

HIGH-EFFICIENCY REMOVAL OF Cu^{2+} , Hg^{2+} AND Cr^{3+} FROM SYNTHETIC WATER BY CHITOSAN: ADSORPTION PERFORMANCE AND MECHANISM

S. V. M. Prasad^{1,2}, K. Raveendrababu³ and S. Ramakrishna^{1,4,✉}

¹Research Centre, Government Degree College for Men, Srikakulam, Andhra Pradesh, affiliated to Dr. B. R. Ambedkar University, Etcherla-532410, (Andhra Pradesh) India

²Department of BS&H, Aditya Institute of Technology & Management, Tekkali-532201, (Andhra Pradesh) India

³Department of Chemistry, SCIM Government College (A), Tanuku-534211 (Andhra Pradesh) India

⁴Department of Chemistry, Government Degree College for Men, Srikakulam-532001 (Andhra Pradesh) India

✉Corresponding author: s7ramakrishna@gmail.com

ABSTRACT

The accumulation of heavy metals in aquatic environments has appeared as a serious environmental and public health worry worldwide. In this work, the adsorption potential of chitosan, a renewable and biodegradable biopolymer, was quantified for the removal of Cu^{2+} , Hg^{2+} and Cr^{3+} ions from hydric media. Batch adsorption studies were conducted, and the residual metal ion concentrations were meticulously calculated with the help of Atomic Absorption Spectroscopy (AAS). Adsorption was strongly pH-dependent, with optimum performance observed at pH 5 due to favourable electrostatic contacts among metal ions and chitosan functional groups. Increasing the initial metal concentration (10–100 mg/L) reduced removal efficiency owing to saturation of active sites, whereas higher adsorbent dosages enhanced metal uptake. Analysis with the Langmuir adsorption isotherm discovered maximum adsorption of 6.433 mg/g for Cu^{2+} , 5.360 mg/g for Hg^{2+} and 3.774 mg/g for Cr^{3+} . The findings demonstrate the potential of chitosan as a naturally derived, biodegradable, and effective adsorbent for the removal of toxic metal ions from water, thereby contributing to the United Nations Sustainable Development Goal 6 (SDG-6): Clean Water and Sanitation.

Keywords: Heavy Metals, Chitosan, Langmuir & Freundlich Adsorption Isotherm, Environmental Remediation.

RASĀYAN J. Chem., Thematic Issue, 2026

INTRODUCTION

This study underscores the effectiveness of chitosan, a biodegradable, natural, and eco-conscious biopolymer, in adsorbing hazardous heavy metals such as Cu^{2+} , Hg^{2+} , and Cr^{3+} from polluted water sources. Offering a cost-effective and sustainable water purification strategy, chitosan is especially valuable for use in rural and under-resourced areas.¹ Its proven capability to bind with these metal ions supports its potential in treating industrial effluents, municipal wastewater, and in mobile or climate-resilient water treatment units in regions with limited infrastructure. Furthermore, its biodegradable character enables integration into green remediation materials like membranes, beads, and composites made from chitosan.² The strong adsorption ability of chitosan toward heavy metals is mainly due to the presence of reactive amino ($-\text{NH}_2$) and hydroxyl ($-\text{OH}$) groups on its molecular structure, which facilitate strong interactions with metal ions. As a polysaccharide sourced from chitin, typically found in shellfish waste, chitosan is non-toxic, eco-friendly, and economically viable for broader environmental applications. Its structure allows for various chemical or physical modifications, such as grafting, crosslinking, or incorporation with magnetic particles, graphene, or hydrogels, thereby improving its stability, adsorption properties, and usability across a wider pH range. Incorporation of magnetic materials enhances the ease of separating chitosan from treated water and supports its regeneration for repeated use, minimising waste generation and operational costs.³ Nonetheless, traditional and some

biopolymer-based techniques still face limitations. Common practices like membrane filtration, ion exchange, and chemical precipitation tend to be expensive and infrastructure-heavy, making them unsuitable for decentralised or low-income areas. They also often lead to the production of toxic sludge requiring careful disposal. Adsorption systems that lack reusability contribute to additional solid waste issues. Many conventional adsorbents are less effective at removing trace levels of heavy metals, particularly when multiple pollutants coexist in wastewater, limiting their real-world performance. Although chitosan is a green and efficient adsorbent, its poor mechanical strength and solubility in acidic media hinder its functionality in variable environmental conditions. Unmodified chitosan may lose efficiency due to changes in pH, temperature, or ionic strength and typically shows a drop in adsorption capacity after a few reuse cycles. Unless enhanced through modification or composite formation, native chitosan may not be economically viable for long-term use.

Additionally, in unmodified forms, longer contact durations are often needed to reach optimal adsorption, which limits its practicality in continuous or fast-flow systems. To address these challenges, more advanced chitosan-based adsorbents such as nanocomposites, magnetic or crosslinked forms are being developed to increase their mechanical durability, selectivity, pH tolerance, and reusability.⁴ Recent efforts in research focus on chemical modifications, such as the addition of functional groups, crosslinking, and nanoparticle embedding, all of which enhance the adsorbent's surface area, stability and affinity for specific metal ions. Magnetic nanoparticle incorporation also streamlines the separation and reuse process, reducing secondary waste and boosting efficiency.⁵ These advancements lead to better Adsorption Kinetics and capacities, expanding the utilisation of chitosan-based materials for continuous-flow treatment and various wastewater compositions.

