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COCONUT SHELL BIOSORBENT FOR THE REMOVAL OF CHROMIUM IONS FROM AQUEOUS SOLUTIONS: EQUILIBRIUM AND THERMODYNAMIC STUDIES

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ABSTRACT

Chromium-containing industrial effluents are contaminants widely dispersed in aquatic environments and represent a major environmental and public health challenge because metal ion is toxic, persistent and carcinogenic. Chromium is a deleterious environmental contaminant which is commonly released into the environment from various associated industrial operations such as electroplating, leather tanning, metal finishing and textile, pigment and mining industries whose untreated disposal generates significant ecological harm. The preparation of magnetically modified coconut shell biosorbent (MSCS) via a simple in-situ co-precipitation method using ferric and ferrous salts was investigated in this study to afford a magnetic solid easily recoverable after chromium ions adsorption from aqueous media. The biosorbent was characterised by FTIR, and SEM-EDX. Single VAR experiments were performed for solution pH, contact time, initial chromium concentration, adsorbent dosage and temperature in terms of batch adsorption tests. The equilibrium and thermodynamic data were then used to further the study of adsorption mechanism. The experimental results fitted more appropriately to the Langmuir isotherm, suggest that adsorption takes place via a monolayer on a surface consisting of identical sites, with Q_{max}=37.54 mg/g. Thermodynamic quantities supported that the adsorption process was thermodynamically favourable and endothermic. In conclusion, coconut shell magnetite is indicated to be effective, cost-efficient and eco-friendly biosorbent which can remove chromium ion from industrial wastewater.

Keywords: Coconut shell; Adsorption; Magnetic biosorbent; Endothermic; Isotherm; Thermodynamic

1 INTRODUCTION

Continuous discharge of heavy-metal-contaminated wastewater from industrial development has been a big environmental issue [2]. Unlike other organic pollutants, heavy metals do not degrade biologically; they can accumulate in biological organisms causing chronic toxicity and bio-magnification through the food chain [5]. Chromium is another heavy metal of utmost concern owing to its widespread use in a variety of industries and the potential human exposure route via food, air, dust and soil [3]. Effluents that are rich in chromium originate from electroplating, leather tanning, wood preservation, textile dyeing, pigment manufacturing, stainless steel production and mining activities [3], Chromium in aquatic systems is found primarily as trivalent chromium [Cr(III)] or hexavalent chromium [Cr(VI)]. Cr(III) is known to be a much less toxic and mobile species with Cr(VI), on the other hand, is highly soluble, mobile mutagenic

and carcinogenic. Chromium in contaminated water can cause skin irritation, kidney dysfunction, liver damage or even respiratory problems and many cancers [37]. Therefore, World Health Organization and a number of environmental protection agencies put forth extremely strict guidelines for chromium levels in drinkable water and industrial effluents [19] Different treatment approaches are used to deal with the chromium-contaminated wastewater, like precipitative metal removal, ion replacement, membrane separation methods, electrochemical contaminant-removal, coagulation-flocculation and solvent extraction [38]. Nevertheless, these approaches are often constrained by high operating expenses, sludge production, membrane fouling and lower performance of the treatment at low metal concentration [5], [7]. Thus, one of the most dependable adsorbent methods for treatment is given by its operational simplicity, high efficiency, low costs, and ease of regeneration [1], [2].

Due to the low-cost, abundance, renewability and environmental friendliness agricultural wastes have received much attention as potential sustainable adsorbent precursors [39]. The high carbon content, well-developed porous structure and mechanical strength of Coconut shell with a large amount of oxygen-containing functional groups facilitate binding metal ions [4], [6], In addition, valuing coconut shell waste to produce adsorbents also conforms to the goals of sustainable waste management and resource circularity.

In the last few decades, magnetic modification of biomass adsorbents has become a simple and an effective approach to improve adsorption performance as well as portable recovery of exhausted adsorbents from treated water[38]. Decoupled from batch or column methods, surface functionalization by varying conditions in the pore space is typically stabilisation of magnetite (Fe_3O_4) nanoparticles on biomass surfaces to improve adsorbent properties and allow rapid magnetic recovery without filtration or centrifugation [2], [8].

While a large number of studies have been published using activated carbons and other agricultural residues as candidate solids to adsorb chromium ions, reports on the adsorption behaviour, Isotherms, thermodynamics, kinetics and process optimization of magnetically modified coconut shell biosorbents are scarce. This study thus aims to prepare and characterize a magnetically modified biosorbent from coconut shell for removing the Cr ions from aqueous media via an adsorption-based process, considering isotherms and thermodynamic studies.

1.1 Identification of Materials

The coconut shells were collected from coconut processing vendors in Agbara, Ogun State, Nigeria. The chromium (VI) source used in all trials was potassium hepta oxodichromate (vi), ($K_2Cr_2O_7$). Analytical grade ferric chloride hexahydrate ($FeCl_3 \cdot 6H_2O$), ferrous chloride tetrahydrate ($FeCl_2 \cdot 4H_2O$), sodium hydroxide (NaOH), hydrochloric acid (HCl) were product of Merck Laboratory, USA. Ammonia solution and 1,5 diphenylcarbazide reagent were sourced from Sigmal-Aldrich. Distilled water was used throughout the experiment.

1.2 Preparation of the adsorbent

The coconut shells were packed, washed, rinsed and oven-dried overnight in a vacuum oven at 150 °C for 6 hours. The process continued with crushing and blending the dried shell into fine powder of particle sizes less than 300 μm and sieved through a standard calibration sieve before stored in an airtight container [2].

