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Application of novel chicken feather nanoparticles in wastewater detoxification. Thermodynamics and mechanism of the adsorption of heavy metal ions

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Abstract

Chicken feather nanoparticles (CFNP) were investigated as a sustainable keratin-based biosorbent for the removal of Pb(II) and Cu(II) from aqueous solution. The physicochemical properties, surface functional groups, equilibrium behaviour, and thermodynamic characteristics of CFNP were evaluated to elucidate its adsorption potential and underlying mechanisms. CFNP exhibited a slightly alkaline pH of 8.45, low moisture content (5.76%), high loss on ignition (81.65%), and low bulk density (0.51 g/cm³), indicating a predominantly organic, keratin-rich and lightweight material. FTIR analysis showed characteristic O–H/N–H, C–H and amide I–III bands, while spectral changes after metal loading indicated participation of oxygen- and nitrogen-containing functionalities in metal uptake. Langmuir model provided the best equilibrium description, with maximum adsorption capacities of 256.41 and 119.05 mg/g for Cu(II) and Pb(II), respectively, and high coefficients of determination ($R^2 = 0.9818$ and 0.9937). The Langmuir separation factors (RL) of 0.403 for Cu(II) and 0.111 for Pb(II) confirmed favourable adsorption. Freundlich n values (>1) and strong Temkin fits further indicated surface heterogeneity and coverage-dependent adsorption energetics. D–R characteristic energies suggested possible ion-exchange contributions, although such values cannot independently establish chemisorption. Thermodynamic analysis showed positive ΔH° values of 22.77 and 26.06 kJ/mol for Cu(II) and Pb(II), respectively, confirming endothermic adsorption, while negative ΔG° values demonstrated spontaneity. Overall, CFNP represents a promising, low-cost and sustainable biosorbent for divalent metal remediation.

KEYWORDS: chicken feather nanoparticles, biosorption, Pb(II), Cu(II), Langmuir, FTIR, thermodynamics, keratin



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1. INTRODUCTION

Heavy-metal contamination remains one of the most persistent challenges in water and wastewater management. Unlike many organic contaminants, metallic ions do not undergo biological degradation and may remain mobile, accumulate in sediments or enter aquatic food chains. Lead, cadmium, nickel, copper and related metals can interfere with neurological, renal, hepatic, reproductive and haematological functions, with the severity of their effects depending on chemical form, exposure duration and individual susceptibility (Tchounwou et al., 2012; Jaishankar et al., 2014). Industrial activities such as mining, metal finishing, battery manufacture, electroplating, pigment production and improper waste disposal continue to release metal-bearing effluents into aquatic systems, particularly in regions where treatment infrastructure and regulatory enforcement remain inadequate (Oladimeji et al., 2024).

Several technologies have been applied to the treatment of metal-contaminated wastewater, including chemical precipitation, coagulation–flocculation, ion exchange, membrane separation, electrochemical treatment and adsorption. Although these methods can achieve substantial removal, their practical use may be limited by high operating costs, energy consumption, membrane fouling, chemical requirements and the generation of metal-rich sludge requiring further treatment (Crini and Lichtfouse, 2019; Burakov et al., 2018; Jaffar et al., 2024). Adsorption is particularly attractive because of its operational simplicity, flexibility and potential effectiveness at relatively low dissolved-metal concentrations. Its success, however, depends strongly on adsorbent cost, availability, regeneration potential and affinity for the target ions (Wang and Chen, 2009; Choi and Lee, 2022; Karnwal, 2024). A wide range of materials has consequently been investigated as heavy-metal adsorbents. These include activated carbon, zeolites, metal oxides, clays, hydroxyapatite, hydrogels, magnetic composites and engineered biochars (Jamil et al., 2010; Zou et al., 2019; Wang et al., 2020; Sepehri et al., 2023; Ahmed et al., 2023; El Hammari et al., 2023; Bai et al., 2024). Advanced inorganic materials often exhibit high adsorption capacities and rapid uptake, but their synthesis may involve costly precursors, energy-intensive processes or chemical modification steps that reduce their environmental and economic advantages. This has encouraged increasing interest in biosorption, in which naturally occurring or waste-derived biological materials are used to bind contaminants from aqueous media.

Biosorption combines wastewater treatment with waste valorisation. Agricultural residues, food-processing wastes and protein-rich biomasses contain carboxyl, amino, hydroxyl, amide and sulphur-bearing groups capable of interacting with dissolved metal ions through electrostatic attraction, ion exchange, surface complexation and coordination (Ali et al., 2016; Salaudeen, 2020; Karim et al., 2023; Sheraz et al., 2024). Materials such as mustard husk, rice straw, banana peel, corn stalks, neem seed husk and other lignocellulosic residues have shown measurable affinity for Pb(II) and related ions (Meena et al., 2008; Ndekei et al., 2021; Yun et al., 2022; Granado-Castro et al., 2024; Yahaya et al., 2024). Nevertheless, the composition of plant wastes can vary substantially with species, growth conditions and pretreatment, leading to inconsistencies in adsorption performance.

Keratinous wastes provide a chemically distinct class of biosorbents. Keratin is a structural protein found in feathers, wool, fur, hair, nails and horns. Its polypeptide framework contains peptide bonds, amino and carboxyl groups, while cysteine residues introduce disulphide and other sulphur-containing functionalities that can participate in metal binding (Aluigi et al., 2007; Eslahi et al., 2013; Saha et al., 2019). Unlike many conventional agricultural residues, keratin biomasses contain a relatively high proportion of nitrogen- and sulphur-bearing sites. These groups may coordinate metal ions directly or contribute to pH-dependent electrostatic interactions at the adsorbent–solution interface (Kar and Misra, 2004; Nikiforova et al., 2019).

Chicken feathers are among the most abundant keratin-rich wastes generated by the poultry industry. Their disposal through landfilling or uncontrolled burning creates odour, sanitation and environmental concerns, while their tightly cross-linked structure makes natural decomposition slow. Converting this waste into an adsorbent therefore offers two linked advantages: reducing the environmental burden associated with feather disposal and producing a low-cost material for wastewater

treatment. Earlier investigations demonstrated that chicken feathers can remove Pb(II) and Cu(II) from aqueous solutions and that their equilibrium behaviour can be represented using conventional adsorption models (Salaudeen et al., 2018). Subsequent reviews have reinforced the potential of keratin biomasses as inexpensive and chemically active materials for heavy-metal sequestration (Salaudeen, 2020; Saha et al., 2019).

The adsorption performance of chicken feathers is controlled by the accessibility of keratin functional groups. In intact fibres, some active sites may be buried within the compact protein matrix or remain inaccessible because of extensive disulphide cross-linking. Conversion of feathers into nanoparticles can expose additional binding sites, increase external surface area and reduce the distance over which ions must diffuse before reaching internal receptor sites. Similar benefits have been reported for regenerated keratin particles, keratin-based nanosponges and nanoengineered protein adsorbents (Zhang et al., 2013; Hoti et al., 2024; Zubair et al., 2025). Nanostructuring may therefore improve adsorption without introducing the high material costs associated with many synthetic nanoadsorbents.