This study builds upon such innovations by examining the adsorption capacity, thermodynamic properties and reusability of chitosan for Cu^{2+} , Hg^{2+} and Cr^{3+} removal.⁶ The selection of chitosan as the core material for this study is rooted in its environmental safety, affordability, and strong metal-chelating ability. Its abundance of functional groups makes it ideal for biosorption of metal ions in water. Conventional techniques, including membrane filtration, ion-exchange processes, and chemical precipitation, often involve high operational costs and complex infrastructure requirements and generate hazardous byproducts; chitosan presents a cleaner and more cost-efficient alternative.⁷ Moreover, its modifiability enables enhancement of its adsorption properties, structural integrity, and resistance to pH fluctuations, addressing the inherent limitations of its native form. This aligns with growing interest in environmentally sound water treatment technologies, particularly in decentralised and underserved communities. The study also builds on earlier findings that support chitosan's ability to adsorb multiple heavy metals simultaneously.⁸ The central aim of this research is to assess chitosan's adsorption efficiency for removing Cu^{2+} , Hg^{2+} and Cr^{3+} from water under controlled batch experimental settings.^{9,10} Additionally, the study seeks to provide meaningful insights into the development of sustainable, low-cost biosorbents for water purification, particularly for communities with limited access to modern treatment technologies. The outcomes are expected to contribute to environmentally responsible and economically feasible strategies for managing metal-contaminated water sources.¹¹

EXPERIMENTAL

Materials and Chemicals

High-molecular-weight chitosan (81% degree of deacetylation) is produced through the deacetylation of chitin, a natural polysaccharide commonly obtained from crustacean shell waste, and to prepare the stock solutions, 99.9% pure copper (II) nitrate trihydrate for copper, 99.99% pure mercury (II) nitrate monohydrate for mercury and 99% pure chromium (III) nitrate nonahydrate for chromium were obtained from Sigma-Aldrich.

Materials and Instruments Used

A digital pH meter (Elico, India) was used. The quantification of copper, mercury, and chromium ions in solution was carried out using Atomic Absorption Spectrophotometry (AAS). For batch adsorption experiments, a JAR test apparatus (SECOR 41, India) was utilised to provide controlled mixing and uniform contact between adsorbent and metal ion solutions.

Equilibrium Adsorption Studies

For adsorption isotherm studies, 100 mg of chitosan was accurately weighed and added to 25 mL of aqueous solutions comprising dissimilar initial metal ion concentrations ranging from 10 to 100 µg/mL. The prepared mixtures were subjected to continuous agitation on a mechanical shaker to ensure proper interaction between the adsorbent and the metal ions until equilibrium was attained, with the contact time optimized to 90 minutes. After the adsorption process, the suspensions were carefully filtered to separate the solid chitosan particles from the liquid phase. The remaining concentrations of Cu(II), Hg(II) and Cr(III) ions in the filtrates were then determined using Atomic Absorption Spectrometry to evaluate adsorption efficiency. The obtained data were subsequently used to construct adsorption isotherms and to analyze the interaction between chitosan and the target heavy metals.

pH Optimisation

The effect of pH on the adsorption efficiency of Cu(II), Hg(II), and Cr(III) was examined through batch experiments. In this study, 25 mL of metal ion solution with a constant initial concentration was mixed with 0.8 g of chitosan and periodically agitated for 45 minutes. This duration was chosen based on preliminary experiments which showed that adsorption equilibrium was reached within this time. Following the adsorption process, the mix was filtered to isolate the solid and liquid phases. The remaining concentrations of metal ions in the filtrate were then measured using Atomic Absorption Spectrometry (AAS). The adsorption capacity of chitosan for the metal ions (q_e , mg/g) was determined using equation (1).

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

Here m = adsorbent mass in grams and V = volume of solution utilised in litres.

Removal percentage of metal ion by chitosan, i.e., % removal (or) %R, was calculated from the difference between the initial concentration (C_0) and the equilibrium concentration (C_e) of the metal ions, as expressed in Equation (2). Likewise, the capacity of adsorption (q_e), representing the metal uptake capacity of chitosan (per unit mass) was determined by the corresponding equation (1).¹²

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

Modelling of Adsorption Equilibrium in Batch Experiments

Evaluation of equilibrium data is necessary to compare biosorbents under different conditions and to optimise treatment processes. Langmuir and Freundlich models are commonly applied to describe adsorption equilibrium in water and wastewater treatment. Adsorption analysis involves equilibrium and kinetic parameters: equilibrium indicates adsorption capacity, while isotherms describe adsorbent–adsorbate interactions. In this work, experimental data were analyzed using both models, with the Freundlich equation (eqn.-3) representing heterogeneous, multilayer adsorption behaviour.

$$q_e = K_F C_e^{1/n} \quad (3)$$

This equation can be easily transformed into its linear form for practical application.

$$n \ln(q_e) = n \ln(K_F) + \ln(C_e) \quad (4)$$

In the Freundlich model, K_F is the equilibrium constant and “ n ” denotes adsorption intensity, obtained from the slope and intercept of the linear plot of $\ln(q_e)$ versus $\ln(C_e)$. A good linear fit confirms model suitability, while $n > 1$ indicates favourable heavy-metal adsorption on chitosan. Conversely, the Langmuir model assumes monolayer adsorption on identical active sites involving partially protonated surface groups, expressed as:

$$q_e (1 + bC_e) = Q^0 b C_e \quad (5)$$

Here, C_e denotes the residual concentration of metal ions in the solution at equilibrium (mg/L), whereas q_e reflects the adsorption capacity at equilibrium (mg/g). Q_0 (mg/g) represents the theoretical high

adsorption capacity for monolayer coverage of the adsorbent surface, whereas the constant b (L/mg) is linked to the adsorption energy and the adsorbent's affinity for the adsorbate. Although complete saturation of the adsorbent may not always occur, Q_0 is useful for comparing the adsorption performance of different adsorbents. The Langmuir adsorption isotherm is generally represented in a linearised form as shown below.

$$\frac{C_e}{q_e} = \frac{1}{Q_0 b} + \frac{C_e}{Q_0} \quad (6)$$

If the adsorption process is according to the Langmuir model, a plot of C_e/q_e vs C_e yields a straight line. The constants Q_0 and b can be found using this linear relationship's slope and intercept. The separation factor, often known as the equilibrium parameter (R_L), is a dimensionless quantity that represents a key feature of the Langmuir isotherm and has the following definition.

$$R_L = \left[\frac{1}{1+b(C_0)} \right] \quad (7)$$

In this expression, b represents the Langmuir adsorption constant (L/mg), while C_0 denotes the initial concentration of heavy metals present in the solution, measured in mg/L. The separation factor (R_L), also known as the equilibrium parameter, provides important information regarding the characteristics and feasibility of the adsorption process. Adsorption is considered favourable when R_L lies between 0 and 1.¹³

Data Analysis

Utilising statistical features of Microsoft Excel, Office XP and OriginPro8.5, statistical analyses were carried out.