1.3 Magnetic modification of the adsorbent

5.0 g powdered coconut shell suspended in 40 mL distilled water, 20 millilitres of 2 M urea solution was added as stabilizer, under continuous stirring [2]. Solutions of ferrous chloride and ferric chloride were added in 2:1 molar ratio. Ammonia solution was then added, until a pH of 11 was achieved. The obtained magnetic composite was rigorously rinsed with deionized water, separated by magnetism, and dehydrated under vacuum at 180 °C for 4 hours.

1.4 Characterization

The unprocessed, altered and non-modified adsorbents, were characterised by Fourier Transform Infrared (FTIR) spectrophotometer (Brüker Tensor 27), using KBr pellets in the spectral density range for radiative wave to frequency modulation at 4000–400 cm^{-1}. The surface topology and the elemental composition of Magnetic biosorbent were investigated by SEM (VEGA3 TESCAN) coupled with EDAX.

1.5 Preparations of aqueous solution

A stock solution of potassium dichromate ($K_2Cr_2O_7$) was prepared in concentrations of 1000 mg L^{-1} by dissolving a known amount of $K_2Cr_2O_7$ in distilled water. The necessary experimental concentrations were then serial diluted. An amount of 0.1 M HCl or 0.1 M NaOH was used to adjust the pH of these solutions.

2 ADSORPTION EXPERIMENTAL STUDIES

Batch equilibrium adsorption studies were carried out in 50 cm^3 conical flasks each having in them 25 cm^3 of metal aqueous samples, ranging in concentrations from 10 to 50 mg/L and constant adsorbent mass (0.1 g) was added in all the case [10]. The flasks were then incubated in a shaking water bath at 150 rpm and kept at constant temperature. The concentrations remaining in aqueous media, once the adsorbent was separated magnetically from the solution, were calculated by determining their absorbance using a UV-spectrophotometric instrument at wavelengths of 230 nm. The chromium ion removal percentage and the adsorbent capacities were evaluated with the following equations:

$$R(\%)=\left(\frac{C_O-C_t}{C_0}\right)\times 100 \qquad (1)$$

Adsorption capacity at any time,

$$q_t=\frac{(C_O-C_t)}{M}\times V \qquad (2)$$

Adsorption capacity at equilibrium,

$$q_e=\frac{(C_O-C_e)}{M}\times V \qquad (3)$$

where the pre-treatment concentration, concentration at time t, and equilibrium concentration (mg/L) of the dye are C_o, C_t and C_e,, respectively, solution volume (L) is V, and the adsorbent mass (g) is M.

Adsorption isotherms studies

The Isotherms data involved an experiment performed by adjusting the initial concentrations (10-50mg/L) of pollutant keeping fixed a 0.1g dose level in 50 mL. Erlenmeyer flasks with agitation at 150 rpm for two hours. Adsorption equilibrium data were studied using Langmuir, Freundlich, Temkin, and Dubinin-Radushkevich isotherms, which are represented by Equations 4 to 8. Parameters for these isotherms were obtained from the least squares fitting technique as described before. The mathematical expressions for these isotherms are shown below:

2.1 Langmuir model expression

The Langmuir adsorption isotherm [22] is usually employed for describing the adsorption process of an adsorbate as a monolayer on energetic homogeneous solid surfaces. The theory is founded upon two main hypotheses, namely that there is no interaction among adsorbed molecules and that all adsorption sites have similary affinity towards the incoming molecules. The Langmuir adsorption isotherm may also be represented in a nonlinear form, as given below:

$$Q_e=\frac{QmaxbC_e}{1+bC_e} \qquad (4)$$

where b is the Langmuir constant (it depends on the adsorption energy and affinity of the binding sites (L/mg), Q_{max} is the maximum adsorption limit (mg/g), Q_e refers to the amount adsorbed per mass of adsorbent, while C_e stands for the adsorbate concentration.

2.2 Freundlich model expression

Adsorption isotherms such as Langmuir [22], where the adsorption of adsorbate is explained for monolayer on energetically continuous homogeneous solid surfaces, has been equally extensively applied over recent times. This is done making two assumptions: the adsorbate molecules do not interact; they also have identical attraction for the impinging molecules. The non-linear form of the Langmuir isotherm model expression can be written as in Eq 4:

This Freundlich isotherm equation holds for nonideal adsorption processes with heterogeneous surfaces having adsorption energies that differ from each other. The most popular form of this isotherm equation is shown below in Equation 14:

$$Q_e=k_f*C_e^{\frac{1}{n}} \qquad (5)$$

where K_f and n stand for the Freundlich isotherm constants. The constant K_f refers to the adsorption capacity, while 1/n denotes the adsorption intensity.

2.3 Temkin model expression for the adsorption isotherms

The adsorption isotherms are described by the Temkin model expressions given by Tempkin [30] that also account for indirect adsorbate/adsorbate interactions during adsorption. Linear relation between increasting surface coverage and decreasing heat of adsorption is also assumed by the model. However, Temkin isotherms can be applied only within an intermediate range of ion concentration. Mathematical form of the Temkin equation in nonlinear form can be written as:

$$Q_e = \frac{RT}{b_T} ln a_T C_e \quad (6)$$

where q_e (mg/g) is the MB dye uptake at equilibrium, and Ce (mg/L) is MB dye concentration at equilibrium. The Temkin constants b_T (kJ/mol) and A_T (L/g) are related to the heat of adsorption and maximum binding energy. T is temperature (K), while R (8.314 J/mol/K) is universal gas constant.