The environmental application of keratin nanoparticles also requires careful mechanistic interpretation. A high percentage removal alone does not explain whether uptake is controlled by surface binding, pore diffusion, electrostatic interactions or coordination with specific functional groups. Kinetic models such as the pseudo-first-order and pseudo-second-order equations are useful for describing adsorption rates, but their goodness of fit should not be treated as conclusive evidence for a particular molecular mechanism (Revellame et al., 2020; Wang and Guo, 2020). Similarly, Langmuir and Freundlich models provide useful summaries of equilibrium behaviour, but their parameters can be misleading when model assumptions are ignored or when linearised equations distort the experimental error structure (Foo and Hameed, 2010; Al-Ghouti and Da'ana, 2020; Majd et al., 2022; Hu et al., 2023).

Thermodynamic assessment is equally important because temperature can influence ion hydration, adsorbent swelling, diffusion and metal–surface affinity. However, the reliability of calculated Gibbs free energy, enthalpy and entropy depends on the definition of the equilibrium constant. Salaudeen and Chibueze (2020) demonstrated that different calculation approaches can generate substantially different thermodynamic parameters when dimensional adsorption constants are used without appropriate standardisation. The thermodynamic behaviour of Pb(II) adsorption on sheep fur has also shown how temperature-dependent data can provide useful evidence of adsorption favourability when interpreted with kinetic and equilibrium results (Salaudeen et al., 2022b). More broadly, mechanistic analysis of heavy-metal adsorption on keratin biomasses has confirmed that thermodynamic parameters are most informative when considered alongside surface chemistry and adsorption modelling rather than in isolation (Salaudeen et al., 2022a).

This integrated approach reflects a wider movement in environmental research away from relying exclusively on bulk concentration changes and towards explaining the processes underlying contaminant behaviour. Mechanism-resolved analytical frameworks, including emerging metabolomics-based approaches, emphasise the value of connecting measured environmental changes with the chemical and biological pathways responsible for them (Salaudeen and Vuanghao, 2025). For adsorbent development, this means that removal efficiency should be accompanied by evidence describing binding-site availability, adsorption energetics and the influence of solution conditions.

Accordingly, this study investigated chicken feather nanoparticles as potential adsorbents for heavy-metal removal from aqueous systems. The physicochemical properties of the adsorbent were evaluated using Fourier-transform infrared spectroscopy (FTIR) to identify the functional groups present in the virgin and metal-loaded adsorbents, while scanning electron microscopy (SEM) was employed to examine their surface morphology. The adsorption behaviour was further evaluated using equilibrium isotherm models, and thermodynamic parameters were determined to assess the feasibility, spontaneity, and energetic characteristics of the adsorption process.

2.0 MATERIALS AND METHODS

2.1 Materials and reagents

Waste chicken feathers were collected from a poultry-processing facility and transported to the laboratory in clean polyethylene bags. Analytical-grade salts of the investigated heavy-metal ions were used to prepare the corresponding aqueous solutions. Hydrochloric or nitric acid and sodium hydroxide were used for pH adjustment. Ethanol, laboratory detergent and deionised water were used during feather cleaning and nanoparticle preparation.

All chemicals were used without further purification. Glassware was soaked in dilute nitric acid, rinsed thoroughly with deionised water and dried before use to minimise trace-metal contamination. The exact manufacturers and purities of the chemicals, together with the investigated metal salts, should be reported in the final manuscript.

2.2 Pretreatment of chicken feathers

The feathers were manually sorted to remove visible debris, blood residues and non-feather materials. They were washed repeatedly with warm water containing a mild laboratory detergent and then rinsed with deionised water until the wash water was clear. Residual oils and surface contaminants were removed by washing with aqueous ethanol. The cleaned feathers were dried at approximately 60 °C to constant mass and cut into short pieces before particle preparation.

The cleaning procedure was intended to remove external contaminants while retaining the keratin structure and its metal-binding functional groups. Comparable washing and pretreatment approaches have been used for keratin fibres intended for extraction, regeneration and adsorption applications (Aluigi et al., 2007; Eslahi et al., 2013; Zhang et al., 2013).

2.3 Preparation of chicken feather nanoparticles

Chicken feather nanoparticles were produced using a keratin size-reduction and dispersion procedure adapted from previously reported approaches for preparing regenerated keratin particles and nanoengineered keratin adsorbents (Zhang et al., 2013; Hoti et al., 2024; Zubair et al., 2025).

The cleaned and dried feathers were mechanically milled until a fine powder was obtained. The powder was subjected to the selected keratin-disintegration or extraction treatment under controlled solid-to-liquid ratio, temperature and reaction time. After treatment, insoluble residues were removed by filtration or centrifugation. Where keratin precipitation was employed, the clarified solution was adjusted gradually to the required precipitation pH, and the recovered keratin was separated by centrifugation.

The recovered material was washed repeatedly with deionised water until the washings approached neutral pH. It was then freeze-dried or vacuum-dried, remilled and dispersed in deionised water by ultrasonication to reduce agglomeration. The resulting powder was designated chicken feather nanoparticles (CFNPs).

Because the references supplied do not contain the exact preparation conditions used in the present experiment, the final manuscript should state the actual extraction reagent, reagent concentration, solid-to-liquid ratio, treatment temperature, extraction duration, precipitation pH, centrifugation speed, drying method, milling time and sonication conditions.

2.4 Physicochemical characterization

The physicochemical properties of the CFNPs were determined using standard gravimetric and instrumental procedures. Moisture content was measured by drying a known mass of the sample at 105 °C to constant weight. Ash content or loss on ignition was determined by heating the dried sample in a muffle furnace under controlled conditions. Bulk density was calculated from the mass of loosely packed CFNPs occupying a known volume. The pH of the adsorbent was measured by equilibrating a known mass of CFNPs with deionised water at a fixed solid-to-liquid ratio.

2.5 Fourier-transform infrared spectroscopy

Fourier-transform infrared spectroscopy was used to identify the major functional groups present on the CFNP surface before and after heavy-metal adsorption. Dried samples were scanned over approximately 4000–400 cm^{-1} under identical acquisition conditions.

Spectral interpretation focused on the N–H and O–H stretching region, aliphatic C–H bands, amide I, amide II and amide III vibrations, as well as sulphur-containing groups derived from cystine and its oxidation products. Changes in peak position, intensity or band shape after adsorption were considered evidence of possible involvement of amino, carboxyl, hydroxyl, amide and sulphur-bearing sites in metal binding. The assignments were guided by reported structural studies of keratin and keratin-based adsorbents (Aluigi et al., 2007; Kar and Misra, 2004; Saha et al., 2019).

2.6 Preparation of heavy-metal solutions

Individual stock solutions of the investigated heavy-metal ions were prepared by dissolving accurately weighed quantities of their analytical-grade salts in deionised water. Working solutions were obtained by serial dilution of the stock solutions.

The initial pH was adjusted using dilute acid or sodium hydroxide. Experiments were conducted below the pH at which precipitation or extensive hydrolysis of the metal ions would occur. This precaution was necessary to ensure that the measured decrease in dissolved-metal concentration resulted predominantly from adsorption rather than bulk precipitation.

Residual metal concentrations were measured using atomic absorption spectrometry. Calibration standards were prepared from certified or laboratory stock solutions, and reagent blanks were included in each analytical batch.

2.7 Adsorption experiments

Adsorption experiments were conducted in capped conical flasks containing a known volume of metal solution and a measured mass of CFNPs. The suspensions were agitated at constant speed in a temperature-controlled orbital shaker. At the end of each experiment, the adsorbent was separated by centrifugation or membrane filtration, and the remaining dissolved-metal concentration was measured. All adsorption tests were performed in triplicate, together with appropriate solution and adsorbent blanks.