RESULTS AND DISCUSSION

The adsorption kinetics are influenced by several factors, like the initial concentration of heavy metal ions, the amount of adsorbent used, and the duration of contact between the adsorbent and the solution. Among these variables, the initial concentration of metal ions is particularly significant because it determines the equilibrium concentration achieved and affects both the rate of removal and the overall behavior of the adsorption process. In this context, the present investigation supports the United Nations Sustainable Development Goal 6 (SDG 6): Clean Water and Sanitation, particularly Target 6.3, by exploring chitosan-based adsorption as a sustainable approach for reducing hazardous heavy-metal contamination and improving water quality.

Characterisation of Commercial Chitosan Powder

The commercial chitosan powder confirms the presence of hydroxyl (–OH) groups and primary amine (–NH₂) groups, indicating extensive hydrogen bonding within the polymer structure.¹⁴ Aliphatic –CH and –CH₂ groups are present along the polysaccharide backbone.¹⁵ The characterisation also reveals carbonyl (C=O) functional groups associated with residual N-acetyl moieties, confirming that the material is partially deacetylated from chitin.¹⁶ In addition, characteristic saccharide ring –CH₂ bending vibrations and glycosidic C–O–C linkages are observed, validating the polysaccharide framework and structural integrity of the chitosan polymer.

Key Factors Affecting Metal Adsorption in Aqueous Solutions

Time of Contact

Using 0.3 g of chitosan, the impact of contact time on the adsorption of Cu, Hg, and Cr ions was investigated at pH 5. The experiments were conducted over a time interval of 5 to 60 minutes, and the results obtained are presented in Table-1 and Fig.-1. The adsorption rates for all three metal ions showed a marked increase from 5 to 30 minutes, reaching maximum efficiency at 35 minutes. Beyond this point, the adsorption percentages remained stable, indicating that equilibrium had been achieved.¹⁷ At an equilibrium contact time of 35 minutes, the removal efficiencies for Cu, Hg, and Cr ions were 84.75%, 76.10%, and 70.85%, respectively. The initial fast adsorption is ascribed to the many active sites on the chitosan surface in comparison to the quantity of metal ions. Due to the limited number of active sites, competition between metal ions increased when these sites were occupied, which led to a gradual decrease in the adsorption rate and, eventually, stabilisation of removal efficiency.¹⁸

Table-1: Influence of Contact Time on Removal of Metal Ions by Chitosan Adsorbent

Time (min)	Initial Conc. (C ₀) (mg/Litre)	Cu		Hg		Cr	
		(C _e) (mg/Litre)	% Removal	(C _e) (mg/Litre)	% Removal	(C _e) (mg/Litre)	% Removal
5	20	10.70	46.50%	12.52	37.40%	15.04	24.80%
10	20	9.82	50.90%	11.22	43.90%	13.92	30.40%
15	20	8.30	58.50%	10.61	46.95%	12.74	36.30%
20	20	7.05	64.75%	8.34	58.30%	11.65	41.75%
25	20	5.91	70.45%	6.93	65.35%	9.61	51.95%
30	20	3.51	82.45%	6.03	69.85%	7.19	64.05%
35	20	3.05	84.75%	4.78	76.10%	5.83	70.85%
40	20	3.05	84.75%	4.75	76.25%	5.81	70.95%
45	20	3.05	84.75%	4.76	76.20%	5.84	70.80%
50	20	3.05	84.75%	4.77	76.15%	5.80	71.00%
55	20	3.05	84.75%	4.74	76.30%	5.82	70.90%
60	20	3.05	84.75%	4.79	76.05%	5.85	70.75%

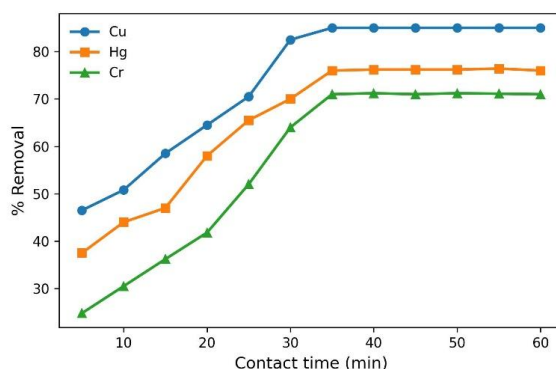


Fig.-1: Influence of Contact Time on removal of metal ions by Chitosan Adsorbent

pH

The efficiency of chitosan in removing heavy metals is strongly dependent on the solution pH. The amino and hydroxyl groups of chitosan exhibit optimal metal ion binding at pH values between 5.0 and 6.0. Under acidic conditions, protonation of the amino groups generates a positively charged surface that repels metal cations, thereby lowering adsorption capacity. At higher pH levels, metal ions can precipitate as insoluble hydroxides, reducing their availability for interaction with chitosan.¹⁹ Experiments were conducted to assess the influence of pH on metal ion adsorption across a pH range of 1.0–9.0, utilising 0.8 g of chitosan and an initial metal ion concentration of 20 mg/L for Cu, Hg, and Cr. Table-2 and Fig.-2 illustrate that adsorption efficiency escalated with pH, attaining a peak at pH 5 for all three metals.