2.4 Dubinin-Radushkevich model expression

The Dubinin – Radushkevich (D-R) model of heterogeneity of the adsorption isotherm for physical adsorption with Gaussian energy distribution described by Eq. [10], D–R model phenomennon show even more control over other models to take into account the temperature dependence. The D–R model It has been frequently used for the separation of physical and chemical adsorption. The multilayer phenomenon operates under the assumption of Van der Waal's forces. As a consequence of its improbable asymptotic behaviour and limitations in predicting Henry's laws constants at low pressure the D–R is used only for intermediate adsorbate concentrations.

$$Q_e = Q_s e^{-\beta\varepsilon^2} \quad (7)$$ where ε can be calculated as;

$$\varepsilon = RT * In(1 + \frac{1}{Ce})$$

where R is the gas constant (8.314 J/mol K) and T is the absolute temperature while Q_s (mg g^{-1}) is the saturation capacity.

This is the mean free energy (E) of sorption per molecule of the sorbate upon its movement from a large distance away to reach the interface with solid, as in equation 17. Here β is the equation constant.

$$E = \frac{1}{\sqrt{-2\beta}} \quad (8)$$

2.5 Thermodynamics parameters

Some important thermodynamic parameters relevant in the understanding of adsorption process, may be studied at these data obtained from experimental isotherms. Parameters like the variations of standard enthalpy (ΔH°), standard entropy (ΔS°) and the standard Gibbs free energy (ΔG°), therefore, needed to be determined. In this case, the effect of temperature from (30-50°C) was studied with initial concentration of 50mg/L a constant MSCS 0.1g dose level in 25ml Erylmeyer flasks and continuously stirred at 150 rpm while remaining the other parameters unchanged to observe the process at equilibrium by the notation:

C+D ⇌ C* D

$$K_D = \frac{q_e}{C_{e*m}} \quad (9)$$

$$\Delta G° = -RTInK_D \quad (10)$$

$$\Delta G = \Delta H - T\Delta S° \quad (11)$$

Equating equations 19 and 20 and solving for ΔS° and ΔH° gives:

$$InK_D = \frac{\Delta S°}{R} - \frac{\Delta H}{RT} \quad (12)$$

From the van't Hoff plot (ln K_D vs. 1/T) for the adsorption process, values of slope and intercept have been used in order to gain thermodynamic parameters.

3 RESULTS AND DISCUSSION

3.1 Characterization of the adsorbent

Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM–EDX) were used to analyze the sample. The techniques were chosen in determining the surface functional groups, morphological and elemental composition of the biosorbent before and after metal ions adsorption. The findings showed that magnetic modification improved the physicochemical characteristics of coconut shell and its applicability as a high-performing adsorbent for extracting chromium ion from aqueous sample [2].

FTIR spectra from Figure 1 exhibited various oxygen containing functional groups on biosorbent surface. The broad absorption band at 3473.88 cm^{-1} was attributed to the O–H stretching vibration of hydroxyl groups related to cellulose, hemicellulose and lignin while the peaks in range from 2922.23 to2855.14cm^{-1} were corresponding to the asymmetric and symmetric stretching vibrations of aliphatic C–H groups respectively[39]. The band at 1744.39 $cm^{-1}$was attributed to C=O stretching vibration; While the peaks,1461.12, 1371.66 and1155.47 cm^{-1} reflect bending vibration of C–H, O–H bending vibration and stretching vibrations of C–O–C stretching, respectively. Furthermore, the band of Fe-O vibration appeared at 723.10 cm^{-1}, thus validating that iron oxide particles were successfully deposited on the coconut shell during magnetization [2]. The noticeable shifts in the hydroxyl and carbonyl bands along with new peaks appearing at 1595.30 cm^{-1} after chromium ion adsorption provided evidence for interaction between metal ions with surface of biosorbent. This suggests that active participation and adsorption of hydroxyl and carbonyl groups via hydrogen bonding and electrostatic interaction are responsible for these spectral changes. These observations are in agreement with those already reported by [2] [9], [11], [12]. SEM micrographs in Fig. 2 a–b showed that the raw coconut shell has a rough and porous structure with irregular cavities which favors adsorption. The results also showed that following magnetic modification, the surface of the biosorbent became more densely packed and compact because iron oxide nanoparticles were deposited[36]. These observations indicate that the magnetic biosorbent has been successfully formed. After chromium ion adsorption, the surface was smoother and less porous, indicating that metal ion is located in open pores and active immobilization sites. Morphological changes similar to the above mentioned have also been found for magnetic agricultural biosorbents according to; [13] [16], [14].

The deposition of iron oxide nanoparticles on the surface of biomass was further confirmed by the EDX spectra presented in Figure 3a-b and the relevant elemental composition obtained from EDX analyse. Results indicate that the iron content raised greatly after magnetization, which may be due to iron oxide particles covered the surface of biomass and influenced its carbon content. After adsorption, there was decreased in iron content thus suggesting that not the loss of iron particles out of the bottle but gradual surface coverage with chromium ion adsorbed. Such persistence of iron content after adsorption proves that the magnetic phase existed stably through the entire period of adsorption. Similar elemental variations have been described by [1], [34], [15], [2]

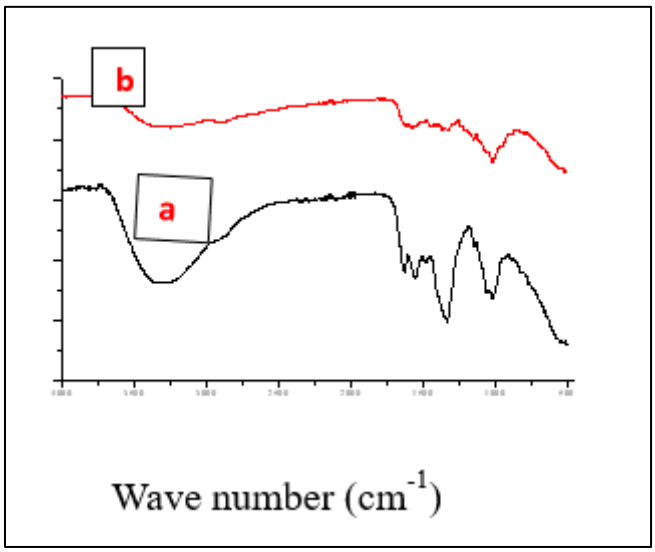


Figure 1: FTIR spectra of; (a) before (b) after adsorption

FTIR, SEM–EDX analyses confirmed successful synthesis of magnetic supported coconut shell biosorbent. These attributes contributed to the efficient adsorption ability of the biosorbent towards chromium ion with the presence of oxygen-containing functional groups, successful attachment of magnetite nanoparticles, better surface morphology and stable structure [21]. Such results illustrate that the use of magnetic modification considerably improved the adsorption

ability of coconut shell and justify its use as an efficient, eco-friendly, low-cost adsorbent material for wastewater remediation.