2.8 Adsorption capacity and removal efficiency

The amount of metal adsorbed at equilibrium was calculated using:

$$q_e \text{ (mg/g)} = \frac{(C_i - C_f) \times V}{w}$$

The adsorption capacity at time (t) was determined from:

$$q_t \text{ (mg/g)} = \frac{(C_i - C_t) \times V}{w}$$

where C_0 , C_e and C_t represent the initial, equilibrium and time-dependent metal concentrations, respectively; (V) is the solution volume; and w is the dry mass of CFNPs.

2.9 Conventional equilibrium modelling

In order to investigate the biosorption isotherm of the heavy metals on the keratin biomaterials, four common isotherm models were employed. They include: Freundlich, Langmuir, Temkin, Dubinin-Radushkevich isotherm models

2.10 Thermodynamic analysis

Thermodynamic parameters were calculated from temperature-dependent equilibrium data using a properly defined dimensionless equilibrium constant (K_c). The standard Gibbs free-energy change was calculated as:

$$\Delta G^\circ = -RT \ln K_c$$

The enthalpy and entropy changes were obtained from the van't Hoff relationship:

$$\ln K_c = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT}$$

where R is the universal gas constant and T is the absolute temperature. A plot of $\ln K_c$ against $1/T$ was used to estimate ΔH° and ΔS° from the slope and intercept.

Negative ΔG° values were interpreted as thermodynamic favourability under the experimental conditions. The sign and magnitude of ΔH° were used to assess the temperature dependence of adsorption, while ΔS° was considered in relation to changes in interfacial organisation, ion hydration and adsorbent–solution interactions.

The equilibrium constant was converted to a dimensionless form before calculating thermodynamic parameters. This was necessary because the use of dimensional Langmuir or distribution constants can generate unit-dependent values. The procedure followed the methodological considerations discussed by Salaudeen and Chibueze (2020) and the thermodynamic interpretation of heavy-metal adsorption on keratin biomasses reported by Salaudeen et al. (2022a).

3.0 RESULTS AND DISCUSSION

Table 1: Physico-chemical analysis of CFNP

Properties	Value
pH	8.45
Moisture content (%)	5.76
Loss of mass on ignition (%)	81.65
Bulk density (g/cm ³)	0.51

The physico-chemical analysis of the chicken feather nanoparticles (CFNP) presented in Table 1 reveals critical surface and structural properties relevant for environmental remediation and adsorption applications. The material exhibits a slightly alkaline pH of 8.45, which influences the surface charge and electrostatic interactions between the adsorbent and metal ions in solution. The low moisture content of 5.76% indicates good storage stability and dry-state integrity, minimizing premature degradation or clumping. Furthermore, the high loss of mass on ignition at 81.65% confirms the predominantly organic and proteinaceous keratin composition of the nanoparticles, which are rich in functional active sites. Finally, a bulk density of 0.51 g/cm³ reflects a light, porous structure favorable for rapid liquid-solid mass transfer and efficient diffusion during batch sorption processes.

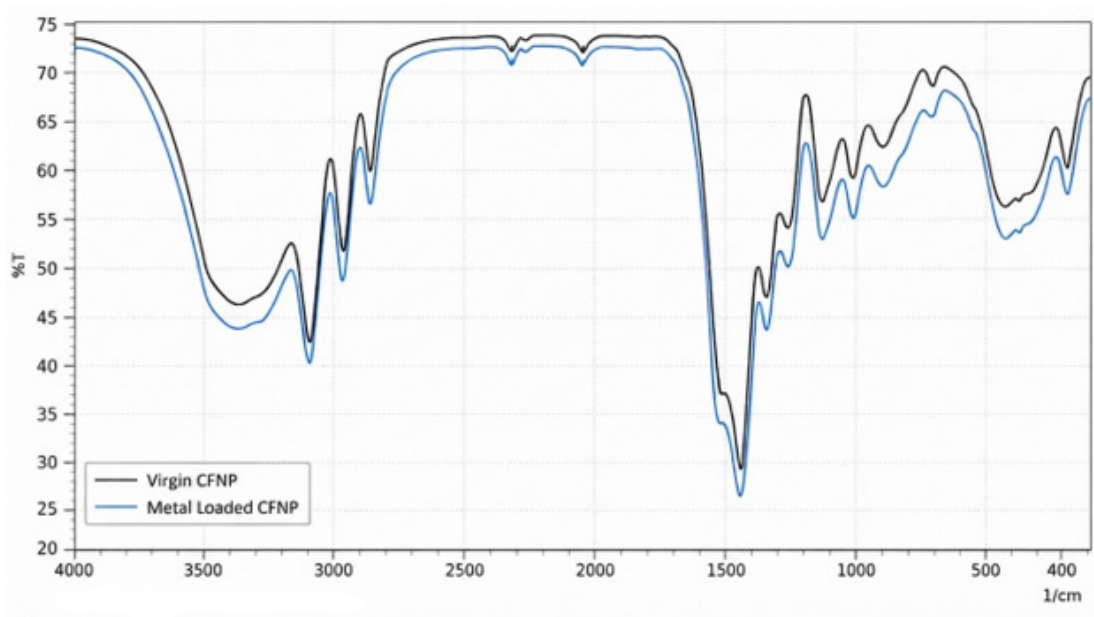


Figure 1: FTIR spectra of virgin and metal-loaded chicken feather nanoparticles (CFNP)

The FTIR spectra of virgin and metal-loaded chicken feather nanoparticles (CFNP) shown in Figure 1 retain the characteristic absorption features of keratin while exhibiting measurable changes after metal adsorption, indicating interaction between the keratin surface and adsorbed metal ions (Kar and Misra, 2004; Saha et al., 2019; Dhaouadi et al., 2020). The broad band in the 3200–3500 cm^{-1} region is attributable mainly to overlapping O–H and N–H stretching vibrations associated with hydroxyl groups and peptide functionalities in keratin (Aluigi et al., 2007; Eslahi et al., 2013; Zhang et al., 2013). Changes in the position or intensity of this broad region following metal loading are therefore consistent with participation of nitrogen- and oxygen-containing functionalities in metal binding (Kar and Misra, 2004; Nikiforova et al., 2019; Saha et al., 2019).

The absorptions around 2850–3000 cm^{-1} are associated with aliphatic C–H stretching vibrations of keratin side chains, while the persistence of these bands after adsorption suggests that the basic protein framework remains substantially intact (Aluigi et al., 2007; Zhang et al., 2013). The intense region around 1600–1700 cm^{-1} corresponds predominantly to amide I, particularly peptide C=O stretching, whereas bands around 1500–1550 cm^{-1} are characteristic of amide II vibrations involving N–H bending and C–N stretching (Aluigi et al., 2007; Eslahi et al., 2013; Saha et al., 2019). Alterations in these amide regions after metal uptake support the involvement of peptide carbonyl and nitrogen-containing groups in surface complexation or coordination with metal ions (Kar and Misra, 2004; Nikiforova et al., 2019; Dhaouadi et al., 2020).