Table-2: Influence of pH on Removal of Metal Ions by Chitosan Adsorbent

pH	Initial Conc. (C ₀) (mg./Litre)	Cu		Hg		Cr	
		(C _e) (mg./Litre)	% Removal	(C _e) (mg./Litre)	% Removal	(C _e) (mg./Litre)	% Removal
1	20	11.28	43.60	13.61	31.95	16.08	19.60
2	20	8.67	56.65	10.01	49.95	13.41	32.95
3	20	6.35	68.25	8.91	55.45	10.62	46.90
4	20	4.07	79.65	5.96	70.20	7.28	63.60
5	20	2.18	89.10	3.89	80.55	5.83	70.85
6	20	3.21	83.95	5.01	74.95	7.12	64.40
7	20	5.06	74.70	7.85	60.75	9.41	52.95
8	20	7.75	61.25	9.87	50.65	11.62	41.90
9	20	10.08	49.60	12.01	39.95	13.18	34.10

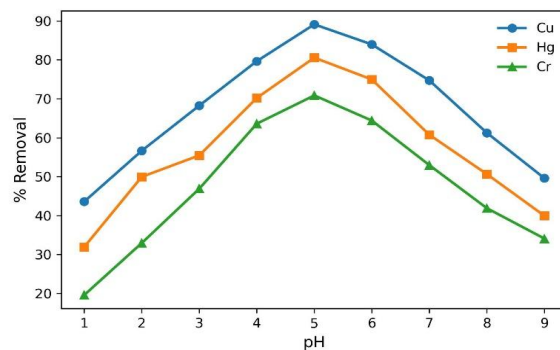


Fig-2: Influence of pH on Removal of Metal Ions by Chitosan Adsorbent

The enhanced adsorption at pH 5 is attributed to favourable electrostatic interactions and partial deprotonation of chitosan's amino groups, which imparts a negative charge to the surface, thereby strengthening the attraction between the adsorbent and the cationic metal ions.²⁰

Initial Concentration

Using 0.8 g of chitosan in 100 mL of solution at $25 \pm 1^\circ\text{C}$, pH 5, and a stirring velocity of 100 rpm, Table- 3 and Fig.-3 show the impact of different initial concentrations of Cu, Hg, and Cr ions (10–100 mg/L) on their removal efficiency. Cu, Hg, and Cr removal efficiencies were 88.80%, 80.12%, and 67.70%, respectively, at an initial concentration of 10 mg/L. The elimination efficiency decreased to 52.28%, 32.97%, and 20.82% for Cu, Hg, and Cr, respectively, when the concentration was raised to 100 mg/L. This pattern can be explained by the chitosan surface's increased active binding site availability at lower metal ion concentrations, which encourages effective adsorption. Effective contact is made possible by the favourable ratio of binding sites to metal ions at low concentrations. On the other hand, site saturation and decreased adsorption efficiency result from the amount of metal ions exceeding the available sites at greater concentrations. Therefore, the observed decline in metal ion removal at elevated concentrations is primarily due to the limited availability of active adsorption sites relative to the increased ion load in solution.²¹

Table-3: Influence of Initial Metal Ions Concentration on Removal by Chitosan Adsorbent

Initial Metal ion Concentration (C_0) mg./Litre	Copper		Mercury		Chromium	
	(C_e) (mg/Lit.)	Percentage Removal	(C_e) (mg/Lit.)	Percentage Removal	(C_e) (mg/Lit.)	Percentage Removal
10	1.12	88.8000	1.9876	80.1240	3.2293	67.7070
20	2.79	86.0500	4.2117	78.9415	6.7755	66.1225
30	6.04	79.8667	8.4253	71.9157	12.0964	59.6787
40	9.18	77.0500	12.721	68.1975	18.6205	53.4488
50	14.32	71.3600	19.3658	61.2684	27.145	45.7100
60	19.51	67.4833	27.2635	54.5608	36.796	38.6733
70	25.91	62.9857	34.792	50.2971	46.4647	33.6219
80	32.83	58.9625	45.2045	43.4944	54.5519	31.8101
90	40.13	55.4111	54.5606	39.3771	66.1883	26.4574
100	47.72	52.2800	67.0231	32.9769	79.1788	20.8212

Adsorbent Dosage

Under the following conditions, Tables-4 and Fig.-4 show how changing the adsorbent dosage affects the amount of Cu, Hg, and Cr ion uptake: a primary metal concentration of 20 mg/L, an operating temperature of $25 \pm 1^\circ\text{C}$, a contact time of 35 minutes, pH = 5, and a stirring speed of 100 rpm. Increasing the adsorbent dosage led to a marked improvement in removal efficiency, rising from 38.85%, 24.45%, and 9.40% to 87.30%, 78.85%, and 54.40% for Cu, Hg, and Cr, respectively.

This improvement in adsorption performance is due to the greater availability of active binding sites on the chitosan surface, which enables more metal ions to be effectively captured from the solution.²² However, at higher adsorbent dosages, particle interactions such as aggregation can occur, potentially

reducing the surface area available for adsorption. This phenomenon may lead to a plateau or minimal increase in removal efficiency despite additional adsorbent being introduced.²³

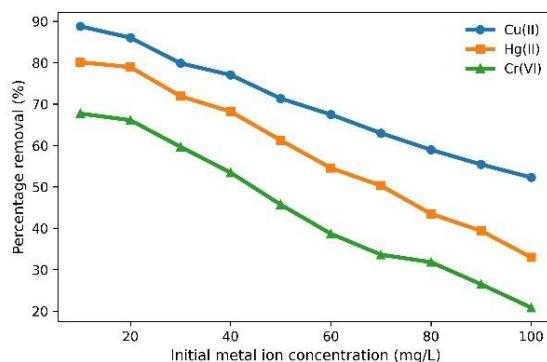


Fig.-3: Influence of Initial Metal Ions Concentration on Removal by Chitosan Adsorbent

Table-4: Influence of Adsorbent Dosage on Removal by using Chitosan Adsorbent.