Figure 2: SEM image of: a SH, b MSCS

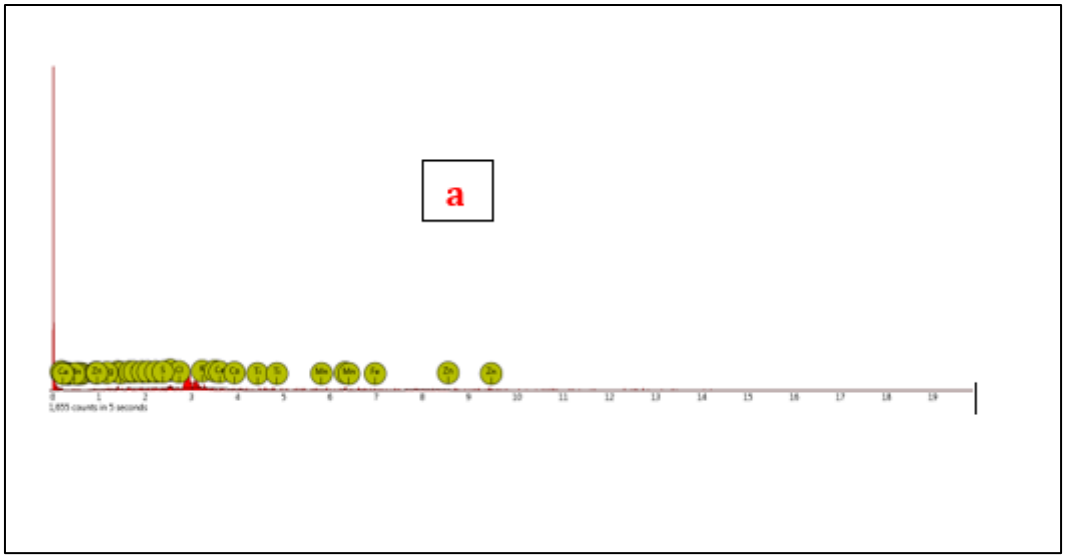


Figure 3a: EDX Spectrum Raw of raw coconut shell

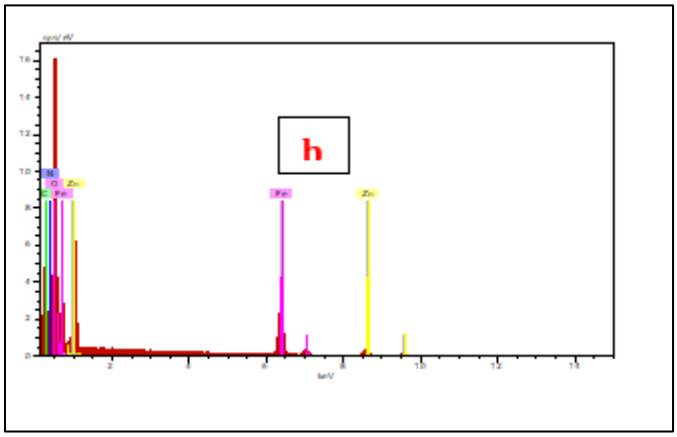


Figure 3b: EDX Spectrum MSCS

3.2 Effect of pH on the Adsorption

The decrease in the chromium ion removal percentage was significantly increased when the pH reduced from 8 to 2, and maximum adsorption occurred under strongly acidic conditions. This behaviour is due to the predominant $HCrO_4^-$ and $Cr_2O_7^{2-}$ speices and protonation of surface functional groups on biosorbent with low pH leads to electrostatic attraction between chromium oxyanions and immobilised positively charged may it be adsorption sites [18], [20], [23]. The increasing electrostatic attraction between the ions and the biosorbent as the solution pH increased was due to surface negative charge of the biosorbent [19], [17]. A small decrease in percentage removal beyond the optimal pH may relate to surface charge changes of biosorbent under alkaline conditions. The authors [24], [26] have also made similar observations and accounted for the better adsorption of cationic dyes at higher pH to lower competition from H^+ ions and stronger electrostatic interactions. Similar trends have been observed by [25],[27],[29], for lignocellulosic biosorbent in methylene blue adsorption.

3.3 Effect of Adsorbent Dosage

In the study, performance of magnetic supported coconut shell biosorbent (MSCS) on removal of chromium ion was assessed in 0.35g/L concentration and found effective as shown in figure 5. The removal efficiency increased from 96.0% at a 0.05 g to 97.0% adsorbent dose level at dosages of 0.10g and then 98.4% at dosages of 0.20 g, and a peak value (98.6%) was obtained by using the dose level of adsorbent material with a fourth quantity (0.40 g). However, for the remaining doses of 0.60, 0.80 and 1.00 g the removal efficiency was slightly lower: 98;4%, 94;8% and 90;4% respectively [38]. The increase in removal of chromium ions at lower doses happens due to greater presence of adsorption sites. However, decreased removal efficiency at high dosages may likely be due to aggregation of the particles and overlapping adsorption sites, causing a decrease of effective surface area available for adsorption. Similar findings were reported by [1], [2], [26], [28].