Changes within approximately 1200–1300 cm^{-1} may additionally reflect perturbation of amide III and C–N-containing functionalities, while variations in the lower-frequency fingerprint region may be associated with sulfur-containing keratin groups and other surface functionalities capable of binding metals (Kar and Misra, 2004; Saha et al., 2019; Zubair et al., 2025). Mechanistically, the spectral changes are consistent with a combination of coordination, surface complexation, ion exchange and electrostatic interactions rather than a single adsorption pathway, which agrees with the established multi-site adsorption behaviour of keratinous biosorbents toward heavy-metal ions (Dhaouadi et al., 2020; Salaudeen et al., 2022a; Saha et al., 2019; Zubair et al., 2025).

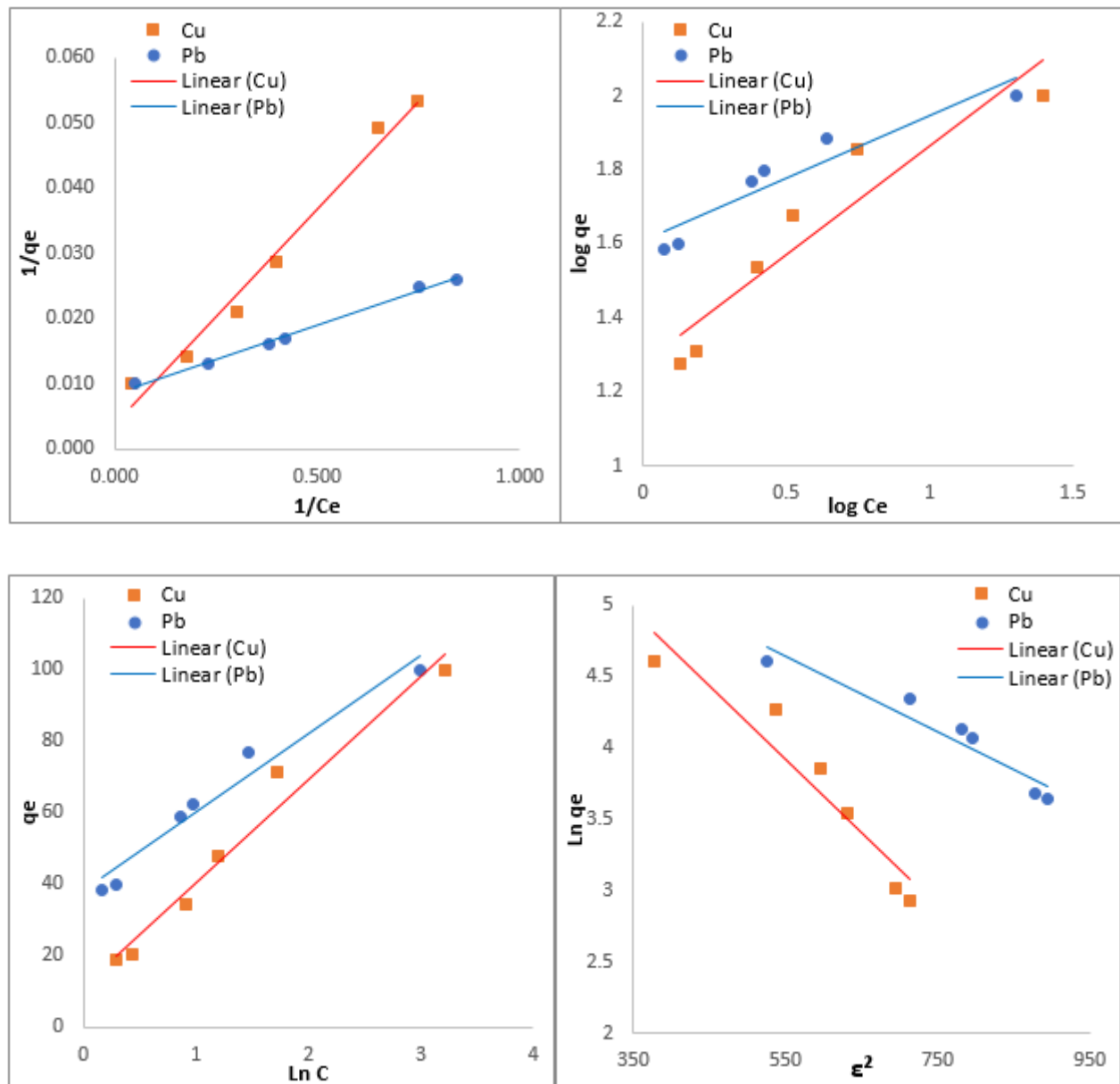


Figure 2: (a) Langmuir, (b) Freundlich, (c) Temkin and (d) D-R isotherm plots for the biosorption of Pb(II) and Cu(II) by CFNP

Table 2: Langmuir, Freundlich, Temkin, and Dubinin–Radushkevich Isotherm Parameters for Pb(II) and Cu(II) Biosorption onto CFNP

Isotherm	Parameter	Cu	Pb
Langmuir	q_{max} , mg/g	256.41	119.05
	Constant (K_L , L/mg)	0.0592	0.3981
	R_L	0.403	0.111
	R^2	0.9818	0.9937
Freundlich	n	1.71	2.95
	K_F , mg/g(L/mg) ^{1/n}	19.05	40.49
	R^2	0.8812	0.8913
Temkin	B_T , J/mol	29.08	22.15
	K_T , L/mg	1.46	5.59
	R^2	0.9692	0.9626
Dubinin-Radushkevich	q_m , mg/g	883.99	441.51
	β , mol ² /kJ ²	0.0052	0.0026
	R^2	0.9099	0.9151

The equilibrium behaviour of Pb(II) and Cu(II) adsorption onto CFNP was evaluated using the Langmuir, Freundlich, Temkin and Dubinin–Radushkevich (D–R) isotherm models shown in Figure 2 and associated parameters presented in Table 2. Collectively, the model parameters provide evidence that metal uptake by CFNP is governed by a combination of surface-site interactions, differences in site energy and progressive occupation of available adsorption sites rather than by a single idealized mechanism. The relatively high coefficients of determination obtained for the Langmuir model, particularly for Pb(II) ($R^2=0.9937$) and Cu(II) ($R^2=0.9818$), indicate that Langmuir provides the strongest description among the models considered. This is consistent with recent reviews showing that Langmuir is frequently the best-performing model for heavy-metal adsorption systems, although model selection should ideally consider nonlinear fitting and error functions rather than R^2 alone (Al-Ghouti et al., 2022; Girish, 2025). The Langmuir maximum adsorption capacities were 256.41 mg/g for Cu(II) and 119.05 mg/g for Pb(II). These values indicate a considerably greater theoretical uptake capacity of CFNP for Cu(II) than for Pb(II), with the Cu(II) capacity being approximately 2.15 times that of Pb(II). The high q_{max} values suggest that CFNP possesses a substantial population of accessible binding sites capable of accommodating divalent metal ions. Comparable high capacities have been reported for functionalized carbon-based and nanostructured adsorbents. For example, L-cysteine-modified activated carbon fibres exhibited Langmuir capacities of 161.03–179.53 mg/g for Pb(II), while amino-functionalized cellulose nanocrystals showed capacities of 65.22 and 58.50 mg/g for Pb(II) and Cu(II), respectively (Zhu et al., 2022; Xu et al., 2021). The higher Cu(II) capacity observed for CFNP therefore indicates particularly favourable interaction between Cu(II) and the functional groups or surface domains of the material.