Amount of Chitosan Powder	Copper		Mercury		Chromium	
	(C _e) (mg/Litre)	Percentage Removal	(C _e) (mg/Litre)	Percentage Removal	(C _e) (mg/Litre)	Percentage Removal
0.1	12.23	38.85	15.11	24.45	18.12	9.40
0.2	10.42	47.90	13.87	30.65	17.01	14.95
0.3	8.35	58.25	11.89	40.55	14.98	25.10
0.4	6.61	66.95	9.65	51.75	13.97	30.15
0.5	4.72	76.40	6.99	65.05	12.09	39.55
0.6	3.01	84.95	5.78	71.10	10.78	46.10
0.7	2.45	87.75	5.01	74.95	9.76	51.20
0.8	2.54	87.30	4.23	78.85	9.12	54.40

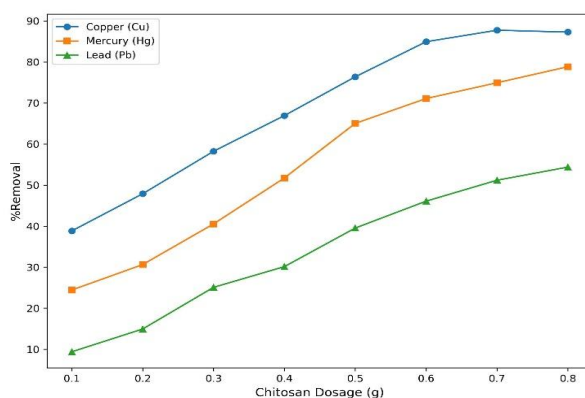


Fig.-4: Influence of Adsorbent Dosage on Removal by using Chitosan Adsorbent

Isothermal Adsorption Studies

Isothermal adsorption studies are essential for demonstrating the distribution of adsorbate molecules between the liquid phase and the solid adsorbent. Additionally, they shed light on the type of interactions that occur between the adsorbent surface and the adsorbate.²⁴ Two widely used isotherm models were used in this investigation to assess the adsorption behaviour: Freundlich and Langmuir. The goodness of fit for each model was assessed by calculating the correlation coefficient (R^2), which indicates how closely the models correspond to the experimental adsorption data.²⁵

Langmuir Adsorption Isotherm Model

The Langmuir adsorption isotherm model is based on several basic assumptions: (i) the adsorbent surface is homogeneous; (ii) each adsorption site can only hold one molecule (monolayer coverage); (iii) all adsorption sites have the same energy levels; and (iv) there are no interactions between adsorbed

molecules on adjacent sites. The analytical method used in this investigation is based on these presumptions. At $25 \pm 1^\circ\text{C}$, the adsorption behaviour of Cu(II), Hg(II), and Cr(III) ions onto chitosan was studied across an initial concentration range of 10–100 mg/L. The linearised Langmuir isotherm (Eqn.-6) was used to analyse equilibrium data in order to assess the suitability of monolayer adsorption. After creating plots of $1/C_e$ vs $1/q_e$ (Fig.-5), linear regression analysis produced correlation coefficients (R^2) of 0.9944 for Cu(II), 0.9908 for Hg(II), and 0.9676 for Cr(III) (Table-6). The surface layer of the Chitosan adsorbent by the metal ions under investigation causes the adsorption isotherms of the Cu(II), Hg(II), and Cr(III) ions to display Langmuir behaviour, which denotes monolayer adsorption. These results highlight the impact of surface site availability and metal ion properties on adsorption mechanism and efficiency. Langmuir isotherm analysis revealed maximum monolayer adsorption capacities (q_m) of 6.433 mg/g for Cu(II), 5.360 mg/g for Hg(II), and 3.774 mg/g for Cr(III), as summarised in Table-6. The intrinsic physicochemical characteristics of the metal ions, such as ionic radius, electronegativity, and hydration energy, control these capacities. The observed differences in removal efficiency and adsorption performance of chitosan powder correlate closely with the ionic characteristics of Cu(II), Hg(II), and Cr(III), such as atomic weight, electronegativity, and standard electrode potential. Generally, metal ions with smaller hydrated radii and higher electronegativity exhibit stronger interactions with chitosan's active sites, leading to higher adsorption affinity and enhanced uptake.²⁶

Table-5: Experimental Equilibrium Adsorption Data used for Langmuir Isotherm Model of Cu, Hg and Cr

Copper				Mercury				Chromium			
(C_e) (mg/Lit.)	q_e (mg/g)	$1/C_e$ (L/mg)	$1/q_e$ (g/mg)	(C_e) (mg/Lit.)	q_e (mg/g)	$1/C_e$ (L/mg)	$1/q_e$ (g/mg)	(C_e) (mg/Lit.)	q_e (mg/g)	$1/C_e$ (L/mg)	$1/q_e$ (g/mg)
1.12	1.1100	0.8929	0.9009	1.9876	1.0016	0.5031	0.9985	3.2293	0.8463	0.3097	1.1816
2.79	2.1513	0.3584	0.4648	4.2117	1.9735	0.2374	0.5067	6.7755	1.6531	0.1476	0.6049
6.04	2.9950	0.1656	0.3339	8.4253	2.6968	0.1187	0.3708	12.0964	2.2380	0.0827	0.4468
9.18	3.8525	0.1089	0.2596	12.721	3.4099	0.0786	0.2933	18.6205	2.6724	0.0537	0.3742
14.32	4.4600	0.0698	0.2242	19.3658	3.8293	0.0516	0.2611	27.145	2.8569	0.0368	0.3500
19.51	5.0613	0.0513	0.1976	27.2635	4.0921	0.0367	0.2444	36.796	2.9005	0.0272	0.3448
25.91	5.5113	0.0386	0.1814	34.792	4.4010	0.0287	0.2272	46.4647	2.9419	0.0215	0.3399
32.83	5.8963	0.0305	0.1696	45.2045	4.3494	0.0221	0.2299	54.5519	3.1810	0.0183	0.3144
40.13	6.2338	0.0249	0.1604	54.5606	4.4299	0.0183	0.2257	66.1883	2.9765	0.0151	0.3360
47.72	6.5350	0.0210	0.1530	67.0231	4.1221	0.0149	0.2426	79.1788	2.6027	0.0126	0.3842