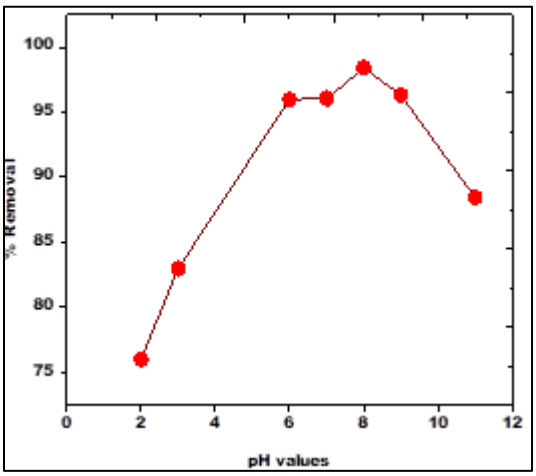


Figure 4: Effect of pH on the removal efficiency

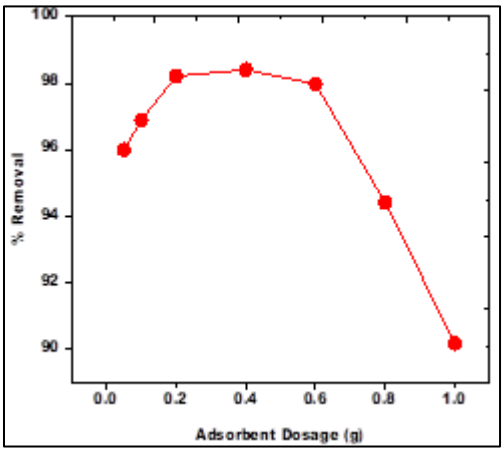


Figure 5: The influence of adsorbent dose level on the removal efficiency

3.4 Adsorption Isotherm Models

Equilibrium adsorption data are necessary to properly understand the adsorption process and gain insight into adsorbent–adsorbate interactions and mechanisms. Different isotherm models like non-linear Langmuir, Freundlich, Temkin and Dubinin-Dodushkevich D-R were selected in analysing the equilibrium adsorption of magnetic supported coconut shell biosorbent (MSCS) for removal of chromium ion. Figure 12 shows isotherm plots and Table 1 includes the parameters from the model.

Results from the isotherm parameters indicated that equilibrium adsorption data followed the models in the following order: Langmuir (R^2 = 0.998) > Freundlich (R^2 = 0.977) > Temkin (R^2 = 0.925) > Dubinin–Radushkevich (R^2 = 0.909). Langmuir model is well-fit due to Q_{max} of 37.54 mg g^{-1} proves the involvement of monolayer adsorption on a uniform surface for methylene blue adsorption. The RL value of 0.1209, and the 1/n value of 0.468 of the Freundlich isotherm indicate that adsorption process was favorable [1], [35], [33]. The Temkin model proved suitable for the adsorption process suggesting interaction between adsorbent and adsorbate. The Dubinin–Radushkevich model yielded the lowest correlation coefficient, while the mean adsorption energy (E) value was 4.92 kJ mol^{-1}, which is below 8 kJ mol^{-1} confirming that the investigated adsorbate - adsorbent interaction type was mainly physisorption process. This is in accordance to the kinetic data and observations from [32], [34]

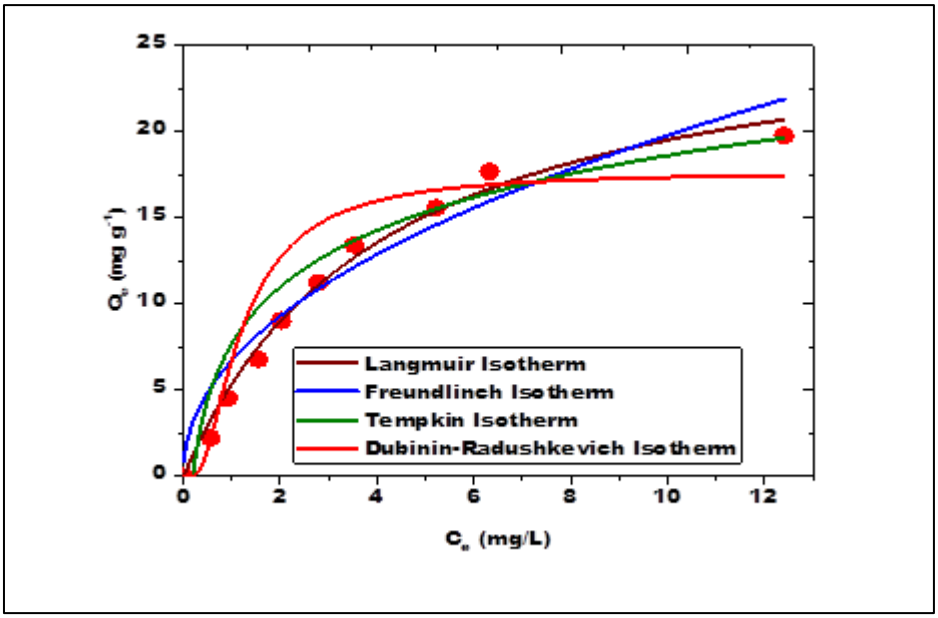


Figure 6: Adsorption isotherms fits

Table 1: Adsorption isotherm parameters

Isotherm Model	Parameter	Value
Langmuir	Qmax (mg g^{-1})	37.53799
	K_L (L mg^{-1})	0.24327
	R_L	0.1209
	R^2	0.998
Freundlich	K_F	6.73718
	1/n	0.468
	R^2	0.977
Temkin	b_T	546.324
	a_T (L mg^{-1})	5.09237
	R^2	0.925
Dubinin–Radushkevich	Qm (mg g^{-1})	17.62015

