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Evaluation of Marine Snail Shells as Low-Cost Adsorbents for the Removal of Selected Synthetic Dyes from Aqueous Solutions

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Abstract: In this study, the potential of a low-cost adsorbent obtained from snail shells was tested for the sequestration of methylene blue (MB) and Congo red (CR) from aqueous solutions. The snail shells were obtained, thoroughly washed, dried, ground into fine powder, and calcined at 750 °C to produce the adsorbent. FTIR revealed the presence of carbonate and surface hydroxyl groups used for the adsorption of the selected dyes. To evaluate the effects of contact time, adsorbent dose, and temperature on the removal of the selected dyes, batch adsorptions were conducted. The results revealed rapid adsorption within the first 30 minutes, indicating the presence of abundant active sites at the earlier stage. The Langmuir model showed a better fit (R^2 = 0.993 for MB and 0.989 for CR), signifying monolayer adsorption on a homogeneous snail shell surface. As revealed by the Kinetic studies, the adsorption of both dyes followed the pseudo-second-order model, indicating a chemisorption-dominated mechanism. Thermodynamic parameters (+ΔH° and +ΔS° values) revealed that the adsorption of both dyes is feasible and endothermic with increased randomness at the solid–liquid interface. The ΔG° values (-1.27 kJ/mol and +0.17 kJ/mol) for MB and CR, respectively, confirmed that adsorption was somewhat spontaneous. Thus, this study contributes to wastewater treatment while encouraging waste remediation to ensure environmental sustainability.

1. Introduction

Discharge of industrial effluents into water bodies has been a severe global environmental challenge, particularly in a developing nation like Nigeria, which has inadequate infrastructure to effectively handle the problem of wastewater. Numerous industries, including cosmetics and polymer industries, usually produce effluents containing remnants of synthetic dyes discharged into the environment. Due to their non-biodegradable nature, synthetic dyes can be present and persist even at low concentrations (Dibal *et al.*, 2025). The aquatic life is often deprived of adequate sunlight required for photosynthetic activities due to the presence of dyes, which consequently makes the dye-polluted wastewater injurious.

These synthetic dyes, well-known carcinogenic substances, can find their way into the body systems of human and aquatic life via the food chain, causing serious disorderliness and damage to ecosystems and human health (Islam et al., 2025; Kolya & Kang, 2024).

Dye-contaminated wastewater can be handled by numerous conventional techniques, including coagulation, membrane separation, and oxidation, but their complex processes, high cost of operation, and possible generation of secondary pollutants restrict their applications (Azzaoui *et al.*, 2019; Akartasse *et al.*, 2022; Zaaboul *et al.*, 2024; Sumaila *et al.*, 2024; Haoufazane *et al.*, 2025; Latifi *et al.*, 2025; Espinosa *et al.*, 2026). Meanwhile, adsorption appears to be a comparatively cheap and highly effective technique that has become a better alternative to other techniques of removing dyes from both wastewater and aqueous solutions (Sumaila *et al.*, 2024; Mustapha *et al.*, 2019).

Owing to its large surface area and high porosity, activated carbon is usually employed as an adsorbent, but its high cost limits its use (Molebatsi *et al.*, 2025). Hence, the need to search for cheap and viable alternatives from agricultural waste like snail shells (Sumaila *et al.*, 2020a; Mustapha *et al.*, 2020).

Snail shells are agricultural wastes that contain a large amount of calcium carbonate, which, when adequately treated with thermal or chemical treatments, can be made to possess surface functional groups and better porosity suitable for adsorption (Nhung *et al.*, 2023; Sumaila *et al.*, 2017). Previously, many studies have shown that adsorbents can be derived from snail shells and effectively employed to remove dyes from aqueous solutions. For instance, Adaramaja *et al* (2024) used thermally treated nanocrystalline snail shells to remove methylene blue dye efficiently from aqueous medium. In the same vein, under controlled conditions, Zwier *et al* (2024) used snail shell powder to highly and efficiently removed safranine dye from wastewater Among the numerous advantages of using snail shells for adsorption are the environmental remediation of snail shells as waste and the conversion of waste into more useful materials, such as adsorbents (Sumaila *et al.*, 2022a; Sumaila *et al.*, 2020b). Therefore, this study aims to assess the dye removal capacity of the snail shells from aqueous solutions.