The Langmuir affinity constants (K_L were 0.0592 L/mg for Cu(II) and 0.3981 L/mg for Pb(II). The larger K_L for Pb(II) suggests stronger apparent equilibrium affinity of Pb(II) for the available CFNP binding sites, despite Cu(II) having the higher overall adsorption capacity. This distinction is important: q_{max} reflects the estimated maximum uptake capacity, whereas K_L is related to adsorbate–adsorbent affinity. Thus, CFNP appears capable of accommodating substantially more Cu(II), while the individual

sites may exhibit stronger apparent affinity toward Pb(II). Similar differences between adsorption capacity and affinity have been observed in multimetal adsorption systems and emphasize that these parameters describe different aspects of equilibrium behaviour (Al-Ghouti et al., 2022; Tighadouini et al., 2022; Girish, 2025).

The separation factor R_L further supports the favourability of adsorption. The values of 0.403 for Cu(II) and 0.111 for Pb(II) fall between 0 and 1, which corresponds to favourable Langmuir adsorption. The much lower R_L for Pb(II) is consistent with its larger K_L , indicating particularly favourable interaction over the investigated concentration range. Similar interpretation has been reported for Cu(II) adsorption onto carbon nanofibres, where ($0 < R_L < 1$) was used as evidence of favourable adsorption (García-Díaz et al., 2018). Importantly, the lower R_L for Pb(II) does not mean that Pb(II) has the greater maximum capacity; rather, it indicates a more favourable equilibrium affinity under the concentration conditions examined.

The Freundlich model produced (n) values of 1.71 for Cu(II) and 2.95 for Pb(II), with corresponding R^2 values of 0.8812 and 0.8913. Both n values are greater than unity, indicating favourable adsorption and suggesting that the heterogeneous-surface interpretation is also relevant to the CFNP system. However, because the Freundlich R^2 values are substantially lower than those of Langmuir, heterogeneous multilayer adsorption alone does not adequately describe the equilibrium data. This distinction is important because a lower Freundlich fit does not imply that CFNP has a perfectly homogeneous surface; rather, it suggests that the overall equilibrium response is better approximated by the finite-site behaviour represented by the Langmuir model. A similar pattern was reported for Pb(II) adsorption on L-cysteine-modified activated carbon fibre, where Langmuir provided a substantially better fit than Freundlich, supporting predominant monolayer uptake on energetically accessible sites (Zhu et al., 2022). More recently, Pb(II), Cu(II) and Zn(II) adsorption on coconut husk also showed favourable Freundlich n values while Langmuir provided the stronger equilibrium description.

The Temkin model produced R^2 values of 0.9692 for Cu(II) and 0.9626 for Pb(II), considerably higher than those obtained from Freundlich. This relatively strong fit provides useful mechanistic information because the Temkin model considers changes in adsorption energy as surface coverage increases. Its good agreement with the experimental data suggests that the adsorption energy is not completely independent of surface occupancy and that interactions between the adsorbed metal ions and the CFNP surface may progressively change as active sites become occupied. Temkin modelling has similarly been used to evaluate adsorbate–adsorbent interactions and the heat associated with adsorption in heavy-metal systems (Tighadouini et al., 2022; Girish, 2025). The Temkin constants obtained here, ($B_T=29.08$) J/mol for Cu(II) and 22.15 J/mol for Pb(II), indicate measurable adsorbate–surface interactions, although they should not be interpreted alone as definitive proof of chemical bonding.

The D–R model yielded q_m values of 883.99 mg/g for Cu(II) and 441.51 mg/g for Pb(II), with R^2 values of 0.9099 and 0.9151, respectively. The substantially larger D–R capacities compared with the Langmuir capacities should be interpreted cautiously because q_m values from different isotherm models are model-dependent estimates and are not necessarily interchangeable measures of experimental adsorption capacity. Recent reviews specifically caution against treating q_{max} from different isotherm equations as directly equivalent performance indicators (Al-Ghouti et al., 2022; Girish, 2025).

Using the conventional D–R relationship $E = \frac{RT}{\beta}$, the reported β values correspond approximately to 9.81 kJ/mol for Cu(II) and 13.87 kJ/mol for Pb(II). Under the traditional interpretation, these values fall within the frequently cited 8–16 kJ/mol range associated with ion-exchange-controlled adsorption. However, this interpretation requires an important qualification. Recent critical evaluations have demonstrated that the D–R characteristic energy obtained from aqueous-phase adsorption should not be used alone to distinguish chemisorption from physisorption, because the model does not adequately

account for solvent-related processes and ion exchange at solid–water interfaces (Puccia and Avena, 2021; Bezzina et al., 2023). Therefore, the present D–R values are better interpreted as evidence of appreciable adsorption-energy characteristics and possible ion-exchange contributions rather than definitive proof of chemisorption.

Mechanistically, the combined isotherm behaviour suggests that Pb(II) and Cu(II) uptake by CFNP probably involves multiple simultaneous interactions. The strong Langmuir response indicates substantial occupation of finite high-affinity sites, while the good Temkin fit indicates progressive changes in adsorption energy with surface coverage. Depending on the surface chemistry of CFNP, plausible interactions include electrostatic attraction, ion exchange and complexation with oxygen- or nitrogen-containing functional groups. For metal-loaded carbon fibres and cellulose-based nanomaterials, functional groups capable of coordinating metal ions have been implicated in adsorption, with surface chemistry playing an important role in metal retention (Zhu et al., 2022; Xu et al., 2021; García-Díaz et al., 2018). The difference between Cu(II) and Pb(II) may additionally reflect differences in ionic characteristics, hydration behaviour, coordination preferences and competition for available surface sites (Tighadouini et al., 2022).

Overall, the Langmuir model provides the strongest equilibrium description, with ($R^2=0.9818$) for Cu(II) and ($R^2=0.9937$) for Pb(II), while the favourable (R_L) and Freundlich n values confirm that adsorption is thermodynamically favourable within the investigated concentration range. The high $q_{\max}$ values demonstrate the considerable adsorption potential of CFNP, particularly toward Cu(II), whereas the higher K_L and lower R_L for Pb(II) indicate stronger apparent equilibrium affinity. The relatively high Temkin fits and D–R parameters further indicate that adsorption involves changes in surface energy and potentially ion-exchange contributions. Thus, the equilibrium data are most consistent with a predominantly finite-site/monolayer adsorption process occurring on a chemically diverse surface, accompanied by heterogeneous energetic interactions and possible ion-exchange or complexation mechanisms. Nevertheless, definitive assignment of the molecular mechanism should be supported by complementary evidence such as FTIR shifts, XPS, zeta potential, SEM–EDS mapping and/or elemental analysis before claiming a specific chemical bonding mechanism (Zhu et al., 2022; Xu et al., 2021; Girish, 2025).