Freundlich Adsorption Isotherm

The Freundlich isotherm, which implies a heterogeneous adsorbent surface with different site energies, was used to analyse the adsorption data for Cu(II), Hg(II), and Cr(III). The model showed a good fit with experimental results, indicating multilayer adsorption. The calculated Freundlich constants (K_f) were 1.25 mg/g for Cu(II), 1.04 mg/g for Hg(II), and 0.80 mg/g for Cr(III), reflecting the adsorption capacity. The adsorption intensity (n) values were 2.20, 2.59 and 2.95, respectively, all within the favourable range ($0 < n < 10$).

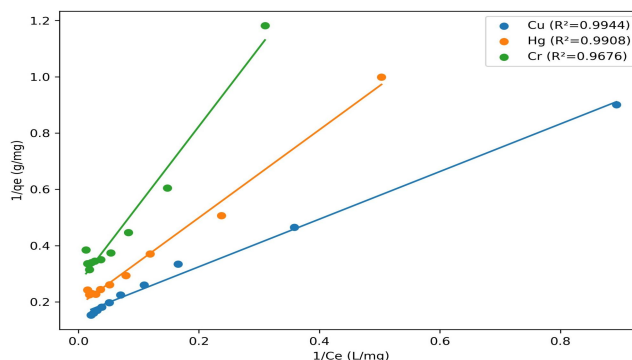


Fig.-5: Linear Langmuir Isotherm Analysis for Cu, Hg, and Cr Adsorption

These results confirm the chitosan suitability for removing these metal ions from aqueous solutions.²⁷ Strong affinity between chitosan and the metal ions is indicated by "n" values larger than 1 for all three

metal ions, indicating favourable adsorption circumstances. Furthermore, these results suggest that physical interactions rather than chemical bonds dominate the adsorption mechanism.

Table-6: Langmuir and Freundlich Isotherm Parameters for the Adsorption of Cu, Hg, and Cr Ions

Metal ions	Langmuir Isotherm parameters			Freundlich Isotherm parameters		
	q_m (milligram/gram)	b (Litre/milligram)	R^2	n	(K_f) (milligram/gram)	R^2
Cu	6.433	0.1837	0.9944	2.20	1.25	0.9739
Hg	5.360	0.1194	0.9908	2.59	1.04	0.8703
Cr	3.774	0.0948	0.9676	2.95	0.80	0.7737

Furthermore, the heterogeneous nature of the chitosan surface—which has numerous micro- and mesoporous sites with different affinities toward metal ions—is shown by the Freundlich model's applicability. These findings support the interpretation that chitosan provides a non-uniform surface for adsorption, where multilayer adsorption can occur at localised sites with different energies, as illustrated in Fig.-7.²⁸ The interaction between the sorbent and sorbate can be measured using the dimensionless separation factor (R_L), which characterises the features of the adsorption isotherm. The R_L value indicates whether the adsorption is linear ($R_L = 1$), unfavourable ($R_L > 1$), favourable ($0 < R_L < 1$) or irreversible ($R_L = 0$). Equation (7) is used to calculate R_L ; the factor is obtained by substituting the initial concentration (C_0) and the Langmuir constant (b).

Table-7: Equilibrium Logarithmic Parameters used for Freundlich Isotherm Modeling of Cu, Hg, and Cr Adsorption on Chitosan

Copper		Mercury		Chromium	
$\log(C_e)$ (mg/L)	$\log(q_e)$ (mg/g)	$\log(C_e)$ (mg/L)	$\log(q_e)$ (mg/g)	$\log(C_e)$ (mg/L)	$\log(q_e)$ (mg/g)
0.0492	0.0453	0.2983	0.0007	0.5091	-0.0725
0.4456	0.3327	0.6245	0.2952	0.8309	0.2183
0.7810	0.4764	0.9256	0.4309	1.0827	0.3499
0.9628	0.5857	1.1045	0.5327	1.2700	0.4269
1.1559	0.6493	1.2870	0.5831	1.4337	0.4559
1.2903	0.7043	1.4356	0.6119	1.5658	0.4625
1.4135	0.7413	1.5415	0.6436	1.6671	0.4686
1.5163	0.7706	1.6552	0.6384	1.7368	0.5026
1.6035	0.7947	1.7369	0.6464	1.8208	0.4737
1.6787	0.8152	1.8262	0.6151	1.8986	0.4154

R_L i.e., the separation factor, is a dimensionless parameter derived from the Langmuir isotherm and serves as a key criterion for assessing the favorability of an adsorption process. The relationship between R_L and the initial concentrations of Cu^{2+} , Hg^{2+} , and Cr^{3+} ions was investigated and is presented in Table 8 and Fig.-7. The calculated R_L values for all three metal ions were found to be between 0 and 1 ($0 < R_L < 1$), representing that the adsorption of Cu, Hg, and Cr onto chitosan powder was favorable under the studied conditions.²⁹