	$\beta \times 10^{-7}$ ($mol^2\ J^{-2}$)	2.463
	E ($kJ\ mol^{-1}$)	4.92
	R^2	0.909

3.5 Adsorption Thermodynamic Studies

Thermodynamic parameters (Table 3), were determined for chromium ion adsorption onto magnetized supported coconut shell (MSCS) sponge-based materials to evaluate feasibility, spontaneity and mechanism of adsorption and Van't Hoff Plot is depicted in Figure 7. The Gibbs free energy change (ΔG°), entropy change (ΔS°), and enthalpy change (ΔH°) values came from adsorption data at various temperatures. Adsorption equilibrium data were calculated at various temperatures and implemented into the Van't Hoff equation to determine thermodynamic quantities. Where ΔG° ($kJ\ mol^{-1}$) is the change in Gibbs free energy; ΔH° ($kJ\ mol^{-1}$) is the enthalpy change; ΔS° ($J\ mol^{-1}\ K^{-1}$) is the entropy change, R (8.314 $J\ mol^{-1}\ K^{-1}$) is universal gas constant, T (K): absolute temperature and K_d: distribution coefficient.

The Gibbs free energy (ΔG°) values published for each studied temperature demonstrate that adsorption of Cr ion unto coconut biosorbent is thermodynamically favourable. Further, the increasingly negative ΔG° values with increase of temperature indicated that increased temperatures would favour adsorption [2], [39], [36]

The value of enthalpy (ΔH°) is positive so the adsorption process was endothermic, meaning that heat is absorbed during adsorption [38]. This observation matches the experimental results as the amount of adsorption tend to escalate when increment in temperature occurred, implying that higher temperatures favoured the uptake of methylene blue on adsorbent [32] [34].

This change in ΔS° is positive, indicating that greater randomness exists at the solid–solution interface on adsorption [36]. The increase in disorder is possibly due to the fact that methylene blue molecules replace water molecules on adsorbent surfaces when the adsorption occurs [39]. The combination of high ΔH° and ΔS° values with low ΔG° demonstrate the adsorption process is viable, spontaneous, thermodynamically favourable within the studied temperature range [22], Overall comparison (Table 2) confirms that magnetized coconut shell biosorbent for the chromium ion removal, outperforms other adsorbents obtained from agricultural wastes enabling to use its potentiality in wastewater treatment [37].

Table 2: Comparison of the adsorption capacities of different adsorbents for Cr ion removal

Adsorbent	**Maximum adsorption capacity, Q_{max} ($mg\ g^{-1}$)**	**Reference**
White pine	38.00	Salazar-Rabago et al. (2017)
Sago waste (treated with phosphoric acid	36.82	Amode et al. (2016)
Bark from bush cane plant	23.49	Enenebeaku et al. (2017)
Banana peels	20.80	Annadurai et al. (2002)
Chaffs from cereals	20.30	Han et al. (2010)
Coffee residues after brewing	18.78	Franca et al. (2009)
Peels from oranges	94.70	Sahu et al. (2020)
Coconut shell	125.30	Effah et al. (2022)
Rice husk	89.30	Azeez and Musa (2021)
Banana peel (modified)	103.60	Rani and Gupta (2020)
Palm kernel shell	138.40	Adewuyi et al. (2023)
Magnetized sorghum husk (MSH)	30.04	Adeogun et al. (2019)
Magnetized supported coconut shell (MSCS)	37.54	Present study

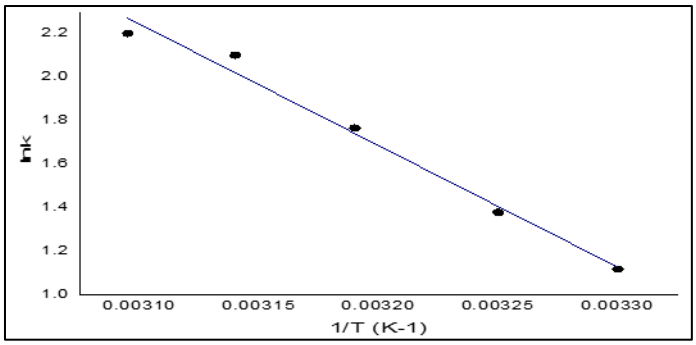


Figure 7: Van't Hoff fit for adsorption of Chromium ion

Table 3: Thermodynamic parameters

Temp (K)	In K_d	ΔG (kJ mol^{-1})	ΔH (kJ mol^{-1})	ΔS (J mol -1 K-1)	R^2
303.15	1.1165	-2.814	46.515	162.855	0.989
308.15	1.3781	-3.531			
313.15	1.767	-4.600			
318.15	2.102	-5.559			
323.15	2.202	-5.916			

4 CONCLUSION

The study successfully illustrated the preparation of magnetized supported coconut shell (MSCS) which was an environmentally non-toxic and inexpensive biosorbent for removing chromium ion from aqueous media. Characterisation outcomes from FTIR, and SEM–EDX confirmed that the coconut shell was successfully modified, and that functional groups, iron oxide phases and surface characteristics, facilitated chromium ion adsorption. The batch adsorption experiments demonstrated that the operating conditions (pH, contact time, adsorbent dosage level, concentration and temperature) greatly influenced removal effectiveness of Chromium ion. The initial adsorption phase was fast, achieving equilibrium at around 120 min with maximum removal efficiencies observed to be approximately 98.4% for the optimum dosages of adsorbent investigated. The Langmuir isotherm model (R^2 = 0.998) proved most suitable for the equilibrium data, with a maximum adsorption volume of 37.54 mg g^{-1} and R_L value = 0.1209 confirming favourable adsorption of chromium ion onto MSCS. Thermodynamic investigation exhibited negative Gibbs free energy values for all studied temperatures, while the positive ΔH° = 46.515 kJ mol^{-1} and ΔS° = 162.855 J mol^{-1} K^{-1} revealed that adsorption was spontaneous, endothermic and random at solid layer–solution interface. The findings show that magnetized supported coconut shell is a potential biosorbent in metal ion removal from contaminated wastewater, with high efficiency, cost-effectiveness and sustainability.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

No conflict of interest to be disclosed.