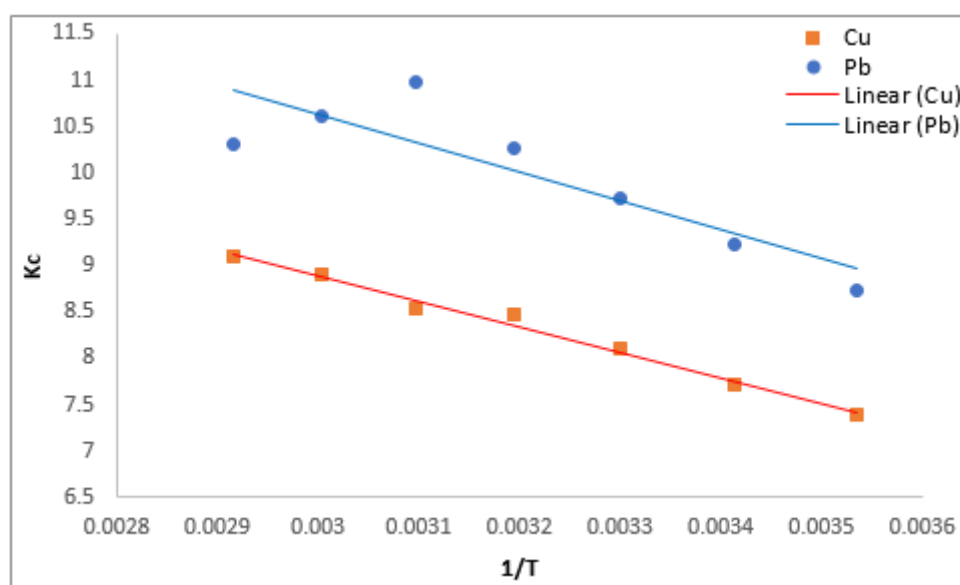


Figure 3: van't Hoff plot of the biosorption of Pb(II) and Cu(II) by CFNP

Table 3: Thermodynamic parameters for the biosorption of Pb(II) and Cu(II) by CFNP

Metal	ΔH° (kJ mol ⁻¹)	ΔS° (J mol ⁻¹ K ⁻¹)	T (K)	ΔG° (kJ mol ⁻¹)
Cu	22.77	142.19	283	-17.47
			293	-18.89
			303	-20.31
			313	-21.74
			323	-23.16
Pb	26.06	166.60	283	-21.09
			293	-22.76
			303	-24.42
			313	-26.09
			323	-27.76

The thermodynamic plot and parameters presented in Figure 3 and Table 3 provide important information on the feasibility, energetic requirements, and temperature dependence of Cu(II) and Pb(II) adsorption. The positive standard enthalpy changes (ΔH°) of 22.77 kJ mol⁻¹ for Cu(II) and 26.06 kJ mol⁻¹ for Pb(II) indicate that adsorption is endothermic. Thus, uptake is energetically favoured by increasing temperature, suggesting that additional thermal energy facilitates interactions between the metal ions and available adsorption sites. Similar temperature-dependent behaviour has been discussed for heavy-metal biosorption, including adsorption onto keratinous materials such as chicken feather and sheep fur (Salaudeen and Chibueze, 2020; Salaudeen et al., 2022a,b). The higher ΔH° obtained for Pb(II) relative to Cu(II) indicates a somewhat greater energetic requirement for Pb(II) adsorption.

The positive entropy changes (ΔS°) of 142.19 and 166.60 J mol⁻¹ K⁻¹ for Cu(II) and Pb(II), respectively, indicate increased randomness at the solid–solution interface during adsorption. Such an increase may arise from restructuring of the interfacial environment and displacement of water molecules and/or counterions associated with hydrated metal ions and adsorbent surface sites during metal binding. Thermodynamic and mechanistic investigations of heavy-metal adsorption on keratin biomasses similarly demonstrate that adsorption behaviour reflects changes occurring at the adsorbent–solution interface (Salaudeen et al., 2022a). Keratin-based materials are particularly relevant because their functional groups provide binding sites for metal cations (Kar and Misra, 2004; Nikiforova et al., 2019).

More importantly, ΔG° is negative throughout the investigated temperature range, confirming the thermodynamic spontaneity of both adsorption processes. For Cu(II), ΔG° becomes progressively more negative from -17.47 kJ mol⁻¹ at 283 K to -23.16 kJ mol⁻¹ at 323 K. Pb(II) exhibits the same trend, decreasing from -21.09 kJ mol⁻¹ at 283 K to -26.09 kJ mol⁻¹ at 313 K in the values presented in the table. The increasingly negative ΔG° with temperature further supports the endothermic character of adsorption and demonstrates that higher temperatures enhance thermodynamic favourability. Salaudeen and Chibueze (2020) specifically examined thermodynamic-parameter determination using Pb(II) adsorption onto chicken feather, while Salaudeen et al. (2022a) subsequently investigated the thermodynamics and mechanisms of heavy-metal adsorption on keratin biomasses. Overall, Pb(II) exhibits more negative ΔG° values and higher ΔG° than Cu(II), suggesting a stronger thermodynamic driving force for Pb(II) uptake under the investigated conditions.

CONCLUSION

The study demonstrates that chicken feather nanoparticles (CFNP) are promising sustainable biosorbents for Pb(II) and Cu(II) removal from aqueous systems. Their alkaline character, low moisture content, high organic fraction and low bulk density provide suitable physicochemical properties for

adsorption applications. FTIR analysis indicates that hydroxyl, amine and amide-containing functional groups participate in metal uptake, while changes after adsorption suggest interactions between the keratin surface and metal ions. Equilibrium analysis shows that Langmuir provides the strongest description, with a substantially higher adsorption capacity for Cu(II) than Pb(II), although Pb(II) exhibits greater apparent affinity for the available binding sites. The favourable separation factors and Freundlich parameters confirm favourable adsorption, while the Temkin and D–R models indicate changes in adsorption energy and possible contributions from ion exchange. Thermodynamic analysis further demonstrates that both adsorption processes are spontaneous and endothermic, with increasing temperature enhancing metal uptake. Overall, CFNP represents a promising waste-derived material for heavy-metal remediation and provides an environmentally sustainable approach for converting poultry waste into a value-added functional adsorbent.