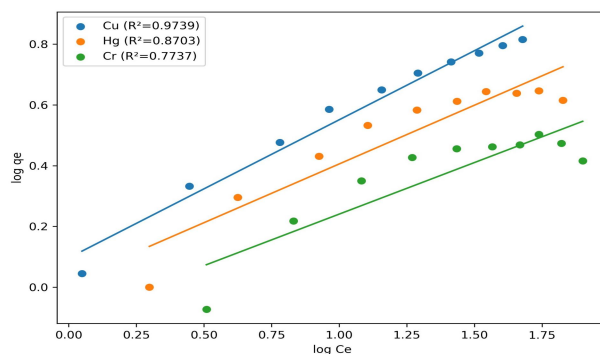


Fig.-6: Freundlich Isotherm for Cu, Hg, and Cr Adsorption

Furthermore, the trend showed a consistent decrease in R_L values with higher initial concentrations of metal ions, signifying that the process of adsorption becomes increasingly favorable with rising concentrations. This negative correlation indicates a strong affinity between the metal ions and the active binding sites on chitosan, especially when the concentration gradient between the solution and adsorbent is high. These results confirm the suitability of chitosan powder as an effective biosorbent for Cu^{2+} , Hg^{2+} , and Cr^{3+} separation from aqueous media.

Table-8: R_L i.e., the separation factor value for Cu, Hg & Cr ions

Initial Concentration (mg/Litre)	Cu: R_L	Hg: R_L	Cr: R_L
10	0.35249	0.45579	0.51335
20	0.21395	0.29516	0.34530
30	0.15359	0.21825	0.26015
40	0.11979	0.17313	0.20868
50	0.09818	0.14347	0.17422
60	0.08318	0.12249	0.14952
70	0.07216	0.10686	0.13096
80	0.06371	0.09477	0.11650
90	0.05704	0.08514	0.10491
100	0.05163	0.07728	0.09542

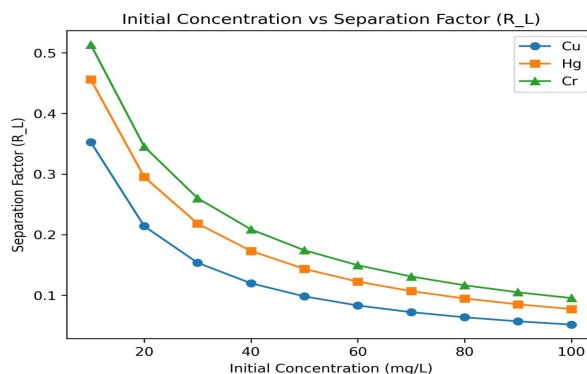


Fig.-7: Plot of Initial Concentration of Cu^{2+} , Hg^{2+} and Cr^{3+} Ions versus Separation Factor (R_L)

CONCLUSION

Heavy metal ion removal from contaminated water requires intricate adsorption processes that are impacted by a number of variables. Chitosan powder was thoroughly examined in the current work as a biosorbent for the removal of Cu(II) , Hg(II) , and Cr(III) ions, demonstrating its efficacy as an environmentally benign and effective adsorbent material. The dosage of the adsorbent, the starting concentration of metal ions, the pH of the solution, and the length of contact between the adsorbent and the solution all had a significant impact on the adsorption performance. In over 35 minutes, the system achieved adsorption equilibrium, and at a pH of 5.0, the maximum metal ion removal efficiency was noted. When Langmuir and Freundlich isotherm models were used to evaluate the adsorption data, the Langmuir model showed a stronger correlation, indicating that monolayer formation on a homogeneous surface with similar active sites is the primary mechanism of adsorption. The Freundlich model, on the other hand, indicated the existence of surface heterogeneity, with adsorption occurring at locations with varying energy levels.

Overall, the results show that chitosan powder is a very effective biosorbent for the removal of heavy metals, which is in line with previous studies on natural adsorbents and highlights its potential as a sustainable material for environmental remediation and water purification. Thus, the present study contributes to the United Nations Sustainable Development Goal 6 (SDG-6): Clean Water and Sanitation, particularly Target 6.3, by providing a sustainable biosorption approach for reducing hazardous heavy-metal contamination and improving water quality.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Dr. B. R. Ambedkar University, Etcherla, Andhra Pradesh, for providing support and encouragement to carry out this work as part of the thesis research. The authors also thank the Research Centre, Government Degree College for Men, Srikakulam, for laboratory support. No financial support was received for this study.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-6: Clean Water and Sanitation*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

S. V. M. Prasad  <https://orcid.org/0000-0003-1594-6803>

K. Raveendrababu  <https://orcid.org/0000-0002-4877-561X>

S. Ramakrishna  <https://orcid.org/0000-0002-4917-615X>

Open Access: This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

Cite this article as: S. V. M. Prasad *et al.*, *Rasayan J. Chem.*, Vol.19, Special Issue, 94-105(2026), <https://doi.org/10.31788/RJC.2026.1959926>

