye onto the m-ECH-DSP nanocomposite (Fig. 10 and Table 3). Among the assessed models, the pseudo-first-order kinetic model demonstrated inadequate concordance with experimental data, as evidenced by its relatively elevated error value ($\chi^2 = 0.039$) and a correspondingly low correlation coefficient ($R^2 = 0.942$). The computed equilibrium adsorption capacity ($q_e = 7.39 \text{ mg g}^{-1}$) exhibited some

discrepancy from the experimentally derived value, indicating that the pseudo-first-order model was inadequate for precisely characterizing the adsorption mechanism.

Conversely, pseudo-second-order exhibited superior correlation with experimental data, evidenced by a higher R^2 value of 0.988 and a lower error of $\chi^2 = 0.011$. Moreover, the computed equilibrium adsorption capacity was determined to be in closer proximity to the experimental adsorption value. The superior fit of the pseudo-second-order model suggests that the adsorption rate may be influenced by surface interactions between the adsorbate and the adsorbent. However, the applicability of the pseudo-second-order model alone does not conclusively establish a chemisorption mechanism. Therefore, adsorption behavior should be interpreted in conjunction with other characterization and adsorption studies.

The intraparticle diffusion model displayed a low error value ($\chi^2 = 0.006$), and a strong correlation coefficient ($R^2 = 0.991$) shows that intraparticle diffusion plays a substantial role at adsorption process. Non-zero intercept value ($C = 6.05 \text{ mg g}^{-1}$) shows that intraparticle diffusion were exclusive rate-controlling mechanism; rather, boundary layer diffusion (film diffusion) also affects the adsorption behavior of SO onto m-ECH-DSP.

Pseudo-second-order kinetic were determined to be suitable for the adsorption of Safranin O dye onto m-ECH-DSP. The data obtained indicate that film diffusion and intraparticle diffusion considerably contribute to the adsorption mechanism. Findings validate that the adsorption process was regulated by a confluence of chemical interactions and concurrent mass transfer events during dye absorption. Although the intraparticle diffusion model provided useful insight into mass-transfer behavior, detailed identification of individual diffusion stages would require presentation of multi-linear Weber–Morris plots. Such analysis was beyond the scope of the present work and should be considered in future investigations.

3.4 Adsorption Isotherm Analysis of SO Dye

The experimental adsorption from the concentration experiments was evaluated using standard adsorption isotherm models to assess the interaction mechanism and the adsorption behavior of the SO dye on m-ECH-DSP. Nonlinear regression fitting analyses were conducted for the chosen isotherm models, with the resultant data illustrated in Fig. 11 and Table 4.

Table 4. Parameters of adsorption isotherm models

Langmuir	$K_L(\text{Lmg}^{-1})$	$q_{\max}(\text{mg g}^{-1})$	R^2	χ^2	
	0.432	12.6	0.992	0.118	
Freundlich	$K_F(\text{Lmg}^{-1})$	N	R^2	χ^2	
	4.03	3.92	0.964	0.284	
D-R	$q_{\max}(\text{mgg}^{-1})$	$\beta(\text{Lmg}^{-1})$	$\varepsilon(\text{kJmol}^{-1})$	R^2	χ^2
	10.4	2.24	1.66	0.918	0.631

The adsorption equilibrium data derived from concentration-dependent tests were evaluated using established isotherm models to elucidate the adsorption mechanism of Safranin O (SO) dye onto the m-ECH-DSP nanocomposite. Nonlinear regression studies of the chosen isotherm models were conducted, and the resultant fitting outcomes were illustrated in Fig. 11 and Table 4.

Langmuir isotherm model posits monolayer adsorption at a uniform adsorbent surface with similar active sites. The elevated correlation coefficient ($R^2 = 0.992$) achieved for the Langmuir model indicates remarkable concordance among experimental and theoretical adsorption data. The maximal adsorption capacity signifies a robust interaction and effective adsorption of SO dye molecules onto the adsorbent surface, at which saturation is reached. The comparatively low chi-square score ($\chi^2 = 0.118$), provides additional validation for the appropriateness and dependability of the Langmuir model. The data indicate that the adsorption process primarily takes place by monolayer adsorption on a rather uniform adsorbent surface.

Freundlich isotherm model, characterizes multilayer adsorption at heterogeneous surfaces exhibited lower correlation coefficient ($R^2 = 0.964$) and a higher chi-square value ($\chi^2 = 0.284$), signifying a weaker concordance with the experimental data relative to Langmuir model. Freundlich ($n = 3.92$) with $n > 1$, verifies good adsorption behavior and reveals heterogeneous adsorption sites at surface of m-ECH-DSP nanocomposite. Nonetheless, the overall adsorption behavior was more precisely depicted by the Langmuir model. Earlier investigations reported that green-synthesized ZnO nanoparticles prepared using *Laurus nobilis* leaf extract achieved 99% methylene blue removal under optimized adsorption conditions. The nanoparticles showed an adsorption capacity of 33.75 mg/g and followed pseudo-second-order kinetics with the Freundlich and Langmuir isotherm behavior. Eco-friendly synthesis highlighted their suitability for sustainable dye remediation applications (Kavaz, 2024).