REFERENCES

- Ahmed, W., Mehmood, S., Mahmood, M., Ali, S., Shakoor, A., Núñez-Delgado, A., Asghar, R. M. A., Zhao, H., Liu, W., & Li, W. (2023). Adsorption of Pb(II) from wastewater using a red mud modified rice-straw biochar: Influencing factors and reusability. *Environmental Pollution*, 326, 121405. <https://doi.org/10.1016/j.envpol.2023.121405>
- Al-Ghouti, M. A., & Da'ana, D. A. (2020). Guidelines for the use and interpretation of adsorption isotherm models: A review. *Journal of Hazardous Materials*, 393, 122383. <https://doi.org/10.1016/j.jhazmat.2020.122383>
- Al-Ghouti, M. A., et al. (2022). Isotherm models for adsorption of heavy metals from water—A review. *Chemosphere*, 307, 135545. <https://doi.org/10.1016/j.chemosphere.2022.135545>
- Ali, R. M., Hamad, H. A., Hussein, M. M., & Malash, G. F. (2016). Potential of using green adsorbent for heavy metal removal from aqueous solutions: Adsorption kinetics, isotherm, thermodynamic, mechanism and economic analysis. *Ecological Engineering*, 91, 317–332. <https://doi.org/10.1016/j.ecoleng.2016.03.015>
- Aluigi, A., Zoccola, M., Vineis, C., Tonin, C., Ferrero, F., & Canetti, M. (2007). Study on the structure and properties of wool keratin regenerated from formic acid. *International Journal of Biological Macromolecules*, 41, 266–273. <https://doi.org/10.1016/j.ijbiomac.2007.03.002>
- Bai, T., Zhao, J., Tian, L., Zhang, L., & Jin, Z. (2024). The adsorption of Pb(II) from aqueous solution using KOH-modified banana peel hydrothermal carbon: Adsorption properties and mechanistic studies. *Materials*, 17, 311. <https://doi.org/10.3390/ma17020311>
- Bezzina, J. P., et al. (2023). The Dubinin–Radushkevich models: Dissecting the ps/p to cs/ce replacement in solid-aqueous interfacial adsorption and tracking the validity of $E = 8 \text{ kJ mol}^{-1}$ for assigning sorption type. *Chemical Engineering Research and Design*. <https://doi.org/10.1016/j.cherd.2023.09.020>
- Burakov, A. E., Galunina, E. V., Burakova, I. V., Kucherova, A. E., Agarwal, S., Tkachev, A. G., & Gupta, V. K. (2018). Adsorption of heavy metals on conventional and nanostructured materials for wastewater treatment purposes: A review. *Ecotoxicology and Environmental Safety*, 148, 702–712. <https://doi.org/10.1016/j.ecoenv.2017.11.034>
- Choi, W. S., & Lee, H. J. (2022). Nanostructured materials for water purification: Adsorption of heavy metal ions and organic dyes. *Polymers*, 14, 2183. <https://doi.org/10.3390/polym14112183>
- Crini, G., & Lichtfouse, E. (2019). Advantages and disadvantages of techniques used for wastewater treatment. *Environmental Chemistry Letters*, 17, 145–155. <https://doi.org/10.1007/s10311-018-0785-9>
- Dhaouadi, F., Sellaoui, L., Badawi, M., Sellaoui, L., Reynel, H., Mendoza-Castillo, D. I., Jaime-Leal, J. E., Bonilla-Petriciolet, A., & Lamine, A. B. (2020). Statistical physics interpretation of the adsorption mechanism of Pb^{2+} , Cd^{2+} and Ni^{2+} on chicken feathers. *Journal of Molecular Liquids*, 319, 114168. <https://doi.org/10.1016/j.molliq.2020.114168>
- El Hammari, L., Hamed, R., Azzaoui, K., Jodeh, S., Latifi, S., Saoiabi, S., Boukra, O., Krime, A., Boukra, A., Saoiabi, A., Hammouti, B., Khan, M. M., Sabbahi, R., Hanbali, G., Berisha, A., Taleb, M., & Dagdag, O. (2023). Optimization of the adsorption of lead(II) by hydroxyapatite using a factorial design: Density functional theory and molecular dynamics. *Frontiers in Environmental Science*, 11, 1112019. <https://doi.org/10.3389/fenvs.2023.1112019>
- Eslahi, N., Dadashian, F., & Nejad, N. H. (2013). An investigation on keratin extraction from wool and feather waste by enzymatic hydrolysis. *Preparative Biochemistry and Biotechnology*, 43, 624–648. <https://doi.org/10.1080/10826068.2012.758951>
- Foo, K. Y., & Hameed, B. H. (2010). Insights into the modeling of adsorption isotherm systems. *Chemical Engineering Journal*, 156, 2–10. <https://doi.org/10.1016/j.cej.2009.09.013>
- García-Díaz, I., López, F. A., & Alguacil, F. J. (2018). Carbon nanofibers: A new adsorbent for copper

- removal from wastewater. *Metals*, 8(11), 914. <https://doi.org/10.3390/met8110914>
- Girish, C. R. (2025). Determination of thermodynamic parameters in adsorption studies: A review. *Chemical Papers*, 79, 5687–5706. <https://doi.org/10.1007/s11696-025-04218-x>
- Granado-Castro, M. D., Galindo-Riaño, M. D., Gestoso-Rojas, J., Sánchez-Ponce, L., Casanueva-Marenco, M. J., & Díaz-de-Alba, M. (2024). Ecofriendly application of Calabrese broccoli stalk waste as a biosorbent for the removal of Pb(II) ions from aqueous media. *Agronomy*, 14, 554. <https://doi.org/10.3390/agronomy14030554>
- Hoti, G., Caldera, F., Trotta, F., Zoccola, M., Patrucco, A., & Anceschi, A. (2024). A novel approach for nanosponge: Wool waste as a building block for the synthesis of keratin-based nanosponge and perspective application in wastewater treatment. *ACS Omega*, 9, 43319–43330. <https://doi.org/10.1021/acsomega.3c09133>
- Hu, Q., Lan, R., He, L., Liu, H., & Pei, X. (2023). A critical review of adsorption isotherm models for aqueous contaminants: Curve characteristics, site energy distribution and common controversies. *Journal of Environmental Management*, 329, 117104. <https://doi.org/10.1016/j.jenvman.2022.117104>
- Jaffar, F. H., Othman, M. H. D., Ismail, N. J., Puteh, M. H., Kurniawan, T. A., Bakar, S. A., & Abdullah, H. (2024). Hydroxyapatite-based materials for adsorption and adsorptive membrane processes for heavy metal removal from wastewater: Recent progress, bottlenecks and opportunities. *Journal of the Taiwan Institute of Chemical Engineers*, 164, 105668. <https://doi.org/10.1016/j.jtice.2024.105668>
- Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology*, 7, 60–72. <https://doi.org/10.2478/intox-2014-0009>
- Jamil, T. S., Ibrahim, H. S., Abd El-Maksoud, I. H., & El-Wakeel, S. T. (2010). Application of zeolite prepared from Egyptian kaolin for removal of heavy metals: I. Optimum conditions. *Desalination*, 258, 34–40. <https://doi.org/10.1016/j.desal.2010.03.052>
- Kar, P., & Misra, M. (2004). Use of keratin fiber for separation of heavy metals from water. *Journal of Chemical Technology and Biotechnology*, 79, 1313–1319. <https://doi.org/10.1002/jctb.1128>
- Karim, A., Raji, Z., Karam, A., & Khalloufi, S. (2023). Valorization of fibrous plant-based food waste as biosorbents for remediation of heavy metals from wastewater—A review. *Molecules*, 28, 4205. <https://doi.org/10.3390/molecules28104205>
- Karnwal, A. (2024). Unveiling the promise of biosorption for heavy metal removal from water sources. *Desalination and Water Treatment*, 319, 100523. <https://doi.org/10.1016/j.dwt.2024.100523>
- Majd, M. M., Kordzadeh-Kermani, V., Ghalandari, V., Askari, A., & Sillanpää, M. (2022). Adsorption isotherm models: A comprehensive and systematic review (2010–2020). *Science of the Total Environment*, 812, 151334. <https://doi.org/10.1016/j.scitotenv.2021.151334>
- Meena, A. K., Kadirvelu, K., Mishra, G. K., Rajagopal, C., & Nagar, P. N. (2008). Adsorption of Pb(II) and Cd(II) metal ions from aqueous solutions by mustard husk. *Journal of Hazardous Materials*, 150, 619–625. <https://doi.org/10.1016/j.jhazmat.2007.05.011>
- Ndekei, A., Gitita, M., Njomo, N., & Mbui, D. (2021). Synthesis and characterization of rice husk biochar and its application in the adsorption studies of lead and copper. *International Research Journal of Pure and Applied Chemistry*, 22, 36–50. <https://doi.org/10.9734/irjpac/2021/v22i430402>
- Nikiforova, T., Kozlov, V., & Islyaikin, M. (2019). Sorption of d-metal cations by keratin from aqueous solutions. *Journal of Environmental Chemical Engineering*, 7, 103417. <https://doi.org/10.1016/j.jece.2019.103417>
- Oladimeji, T. E., Oyedemi, M., Emetere, M. E., Agboola, O., Adeoye, J. B., & Odunlami, O. A. (2024). Review on the impact of heavy metals from industrial wastewater effluent and removal technologies. *Heliyon*, 10, e40370. <https://doi.org/10.1016/j.heliyon.2024.e40370>