2. Methodology

2.1 Material

Snail shells were gathered as waste from a dumpsite within the Minna Local Food market, Niger State, Nigeria. The Dyes (methylene blue and Congo red), chemicals, and reagents used in this study were obtained from Sigma Aldrich.

2.2 Preparation of Snail Shell Adsorbent

The snail shells were carefully washed in tap water to remove impurities, air-dried at room temperature for 48 hours, ground using a mechanical grinder, and sieved using a 250 µm sieve. (Sumaila *et al.*, 2020a).

Subsequently, the sieved shells were calcined in a muffle furnace at temperatures of 750 °C for 2 hours to decompose the $CaCO_3$) into CaO according to the following chemical equation (Sumaila *et al.*, 2020b):

$$CaCO_{3\ (s)} \rightarrow CaO_{(s)} + CO_2$$

The calcined shells (adsorbent) were allowed to cool in a desiccator to avoid moisture from the surroundings.

2.3 Characterization of Adsorbent

The adsorbent was characterized using Fourier Transform Infrared Spectroscopy (FTIR) to identify the functional groups present on its surface in the wavelength range of 4000–400 cm^{-1} (Sumaila *et al.,* 2023).

2.4 Preparation of Dye Solutions

The dye solutions of methylene blue and Congo red were prepared by dissolving 1.0 g of each dye in 1000 cm3 of distilled water and thoroughly stirring for complete dissolution. A UV–Visible spectrophotometer was employed to scan the prepared solutions over a wavelength range of 200–800 nm to obtain the λ_{max} of 497 nm and 664 nm, for Congo red and methylene blue, respectively. Subsequently, all absorbance measurements were done using these wavelengths.

2.5 Adsorption Experiments

To determine how contact time, adsorbent dosage, and temperature influence the removal efficiency of the selected dyes, batch adsorption studies were done using the prepared adsorbent.

To study the influence of contact times (10, 20, 30, 60, 90, and 120 minutes) on the adsorption, 50 cm3 of the dye solution was interacted with 0.5 g of the adsorbent, shaken at 150 rpm, and filtered using Whatman No. 1 filter paper, while the concentration of the filtrates was determined using A UV-Visible spectrophotometer.

Subsequently, the influence of adsorbent dosage was assessed by varying the dose (0.1 to 1.0 g) at constant dye concentration, contact time, and agitation speed. Each mixture of the dye solutions and adsorbent was filtered at the optimum contact time, while the concentrations of the filtrate were determined using spectrophotometry.

Similarly, the study of the influence of temperatures (25 °C, 35 °C, 45 °C, 55 °C, and 65 °C) on the adsorption using the snail shells was done at optimum adsorbent dosage and contact time. The amount of dye removed (qe) and the percentage removal efficiency at equilibrium were determined using **Equations 1 and 2**:

$$q_e = \frac{(C_0 - C_e)V}{m} \quad (1)$$

$$\% \text{ Removal} = \frac{(C_0 - C_e) \text{ x } 100}{C_0} \quad (2)$$

Where: C_0= initial dye concentration (mg/L), C_e = equilibrium dye concentration (mg/L), V = volume of dye solution (L), and m = mass of adsorbent used (g).

2.6 Adsorption Isotherm and Kinetic Studies

The Langmuir and the Freundlich Isotherm Models were used to analyze the adsorption data to explain the relationship between dye molecules in solution and those adsorbed on the surface of the adsorbent. This is done to reveal the best-fitting model between the two models using the correlation coefficient (R^2) values.