REFERENCES

1. Q. Zia, M. Tabassum, R. Gong, and J. Li, *Journal of Fiber Bioengineering and Informatics*, **12**, 103(2019), <https://doi.org/10.3993/jfbim00301>.
2. R. Vieira, M. L. Oliveira, E. Guibal, E. Rodriguez-Castellon, and M. Beppu, *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, **374**, 108(2011), <https://doi.org/10.1016/j.colsurfa.2010.11.022>.
3. M. A. Kaczorowska and D. Bozejewicz, *Sustainability*, **16**, 2615(2024), <https://doi.org/10.3390/su16072615>.
4. S. Begum, N. Y. Yuhana, M. S. Noorashikin, N. Kamarudin, and A. Bakar, *Carbohydrate Polymers*, **259**, 117613(2021), <https://doi.org/10.1016/j.carbpol.2021.117613>.
5. Upadhyay, U., I. Sreedhar, S. Singh, C. Patel, and K. L. Anitha, *Carbohydrate Polymers*, **251**, 117000(2020), <https://doi.org/10.1016/j.carbpol.2020.117000>.
6. G. Kyzas, D. Bikiaris, and N. Lazaridis, *Langmuir*, **24**, 4791(2008), <https://doi.org/10.1021/la7039064>.
7. K. Wang, Z. Song, Z. Xu, Y. Xi, Y. Cui, and H. Zhou, *RSC Advances*, **15**, 21121(2025), <https://doi.org/10.1039/d5ra02862k>.
8. M. Khajavian, S. Kaviani, I. Piyanzina, D. Tayurskii, and O. Nedopekin, *International Journal of Biological Macromolecules*, **257**, 128706(2023), <https://doi.org/10.1016/j.ijbiomac.2023.128706>.
9. R. Vieira, M. L. Oliveira, E. Guibal, E. Rodriguez-Castellon, and M. Beppu, *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, **374**, 108(2011), <https://doi.org/10.1016/j.colsurfa.2010.11.022>.
10. Jha, P. K., G. P. Halada, and S. M. McLennan, *Coatings*, **3**, 140(2013), <https://doi.org/10.3390/coatings3030140>.
11. R. Et-Tanteney, I. Allaoui, I. Manssouri, B. E. Amrani, and K. Draoui, *Results in Chemistry*, **13**, 102056(2025), <https://doi.org/10.1016/j.rechem.2025.102056>.
12. I. Issahaku, I. K. Tetteh, and A. Y. Tetteh, *Environmental Advances*, **11**, 100351(2023), <https://doi.org/10.1016/j.envadv.2023.100351>.
13. M. Toral, J. González-Navarrete, A. Leiva, H. Ríos, and M. Urzúa, *European Polymer Journal*, **45**, 730 (2009), <https://doi.org/10.1016/j.eurpolymj.2008.12.011>.

14. H. Martín López, S. Pech, E. Herrera-Pool, N. Medina-Torres, J. C. Cuevas-Bernardino, T. Ayora, H. Espinosa-Andrews, A. Ramos-Díaz, S. Trombotto, and N. Pacheco López, *Agriculture*, **10**, 464(2020), <https://doi.org/10.3390/agriculture10100464>.
15. Lu, R., W. Gan, B. Wu, Z. Zhang, Y. Guo, and H. Wang, *The Journal of Physical Chemistry B*, **109**, 14118 (2005), <https://doi.org/10.1021/jp051565q>.
16. C. Zhang, Q. Ping, H. Zhang, and J. Shen, *European Polymer Journal*, **39**, 1629(2003), [https://doi.org/10.1016/S0014-3057\(03\)00068-5](https://doi.org/10.1016/S0014-3057(03)00068-5).
17. N. Nikonenko, D. Buslov, N. Sushko, and R. Zhabankov, *Biopolymers*, **57**, 257(2000), [https://doi.org/10.1002/1097-0282\(2000\)57:4<257::AID-BIP7>3.0.CO;2-3](https://doi.org/10.1002/1097-0282(2000)57:4<257::AID-BIP7>3.0.CO;2-3).
18. M. Rinaudo, *Progress in Polymer Science*, **31**, 603(2006), <https://doi.org/10.1016/j.progpolymsci.2006.06.001>.
19. W. S. Wan Ngah and M. A. K. M. Hanafiah, *Bioresource Technology*, **99**, 3935(2008), <https://doi.org/10.1016/j.biortech.2007.06.011>.
20. H. M. Meena, S. Kukreti, and P. S. Jassal, *Results in Engineering*, **23**, 102467(2024), <https://doi.org/10.1016/j.rineng.2024.102467>.
21. D. A. Gkika, A. K. Tolkou, I. A. Katsoyiannis, and G. Z. Kyzas, *Separation and Purification Technology*, **368**, 132996(2025), <https://doi.org/10.1016/j.seppur.2025.132996>.
22. M. S. Rostami and M. M. Khodaei, *International Journal of Biological Macromolecules*, **270**, 132386(2024), <https://doi.org/10.1016/j.ijbiomac.2024.132386>.
23. M. Achak, A. Hafidi, N. Ouazzani, S. Sayadi, and L. Mandi, *Journal of Hazardous Materials*, **166**, 117(2009), <https://doi.org/10.1016/j.jhazmat.2008.11.036>.
24. Kanwal, S., P. Devi, Z. Ahmed, and N. A. Qambrani, *Desalination and Water Treatment*, **319**, 100441(2024), <https://doi.org/10.1016/j.dwt.2024.100441>.
25. H.-K. Chung, W.-H. Kim, J. Park, J. Cho, T.-Y. Jeong, and P.-K. Park, *Journal of Industrial and Engineering Chemistry*, **28**, 241(2015), <https://doi.org/10.1016/j.jiec.2015.02.021>.
26. R. Pawar, Lalmunsiam, H. Bajaj, and S.-M. Lee, *Journal of Industrial and Engineering Chemistry*, **34**, 213(2016), <https://doi.org/10.1016/j.jiec.2015.11.014>.
27. A.-G. Tenea, C. Dinu, P. A. Rus, I. A. Ionescu, S. Gheorghe, V. I. Iancu, G. G. Vasile, L. F. Pascu, and F. L. Chiriac, *Heliyon*, **10**, e35364(2024), <https://doi.org/10.1016/j.heliyon.2024.e35364>.
28. K. Ebisike, A. Elvis Okoronkwo, K. Kanayo Alaneme, and O. Jeremiah Akinribide, *Results in Chemistry*, **5**, 100730(2023), <https://doi.org/10.1016/j.rechem.2022.100730>.
29. C.-J. Sun, L.-Z. Sun, and X. Sun, *Industrial & Engineering Chemistry Research*, **52**, 14251(2013), <https://doi.org/10.1021/ie401571p>.

[RJC- 9926/2026]