- Puccia, V., & Avena, M. (2021). On the use of the Dubinin–Radushkevich equation to distinguish between physical and chemical adsorption at the solid-water interface. *Colloid and Interface Science Communications*, 41, 100376. <https://doi.org/10.1016/j.colcom.2021.100376>
- Revellame, E. D., Fortela, D. L., Sharp, W., Hernandez, R., & Zappi, M. E. (2020). Adsorption kinetic modeling using pseudo-first-order and pseudo-second-order rate laws: A review. *Cleaner Engineering and Technology*, 1, 100032. <https://doi.org/10.1016/j.clet.2020.100032>
- Saha, S., Zubair, M., Khosa, M. A., Song, S., & Ullah, A. (2019). Keratin and chitosan biosorbents for wastewater treatment: A review. *Journal of Polymers and the Environment*, 27, 1389–1403. <https://doi.org/10.1007/s10924-019-01433-x>
- Salaudeen, A. O. (2020). Biosorption of heavy metals from aqueous solutions: An insight and review. *Archives of Industrial Engineering*, 3, 1–31. [https://doi.org/10.31829/2637-9252/aie2020-3\(1\)-113](https://doi.org/10.31829/2637-9252/aie2020-3(1)-113)
- Salaudeen, A. O., Aduloju, E. I., Okike, O., Oladokun, B. N., & Adedeji, S. A. (2022b). Adsorption of Pb(II) using sheep fur: Isotherm, kinetics and thermodynamic studies. *Asian Journal of Applied Chemistry Research*, 12, 27–33. <https://doi.org/10.9734/AJACR/2022/v12i4229>
- Salaudeen, A. O., Bonilla-Petriciolet, A., Mendoza-Castillo, D. I., Okafor, C. C., Sellaoui, L., & Badawi, M. (2022a). Thermodynamics and mechanism of the adsorption of heavy metal ions on keratin biomasses for wastewater detoxification. *Adsorption Science & Technology*, 2022, 7384924. <https://doi.org/10.1155/2022/7384924>
- Salaudeen, A. O., Chibueze, C. O. (2020). Comparing the different methods used in the determination of thermodynamic parameters using adsorption of Pb(II) onto chicken feather as an example. *Journal of Materials Science Research and Reviews*, 6, 1–11. <https://journaljmsrr.com/index.php/JMSRR/article/view/114>
- Salaudeen, A. O., Vuanghao, L. (2025). Metabolomics approach in environmental studies: Methodologies, application and challenges. *Critical Reviews in Analytical Chemistry*, 1–17. <https://doi.org/10.1080/10408347.2025.2521734>
- Salaudeen, A. O., Wosilat, F. A., Haruna Dede, A., & Habeeb, A. (2018). Isotherm studies of the biosorption of Pb(II) and Cu(II) using chicken feather. *Asian Journal of Advanced Research and Reports*, 1, 1–9. <https://doi.org/10.9734/ajarr/2018/v1i413094>
- Sepehri, S., Kanani, E., Abdoli, S., Rajput, V. D., Minkina, T., & Asgari Lajayer, B. (2023). Pb(II) removal from aqueous solutions by adsorption on stabilized zero-valent iron nanoparticles—A green approach. *Water*, 15, 222. <https://doi.org/10.3390/w15020222>
- Sheraz, N., Shah, A., Haleem, A., & Iftikhar, F. J. (2024). Comprehensive assessment of carbon-, biomaterial- and inorganic-based adsorbents for the removal of the most hazardous heavy metal ions from wastewater. *RSC Advances*, 14, 11284–11310. <https://doi.org/10.1039/D4RA00976B>
- Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. In A. Luch (Ed.), *Molecular, Clinical and Environmental Toxicology* (Experientia Supplementum, Vol. 101, pp. 133–164). Springer. https://doi.org/10.1007/978-3-7643-8340-4_6
- Tighadouini, S., Radi, S., Roby, O., Hammoudan, I., Saddik, R., Garcia, Y., Almarhoon, Z. M., & Mabkhot, Y. N. (2022). Kinetics, thermodynamics, equilibrium, surface modelling, and atomic absorption analysis of selective Cu(II) removal from aqueous solutions and rivers water using silica-2-(pyridin-2-ylmethoxy)ethan-1-ol hybrid material. *RSC Advances*, 12(1), 611–625. <https://doi.org/10.1039/D1RA06640D>
- Wang, J., & Chen, C. (2009). Biosorbents for heavy metals removal and their future. *Biotechnology Advances*, 27, 195–226. <https://doi.org/10.1016/j.biotechadv.2008.11.002>
- Wang, J., & Guo, X. (2020). Adsorption kinetic models: Physical meanings, applications, and solving methods. *Journal of Hazardous Materials*, 390, 122156. <https://doi.org/10.1016/j.jhazmat.2020.122156>

- Wang, L., Shi, C., Pan, L., Zhang, X., & Zou, J.-J. (2020). Rational design, synthesis, adsorption principles and applications of metal oxide adsorbents: A review. *Nanoscale*, 12, 4790–4815. <https://doi.org/10.1039/C9NR09274A>
- Xu, Q., Huang, X., Guo, L., Wang, Y., & Jin, L. (2021). Enhancing removal of Cr(VI), Pb²⁺, and Cu²⁺ from aqueous solutions using amino-functionalized cellulose nanocrystal. *Molecules*, 26(23), 7315. <https://doi.org/10.3390/molecules26237315>
- Yahaya, N., Saad, Y., & Abubakar, A. (2024). Adsorption studies of Pb²⁺, Cu²⁺ and Cr³⁺ from aqueous solution using *Azadirachta indica* seed husk and *Adansonia digitata* seeds. *Science Journal of Chemistry*, 12, 73–85. <https://doi.org/10.11648/j.sjc.20241204.12>
- Yun, X., Ma, Y., Zheng, H., Zhang, Y., Cui, B., & Xing, B. (2022). Pb(II) adsorption by biochar from co-pyrolysis of corn stalks and alkali-fused fly ash. *Biochar*, 4, 66. <https://doi.org/10.1007/s42773-022-00189-4>
- Zhang, J., Li, Y., Li, J., Zhao, Z., Liu, X., Li, Z., Han, Y., Hu, J., & Chen, A. (2013). Isolation and characterization of biofunctional keratin particles extracted from wool wastes. *Powder Technology*, 246, 356–362. <https://doi.org/10.1016/j.powtec.2013.05.034>
- Zhu, L., Yao, Y., Chen, D., & Lan, P. (2022). The effective removal of Pb²⁺ by activated carbon fibers modified by L-cysteine: Exploration of kinetics, thermodynamics and mechanism. *RSC Advances*, 12(31), 20062–20073. <https://doi.org/10.1039/D2RA01521H>
- Zou, C., Jiang, W., Liang, J., Sun, X., & Guan, Y. (2019). Removal of Pb(II) from aqueous solutions by adsorption on magnetic bentonite. *Environmental Science and Pollution Research*, 26, 1315–1322. <https://doi.org/10.1007/s11356-018-3652-0>
- Zubair, M., Roopesh, M. S., & Ullah, A. (2025). Green nanoengineered keratin-derived bio-adsorbent for heavy metals removal from aqueous media. *Advanced Sustainable Systems*, 9, e2400491. <https://doi.org/10.1002/adsu.202400491>