Similarly, based on the R^2 values, the adsorption mechanism and rate-controlling steps of the adsorption were determined to choose between the Pseudo-First-Order and Pseudo-Second-Order models, which kinetic model is the most suitable for the adsorption.
More so, the Van't Hoff equation (**Equation 3**) was used to determine the ΔG°, ΔH°, and ΔS° to determine the feasibility and nature of the adsorption process by snail shells:

$$\Delta G^o = \Delta H - T\Delta S^o \qquad (3)$$

3. Results and Discussion

3.1 FTIR spectrum of the Adsorbent

The FTIR spectrum of the prepared adsorbent (**Figure 1**) showed strong absorption peaks at 1420 cm⁻¹ and 875 cm⁻¹, indicating the presence of CO_3^{2-} from $CaCO_3$, which is the main part of the snail shells. A weak band at 3640 cm⁻¹ was observed, indicating the presence of OH^- as accessible active sites on the adsorbent (Sumaila *et al*., 2023).

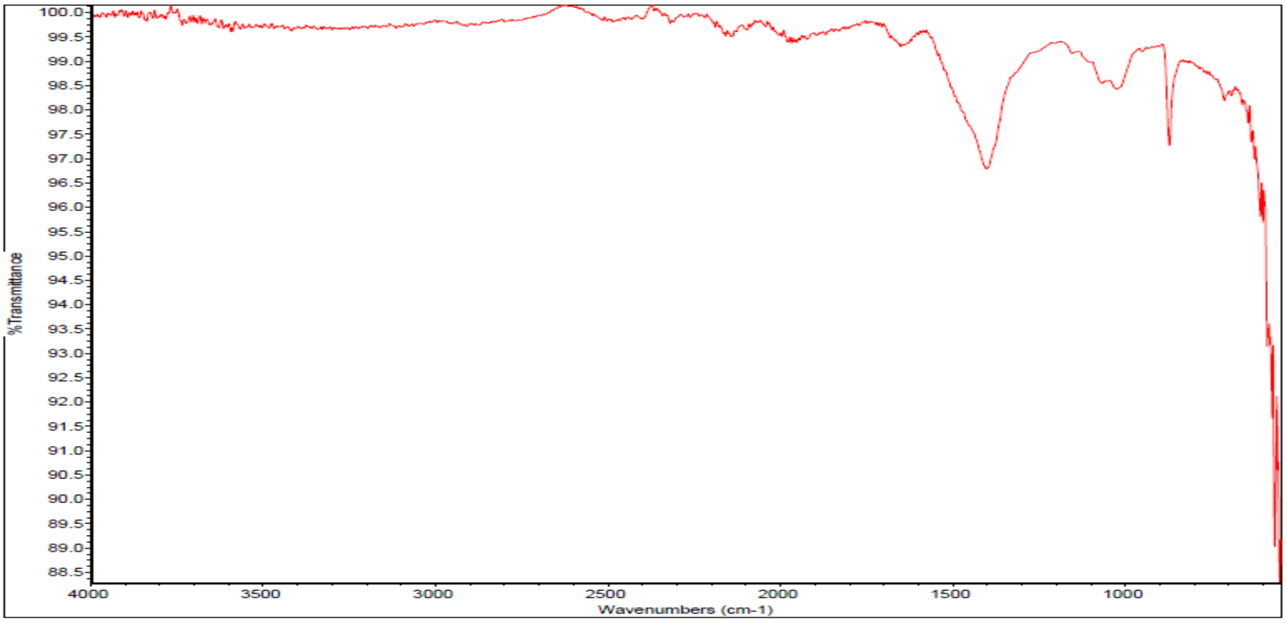


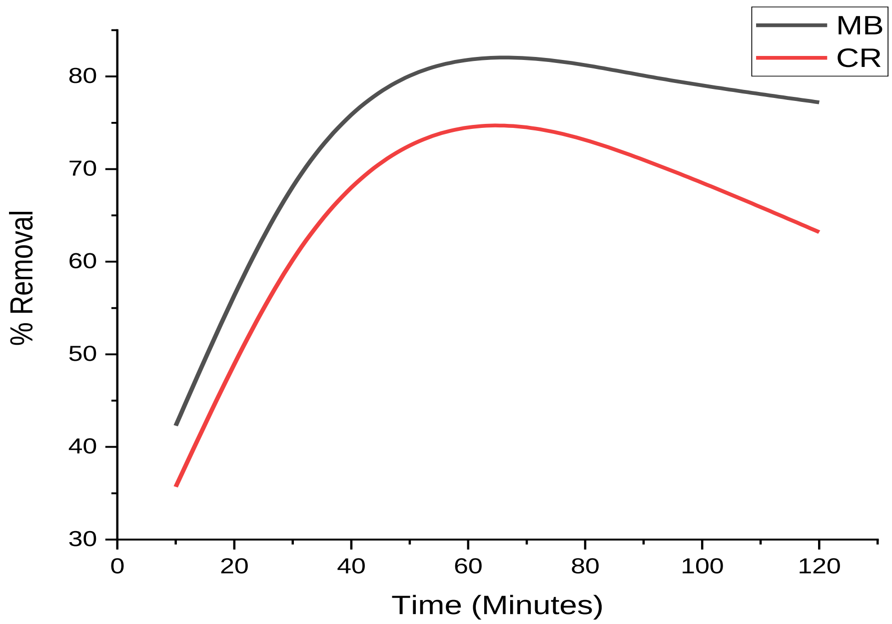
Figure 1: FTIR spectrum of the snail shell

3.2 Effect of Contact Time

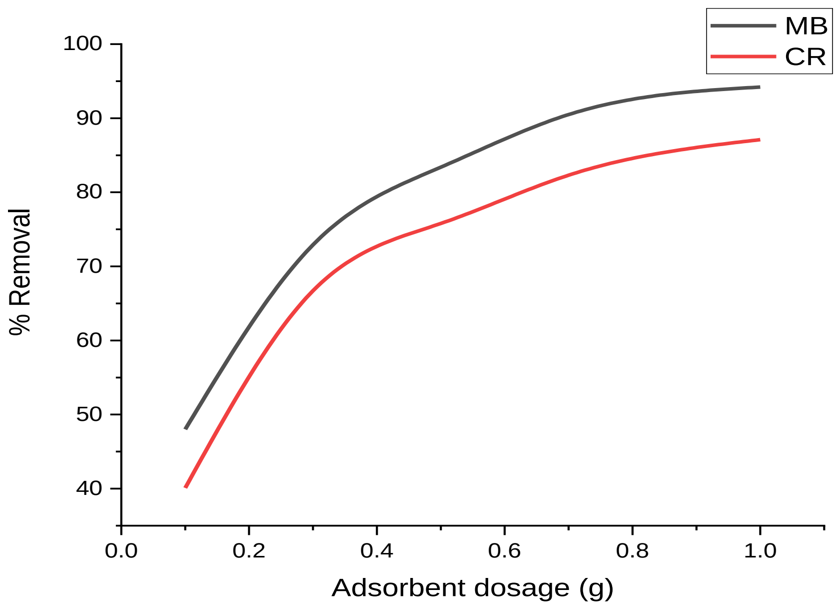
Figures 2 shows that there was a rapid increase in the adsorption of methylene blue and Congo red during the first 30 minutes, after which it decreases is observed.
The initial rapid adsorption may be attributed to the presence of numerous and accessible active sites on the adsorbent surface. Towards the equilibrium, while most of the active sites have been occupied, the adsorption is observed to slow down. Similar observations have been reported by Vara *et al*. (2024) and Mustapha *et al*. (2019) from their studies on dye removal by bio-waste adsorbents.

3.3 Effect of Adsorbent Dosage

As the adsorbent dosage increases from 0.1 to 1.0 g, a higher percentage removal for both dyes is observed.