The Dubinin-Radushkevich (D-R) isotherm model exhibited comparatively lower fitting performance with an R^2 value of 0.918 and a χ^2 value of 0.631. The calculated adsorption energy value ($\varepsilon = 1.66 \text{ kJ mol}^{-1}$) indicates that the adsorption process predominantly occurred through physical adsorption mechanisms such as van der Waals interactions and electrostatic attraction. Overall, the obtained isotherm results confirm that the adsorption of SO dye onto the m-ECH-DSP nanocomposite mainly follows Langmuir monolayer adsorption behavior with favorable adsorption characteristics. The adsorption energy obtained from the D-R model ($\varepsilon = 1.66 \text{ kJ mol}^{-1}$) falls within the range typically associated with physical adsorption processes. This observation suggests that electrostatic attraction, van der Waals forces, and hydrogen bonding may play dominant roles in dye uptake. Although the pseudo-second-order model adequately describes adsorption kinetics, such fitting does not necessarily imply a purely chemisorption-controlled mechanism. Therefore, the adsorption process is likely governed by a combination of physical interactions and surface binding phenomena. While Langmuir, Freundlich, and D-R models provided valuable insight into adsorption behavior, application of additional models such as Temkin and Sips could further improve understanding of adsorbate-adsorbent interactions and surface heterogeneity. Such analyses should be considered in future studies.

3.5 SO Dye Removal from Textile Wastewater

This work utilized textile effluent from a processing industry to examine the practical application of the synthesized m-ECH-DSP nanocomposite for the elimination of SO dye under actual wastewater circumstances. The textile wastewater sample was collected from a local textile processing industry and used as a representative wastewater matrix for evaluating practical adsorption performance. Although detailed physicochemical characterization of the wastewater was not performed in the present study, the wastewater contained various dissolved constituents that may influence adsorption efficiency under real treatment conditions. The wastewater sample was modified to an SO dye concentration of 25 mg L^{-1} , and adsorption tests were used at optimum conditions, including initial

wastewater pH, a 0.14 g adsorbent dosage, and a contact time of 60 minutes. Under these adjusted settings, the m-ECH-DSP nanocomposite attained a dye removal efficiency of 75.09%. The reduction in dye removal efficiency compared with laboratory-prepared solutions may be attributed to the presence of competing organic compounds, suspended solids, dissolved salts, and other contaminants within the textile wastewater matrix. These constituents can compete with Safranin O molecules for active adsorption sites, reduce mass transfer efficiency, and partially block adsorbent pores. Consequently, adsorption performance under real wastewater conditions is generally lower than that observed in controlled laboratory systems. The outcome shows that the synthesized adsorbent has significant promise for efficient elimination of the SO dye from actual industrial textile wastewater systems. In previous studies, the zinc oxide photocatalysis was applied for the degradation of Safranin dyes and Reactive Red 180 under optimized alkaline conditions. Complete dye removal was achieved within 2 h, while the photocatalytic membrane reactor demonstrated superior efficiency for real textile wastewater treatment (Kaya *et al.* 2026).

3.6 Regeneration and Reusability of m-ECH-DSP Adsorbent

Sodium hydroxide was selected as the desorbing agent because alkaline media effectively disrupt electrostatic interactions and hydrogen bonding between adsorbed dye molecules and the adsorbent surface. Furthermore, NaOH is inexpensive, readily available, and widely used in regeneration studies involving dye-loaded biosorbents. Alternative regenerants such as HCl, ethanol, or salt solutions may also be effective and warrant future investigation. The reusability and regeneration efficacy of the synthesized m-ECH-DSP nanocomposite were assessed by successive adsorption-desorption cycles utilizing Safranin O (SO) dye solution. Reusability of adsorbent material were critical factor in assessing its economic viability and practical utility. Alongside superior adsorption performance, effective desorption capacity is crucial for the recovery and reuse of adsorbents in successive treatment cycles.

In the desorption investigation, the dye-impregnated adsorbent was subjected to a 0.1 mol L⁻¹ NaOH solution for 60 minutes during the entire regeneration cycle to enhance the extraction of adsorbed dye molecules from the adsorbent surface. Fig. 12 illustrates the adsorption-desorption behavior of the m-ECH-DSP nanocomposite during 10 consecutive cycles. The results demonstrate that desorption and adsorption efficiencies consistently remained high, approximately 91–98%, during the first five cycles, indicating good regeneration stability during the initial adsorption-desorption cycles. The observed decrease in adsorption performance after repeated regeneration cycles indicates that long-term stability remains a challenge and further

optimization of regeneration conditions may be required to improve durability.