REFERENCES

[1] Akande J.A, Adeogun A.I, Uzosike A.S (2023). Removal of methyl green dye from wastewater, using activated carbon derived from corn cobs: Kinetics, thermodynamics and equilibrium studies. *Global journal of pure and applied chemistry research,12 (2) 22 – 36.*

[2] Adeogun, A. I., Akande, J. A., Idowu, M. A., & Kareem, S. O. (2019). Magnetic tuned sorghum husk biosorbent for effective removal of cationic dyes from aqueous solution: isotherm, kinetics, thermodynamics and optimization studies. Applied Water Science, 9(7), p. 1–17. https://doi.org/10.1007/s13201-019-1037-2

[3] Al-Mashaqbeh, O., Ghazi, S., & Al-Tarawneh, M. (2022). Optimization of operational parameters for cationic dye removal using biosorbents. Environmental Science and Pollution Research, 12345-12360. doi:https://doi.org/10.1007/s11356-021-17845-x

[4] Amode, J. O., Santos, J. H., Zaidi, Z. H., & Yeo, T. C. (2016). Adsorption of methylene blue using phosphoric acid-treated sago waste: Isotherm, kinetics, and thermodynamics. Desalination and Water Treatment, 57(55), 26611–26622.

[5] Annadurai, G., Juang, R. S., & Lee, D. J. (2002). Use of cellulose-based wastes for adsorption of dyes from aqueous solutions. Journal of Hazardous Materials, 92(3), 263–274. https://doi.org/10.1016/S0304-3894(02)00017-1

[6] Ayawei, N., Ebelegi, A. N., & Wankasi, D. (2017). Modelling and interpretation of adsorption isotherms. Journal of Chemistry, 2017, 3039817. https://doi.org/10.1155/2017/3039817

[7] Bayomie, O. S., Kandeel, H., Shoeib, T., Yang, H., Youssef, N., & El-Sayed, M. M. H. (2020). Novel approach for effective removal of methylene blue dye from water using fava bean peel waste. Scientific Reports, 10, 7824. https://doi.org/10.1038/s41598-020-64727-5

[8] Bello, T., Adeyemi, T., & Yusuf, R. (2022). Dye removal from aqueous solutions using raw and treated bean husk biomass. *Environmental Technology & Innovation*. doi:https://doi.org/10.1016/j.eti.2022.102677

[9] Chen, L., Gao, Y., & Li, H. (2023). Mechanistic insights into magnetic nanoparticle-enhanced adsorption of dyes. *Journal of Cleaner Production*. doi:https://doi.org/10.1016/j.jclepro.2023.136198

[10] Dubinin, M. (1960). The potential theory of adsorption of gases and vapors for adsorbents with energetically nonuniform surfaces. *Journal of Materials and Environmental* Science. Chemical reviews, 60(2), 235-241. https://doi.org/10.1021/cr60204a006.

[11] Effah, E. A., Osei, B. A., & Mensah, K. O. (2022). Coconut shell-derived magnetic composites for dye adsorption: Equilibrium, kinetic, and thermodynamic studies. Environmental Technology, 43(18), 2780–2794.

[12] Enenebeaku, C. K., Okoro, U. C., & Eze, S. O. (2017). Adsorption of methylene blue onto bush cane bark: Isotherms, kinetics and thermodynamics. Journal of Environmental Chemical Engineering, 5(4), 3820–3829.

[13] Eze, C., & Okoro, U. (n.d.). Kinetic modeling of cationic dye removal using lignocellulosic biosorbents. *Journal of Environmental Management*. doi:https://doi.org/10.1016/j.jenvman.2021.112851

[14] Fernandes, R., Silva, P., & Almeida, J. (2021). Bean husk as an emerging biosorbent for environmental applications. *Journal of Environmental Chemical Engineering*. doi:https://doi.org/10.1016/j.jece.2021.105562

[15] Foo, K. Y., & Hameed, B. H. (2020). Insights into modeling of adsorption isotherm systems. *Chemical Engineering Journal*. doi:https://doi.org/10.1016/j.cej.2020.124419

[16] Franca, A. S., Oliveira, L. S., & Ferreira, M. E. (2009). Kinetics and equilibrium studies of methylene blue adsorption by spent coffee grounds. Desalination, 249(1), 267–272.

[17] Hameed, B. H., & Ahmad, A. A. (2022). Sorption kinetics and dynamics of methylene blue uptake by lignocellulosic residues: Chemisorption vs. physisorption. Journal of Hazardous Materials, 424, 127410.

[18] Han, R., Zhang, J., Zou, W., Shi, J. and Liu, H. (2005) Equilibrium Biosorption Isotherm for Lead Ion on Chaff. Journal of Hazardous Materials, 125, 266-271.
Hanbali, G., Holail, H., & Hammud, H. (2014). Nonlinear regression error analysis for kinetic and isotherm modeling of heavy metal biosorption. Journal of Environmental Chemical Engineering, 2(4),

[19] Hassan, M., & Xu, J. (2023). Magnetic nanoparticle integration into biomass: Challenges and perspectives. *Environmental Technology & Innovation, 31*. doi:https://doi.org/10.1016/j.eti.2023.103283

[20] Ibrahim, R., & Ahmad, M. (2022). Biosorption of dyes using agricultural biomass: Mechanisms and applications. *Environmental Science and Pollution Research*, 28721–28745. doi:https://doi.org/10.1007/s11356-022-18951-x.