Figures 2: Effect of Contact Time

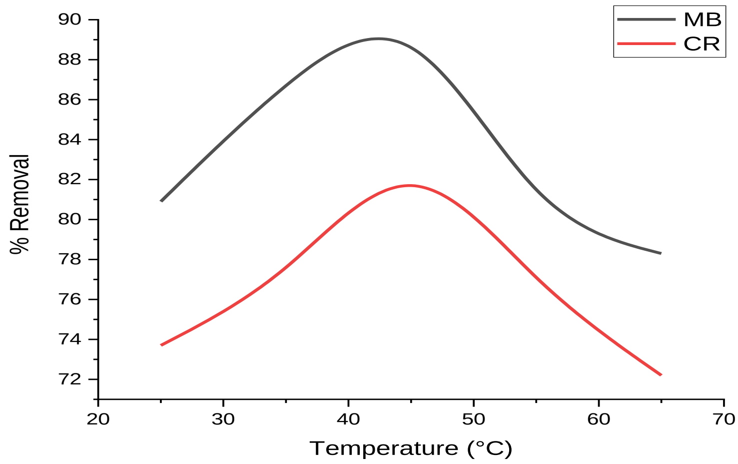


Figures 3: Effect of Adsorbent Dosage

This improved rate of dye uptake with higher adsorbent dosage may result from increased availability of large surface area and accessible active sites. The outcome of this study is in line with previous studies by Ren *et al.* (2025) and Sumaila *et al.* (2024) on adsorption using calcium-rich bio-adsorbents.

3.4 Effect of Temperature

Figure 4 shows that the initial adsorption efficiency of the snail shells significantly improved with temperature, suggesting an endothermic process. Increasing temperature from 25 °C to 45 °C promotes the movement and penetration of more dyes into the adsorbent pores (Sumaila *et al.*, 2024; Mustapha *et al.*, 2019). By comparison, the higher R^2 values for the Langmuir model indicate that adsorption occurs as a monolayer on homogeneous sites (Sumaila *et al.*, 2024; Mustapha *et al.*, 2019).



Figures 4: Effect of Temperature

Table 1: Adsorption Isotherms

Model	Dye	R^2
Langmuir	MB	0.993
Langmuir	CR	0.989
Freundlich (1/n)	MB	0.972
Freundlich (1/n)	CR	0.957

Table 2. Kinetic Modelling

Model	Dye	R^2
Pseudo-first-order	MB	0.922
Pseudo-first-order	CR	0.889
Pseudo-second-order	MB	0.991
Pseudo-second-order	CR	0.981

Table 2 shows that the adsorption data for both dyes best fit into the Pseudo-second-order model compared to the Pseudo-first-order model. This reveals that the adsorption is chemisorption by electron sharing (Sumaila *et al*., 2019; Mustapha *et al*., 2019).

3.5 Thermodynamic Parameters

Table 3. Gibbs free energy (kJ/mol), Enthalpy change (ΔH) (kJ/mol), and Entropy Change (ΔS) kJ/molK) for the Adsorption of the Selected Dyes on the Snail Shells at Temperature 298K

Gibbs free energy (ΔG°) (KJ/mol)		
Dyes		
Temperature (K)	MB	CR
298	−1.27	+0.17
Enthalpy and Entropy Changes		
ΔH°	+21.7	+19.1
ΔS°	+77.1	+63.5

From the thermodynamic calculations, ΔH° and ΔS° for MB and CR were +21.7 kJ/mol and +77.1 J/mol·K, and +19.1 kJ/mol and +63.5 J/mol·K, respectively, signifying that the adsorption is endothermic and experienced increased randomness. In contrast, ΔG° (kJ/mol) for MB and CR at 298K were −1.27 kJ/mol and +0.17 kJ/mol, showing that the adsorptions of MB and CR were mildly spontaneous and temperature dependent, respectively (Sumaila *et al*., 2024; Sumaila *et al*., 2020b).

Conclusion

This study showed that snail shells can be effectively employed as cheap adsorbents for the sequestration of methylene blue and Congo red in aqueous medium. The adsorbent showed a high removal efficiency solely via chemisorption. The chemisorption was spontaneous, endothermic, and entropy dependent. Thus, the use of snail shells is an eco-friendly and sustainable way to remove synthetic dyes from the aqueous media.

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Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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