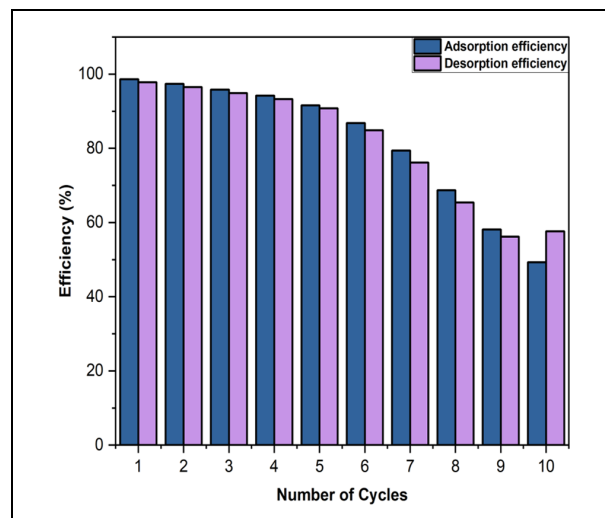


Fig. 12: Regeneration and reusability performance of m-ECH-DSP

The findings demonstrate that the m-ECH-DSP nanocomposite exhibits excellent regeneration capacity and retains structural integrity throughout the initial adsorption-desorption cycles. Nonetheless, an incremental decline in both adsorption and desorption efficiency was noted with the rising cycle number, especially beyond the sixth cycle. By the tenth cycle, adsorption efficiency decreased to approximately 49%, while desorption efficiency remained around 57%, although desorption efficiency persisted within the approximate range of 56–57%. Accordingly, this research seeks to examine seven waste adsorbents that were compared for removing heavy metals from produced water. Date seed ash achieved the highest removal efficiency for Cr³⁺, Cu²⁺, Fe²⁺, Zn²⁺, and Pb²⁺, while activated carbon also showed strong adsorption performance. The findings highlighted the potential of agro-industrial waste materials for sustainable oil wastewater treatment (Bansal *et al.* 2025).

The sharper decline observed after the sixth regeneration cycle may be associated with progressive occupation of residual active sites, incomplete desorption of retained dye molecules, gradual loss of surface functional groups, and minor structural deterioration of the composite matrix under repeated alkaline treatment. These cumulative effects reduce the availability of effective adsorption sites during subsequent cycles.

The noted decrease in performance may be ascribed to gradual depletion of active adsorption sites, partial structural deterioration of the adsorbent matrix, or insufficient desorption and regeneration of dye molecules during successive reuse cycles. The results indicate that the synthesized m-ECH-DSP adsorbent shows favorable reusability for several wastewater treatment cycles, but

its peak adsorption efficacy is mostly maintained in the initial regeneration phases. Although adsorption–desorption performance was evaluated over multiple cycles, detailed physicochemical characterization of the regenerated adsorbent was not conducted. Future studies involving FTIR, XRD, and SEM analyses after repeated regeneration cycles would provide deeper insight into structural stability and degradation mechanisms.

4. CONCLUSION

This study successfully developed an epichlorohydrin-crosslinked chitosan/date seed powder/ZnO nanocomposite adsorbent for the removal of Safranin O (SO) dye from aqueous solutions. Physicochemical characterization through BET, FTIR, XRD, and zeta potential analyses confirmed the successful formation of the nanocomposite and the presence of functional groups and active sites responsible for dye adsorption. The adsorption process was influenced by solution pH, adsorbent dosage, contact time, and initial dye concentration, with a maximum adsorption capacity of 12.6 mg g⁻¹ obtained under optimized conditions.

Kinetic studies demonstrated that the adsorption data were best described by the pseudo-second-order model, while film diffusion and intraparticle diffusion also contributed to the overall adsorption process. Equilibrium data were satisfactorily fitted by the Langmuir isotherm model, suggesting favorable adsorption behavior of SO dye onto the adsorbent surface. However, the adsorption mechanism should be interpreted cautiously, as the low adsorption energy value obtained from the Dubinin–Radushkevich (D–R) model (1.66 kJ mol⁻¹) indicates that physical interactions, including electrostatic attraction, hydrogen bonding, and van der Waals forces, predominantly govern the adsorption process.

The developed ECH-DSP nanocomposite demonstrated a color removal efficiency of 75.09% in real textile wastewater, indicating its potential applicability under practical treatment conditions. Nevertheless, the lower removal efficiency observed in real wastewater compared with synthetic dye solutions suggests that competing contaminants and matrix complexity may influence adsorption performance. Regeneration studies revealed that the adsorbent maintained high adsorption efficiency during the initial adsorption–desorption cycles, followed by a gradual decline in performance after repeated reuse. The reduction in adsorption efficiency to approximately 49% after the tenth cycle indicates moderate long-term stability and highlights the need for further optimization of regeneration conditions.

The utilization of agricultural waste-derived date seed powder as a precursor material contributes to

waste valorization, resource recovery, and environmental sustainability. However, several limitations remain, including the absence of pH_{pzc} measurements, SEM/TEM morphological characterization, and post-regeneration structural analyses. Future studies should focus on advanced characterization, enhancement of adsorption capacity, optimization of regeneration strategies, and pilot-scale wastewater treatment investigations to further evaluate the practical applicability and scalability of the developed adsorbent. Overall, the ECH-DSP nanocomposite represents a promising sustainable adsorbent for dye-contaminated wastewater treatment while requiring further development for large-scale implementation.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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