[21] Kumar, V., & Rao, P. (2023). Thermodynamic studies of dye adsorption on magnetic biosorbents. *Environmental Research*. doi:https://doi.org/10.1016/j.envres.2022.114003

[22] Langmuir, I. (1916). The constitution and fundamental properties of solids and liquids. Part I. Solids. Journal of the American Chemical Society, 38(11), 2221–2295. https://doi.org/10.1021/ja02268a002

[23] Martinez, J., & López, P. (2023). Agricultural waste utilization: Bean husks for wastewater treatment. *Sustainable Materials and Technologies*. doi:https://doi.org/10.1016/j.susmat.2023.e00456

[24] Medina-Zazueta, L., Miranda-Castro, F. C., Romo-Garcia, F., Martínez-Gil, M., Esparza-Ponce, H. E., Encinas-Basurto, D., & Ibarra, J. (2023). Development of sustainable magnetic biosorbent using aqueous leaf extract of Vallesia glabra for methylene blue removal from wastewater. Sustainability, 15(5), 4586. https://doi.org/10.3390/su15054586

[25] Moyo, T., Nkosi, T., & Mamba, B. (2021). Sustainable biosorption technologies for cationic dyes: A review. *Journal of Environmental Chemical Engineering, 9*(5). doi:https://doi.org/10.1016/j.jece.2021.106141

[26] Myers, R. H., Montgomery, D. C., & Anderson-Cook, C. M. (2016). Response Surface Methodology: *Process and Product Optimization Using Designed Experiments* (4th ed.). Wiley. https://doi.org/10.1002/9781118916032

[27] Rani, R., & Gupta, N. (2020). Banana peel biosorbent for removal of synthetic dyes. *Environmental Nanotechnology, Monitoring & Management*. doi:https://doi.org/10.1016/j.enmm.2020.100368

[28] Sahu, R., Singh, P., & Tripathi, M. (n.d.). Adsorption studies of MB using orange peel. *Materials Today: Proceedings*, 3210-3217. doi:https://doi.org/10.1016/j.matpr.2020.03.678

[29] Salazar-Rabago, J.J., Leyva-Ramos, R., Rivera-Utrilla, J., Ocampo-Perez, R., Cerino-Cordova, F.J. (2017). Biosorption mechanism of Methylene Blue from aqueous solution onto White Pine (Pinus durangensis) sawdust: Effect of operating conditions. *Sustainable Environment Research,* 27(1), 32–40. https://doi.org/10.1016/j.serj.2016.11.009

[30] Temkin, M. I. (1940). Kinetics of ammonia synthesis on promoted iron catalysts. Acta Phys. Chim. USSR, 12, 327-356. *Applied Water Science* (2019) 9:160 https://doi.org/10.1007/s13201-019-1037-2.

[31] Teweldebrihan, M. D., Grano, M. A., & Dawit, M. (2024). The application of magnetite biochar composite derived from Parthenium hysterophorus for the adsorption of methylene blue from aqueous solution. Frontiers in Environmental Science, 12, 1375437. https://doi.org/10.3389/fenvs.2024.1375437.

[32] Xu, Y., et al. (2025). Synthesis of magnetic biosorbent from bamboo powders and their application for methylene blue removal from aqueous solution: Kinetics, isotherm, and regeneration studies. Molecules, 30(6), 1320. https://doi.org/10.3390/molecules30061320.

[33] Yagub, M.T., Sen, T.K., Afroze, S. and Ang, H.M. (2014) Dye and Its Removal from Aqueous Solution by Adsorption: A Review. Advances in Colloid and Interface Science, 209, 172-184. *Journal of Environmental Protection*,https://doi.org/10.1016/j.cis.2014.04.002.

[34] Zubrik, A., Jáger, D., Mačingová, E., Matik, M., Hredzák, S. (2023). *Spontaneous degradation of methylene blue adsorbed on magnetic biochars.* Scientific Reports, 13:14601. https://doi.org/10.1038/s41598-023-39976-9.

[35] Akande J.A; O.F Michael, O.F., K.M Olaoluwa, K.M. (2022). Batch adsorption of safranin o dye from wastewater using activated carbon derived from ground nut pod (AGP).*World journal of advanced research. 16(2), 403-423*

[36] J.A., A., E.A., O., A.O., I., El-Rayyes, A., S. Refat, M., & Mohammed Alsuhaibani, A. Microwave-assisted glucose production from Ofada-rice husk via alkaline pretreatment and acid hydrolysis: Kinetic and optimization study. *Bulletin of the Chemical Society of Ethiopia*, *39*(10), 1919–1936. (2025).

[37] Aljazzar O., S., J. A, A., Anthony Okechukwu, U., El-Rayyes, A., A. Albedair, L., & A. Edwin, O. Kinetics and isotherms evaluations on safranin o dye uptake using activated adsorbent prepared from sorghum husks. *Bulletin of the Chemical Society of Ethiopia*, *39*(11), 2295–2313. (2025).

[38] Ali E., Ibrahim A., Ezekiel F.S, Edwin A.O, Akande J.A**,** Akeem A.B, Moamen S.R, Amnah M.A. **.** Cassava chaff Ash as Potential Adsorbent for Arsenic ions Removal from Aqueous solution: Evaluations of Isotherms, Kinetics and Thermodynamic properties. 20 (2) 3386 – 3414. (2025)

[39] Akande James , Shehu Isah, Olayemi Ife, Oguntolu Aderonke and Otugade Zainab. Removal of methyl green dye using activated carbon prepared from corn cobs. International Journal of Frontline Research in Life Science, 02(01), 018–032. (2023).