African Journal of Advanced Pure and Applied Sciences (AJAPAS)
Online ISSN: 2957-644X
Volume 5, Issue 4, 2026
Page No: 371-381
Website: https://aaasjournals.com/index.php/ajapas/index
ISI 2025: 1.126 **SJIFactor 2024: 6.752** **معامل التأثير العربي 2025: 1.65**

Systematic Evaluation of Cd(II) Adsorption onto CTS–Polyester-Gly$_5$ Crosslinked Polymeric Spheres: Operating Parameters, Equilibrium, Kinetic Modeling, and Thermodynamics

Nooraddein A. Ekrayem [1*], Abdulsalam Abdu [2]
[1] Department of Chemical Engineering, College of Engineering, Alasmarya Islamic University, Zliten, Libya
[2] Department of Chemical Engineering - Oil and Gas and Renewable Energy Engineering, College of Engineering, Zawia University, Zawia, Libya

التقييم المنهجي لامتزاز *Cd(II)* باستخدام الكرات البوليمرية المتشابكة *CTS–Polyester-Gly$_5$*: متغيرات التشغيل، والاتزان، والنمذجة الحركية، والديناميكا الحرارية

نوالدين علي اكريم [1*]، عبدالسلام عبدو [2]
[1] قسم الهندسة الكيميائية، كلية الهندسة، الجامعة الأسمرية الإسلامية، زليتن، ليبيا
[2] قسم الهندسة الكيميائية - هندسة النفط والغاز والطاقة المتجددة، كلية الهندسة، جامعة الزاوية، الزاوية، ليبيا

[*]Corresponding author: n.ekrayem@asmarya.edu.ly

Received: August 29, 2026	Accepted: November 06, 2026	Published: November 21, 2026

Abstract:
The adsorption of Cd(II) from aqueous media by CTS–Polyester-Gly$_5$ crosslinked polymeric spheres was examined under different operating conditions. The influence of solution pH, adsorbent dosage, contact time, Cd(II) concentration, and temperature was assessed. The highest experimentally measured adsorption capacity, approximately 28.5–29 mg g^{-1}, was obtained at pH 6. At an adsorbent dosage of 2 g L^{-1}, the removal efficiency was approximately 85%. Uptake was fastest during. the early contact period. and then increased more gradually, approaching a near-equilibrium condition within 720–840 min. Of the isotherm models examined, Langmuir gave the highest coefficient of determination (R^2 = 0.9923), corresponding to a calculated maximum. capacity of about 34.6 mg g^{-1}. For the kinetic data, the pseudo-second-order (PSO) model produced a higher R^2 (0.9956) than the pseudo-first-order (PFO) model (0.9420); however, the PSO-calculated equilibrium capacity was higher than the experimental value. Raising the temperature from 25 to 45 °C increased the adsorption capacity from approximately 28.5 to 31 mg g^{-1} and the removal efficiency after 840 min from about 78% to 89%. The thermodynamic parameters were ΔH° = +33.90 kJ mol^{-1} and ΔS° = +117.79 J mol^{-1} K^{-1}, while ΔG° was −1.22, −2.35, and −3.58 kJ mol^{-1} at 298, 308, and 318 K, respectively. These findings indicate that Cd(II) uptake by CTS–Polyester-Gly5 was favored at higher temperatures under the conditions investigated. The results support further evaluation of these crosslinked. spheres as a candidate adsorbent. for Cd(II)-contaminated water.

Keywords: Cd(II) adsorption; CTS–Polyester-Gly$_5$; adsorption isotherms; adsorption kinetics; thermodynamic analysis.

الملخص:
تعد مياه الشرب من أثمن الموارد الطبيعية الأساسية لاستدامة الحياة وصحة الإنسان، وتحديداً في المناطق التي تعتمد على مصادر متجددة وجوفية تبرز أهمية تقييم جودة المياه ومراقبة الملوثات الكيميائية لضمان مطابقتها للمواصفات القياسية وحماية الصحة العامة للسكان. وتهدف هذه الدراسة بشكل رئيسي إلى تقدير ومقارنة محتوى أيونات النترات (NO3-) في عينات المياه الجوفية والمعبأة بمدينة القبة – ليبيا. اعتمدت الدراسة على جمع 11 عينة من المياه الجوفية و7 عينات من المياه المعبأة التجارية، حيث تم تحليل تراكيز النترات باستخدام جهاز المطياف الضوئي للأشعة فوق البنفسجية والمرئية

 Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

تمت دراسة امتزاز أيونات الكادميوم الثنائي Cd(II) من الأوساط المائية باستخدام الكرات البوليمرية المتشابكة (CTS–Polyester-Gly$_5$) تحت ظروف تشغيلية مختلفة. وتم تقييم تأثير الرقم الهيدروجيني للمحلول (pH)، وجرعة المادة المازة، وزمن التلامس، وتركيز أيونات Cd(II)، ودرجة الحرارة. وقد تم الحصول على أعلى سعة امتزازية مقاسة تجريبياً، والتي بلغت حوالي 28.5–29 ملغم/غم، عند قيمة pH تساوي 6. وعند استخدام جرعة من المادة المازة مقدارها 2 غم/لتر، بلغت كفاءة الإزالة حوالي 85%. كانت عملية الامتزاز أسرع خلال فترة التلامس الأولية، ثم استمرت بالزيادة تدريجياً وبمعدل أبطأ، مقتربةً من حالة الاتزان خلال 720–840 دقيقة. ومن بين نماذج متساويات الحرارة التي تمت دراستها، حقق نموذج لانغمير (Langmuir) أعلى معامل تحديد(R^2 = 0.9923) ، مع سعة امتزازية قصوى محسوبة بلغت حوالي 34.6 ملغم/غم. أما بالنسبة إلى البيانات الحركية، فقد أظهر نموذج المرتبة الثانية الكاذبة (PSO) قيمة أعلى لمعامل التحديد (R^2 = 0.9956) مقارنةً بنموذج المرتبة الأولى الكاذبة (R^2 = 0.9420) (PFO)؛ ومع ذلك، كانت سعة الاتزان المحسوبة باستخدام نموذج PSO أعلى من القيمة التجريبية. أدى رفع درجة الحرارة من 25 إلى 45 درجة مئوية إلى زيادة السعة الامتزازية من حوالي 28.5 إلى 31 ملغم/غم، كما ارتفعت كفاءة الإزالة بعد 840 دقيقة من حوالي 78% إلى 89 %. بلغت المعلمات الثرموديناميكية ΔH° = +33.90 كيلوجول/مول و ΔS° = +117.79 جول/(مول·كلفن)، في حين بلغت قيم ΔG° −1.22 و−2.35 و−3.58 كيلوجول/مول عند درجات الحرارة 298 و308 و318 كلفن، على التوالي. وتشير هذه النتائج إلى أن امتزاز أيونات Cd(II) بواسطة CTS–Polyester-Gly$_5$كان مفضلاً عند درجات الحرارة المرتفعة ضمن الظروف التي تمت دراستها. وتدعم هذه النتائج إجراء المزيد من الدراسات لتقييم الكرات البوليمرية المتشابكة بوصفها مادة مازة مرشحة لمعالجة المياه الملوثة بأيونات Cd(II).

الكلمات المفتاحية: امتزاز الكادميوم الثنائي Cd(II) ؛ CTS–Polyester-Gly$_5$ ؛ متساويات حرارة الامتزاز؛ حركية الامتزاز؛ التحليل الثرموديناميكي.

Introduction

The presence of toxic metals in aquatic environments remains a major water-quality concern because these elements are persistent and cannot be eliminated through biological degradation. Once released, they may remain in water, sediments, and other environmental compartments, where they can enter biological systems and accumulate. Cadmium is of particular concern because of its toxicity to aquatic organisms and its potential adverse effects on human health [1, 2]. Industrial sources include mining and metal processing, electroplating and metal finishing, pigment manufacture, battery production, and smelting operations [1, 3]. The removal of Cd(II) from contaminated water and wastewater is therefore an important environmental objective. Available treatment approaches include chemical precipitation, coagulation–flocculation, ion exchange, membrane separation, electrochemical treatment, and adsorption [4, 5]. Although these processes can remove dissolved metals, their practical implementation may be constrained by chemical and energy demand, secondary-waste generation, membrane-related limitations, or the need for close operational control [1]. Adsorption is widely investigated as an alternative because it can be operated using a broad range of natural, synthetic, and bio-derived materials. In particular, renewable polymers have attracted attention because their chemical structures contain functional groups that can interact with dissolved metal ions and can often be modified to improve treatment performance [4, 5]. Chitosan is one such material. It is produced by the partial deacetylation of chitin and consists mainly of β-(1→4)-linked glucosamine units together with residual N-acetylglucosamine units. Its amino and hydroxyl groups can participate in metal binding through coordination and related interfacial interactions [6], making chitosan-based materials promising candidates for aqueous metal removal [4, 7].

The use of unmodified chitosan, however, may be restricted by its limited mechanical strength and its sensitivity to acidic media. Protonation of amino groups at low pH changes the polymer surface chemistry and can influence metal-ion binding; under sufficiently acidic conditions, the untreated material may also lose structural integrity. Crosslinking [6], grafting [8], blending [9], and composite formation have consequently been explored to improve the stability of chitosan-based adsorbents while retaining accessible binding groups. The extent to which crosslinking affects adsorption depends on the crosslinker chemistry and network density, as well as on whether the modification preserves access to the polymer's active sites [6, 9]. The present work examines CTS–Polyester-Gly$_5$, a chitosan/polyester crosslinked polymer previously prepared and characterized as polymeric spheres [6]. The chitosan component contributes amino and hydroxyl functionalities that may interact with Cd(II), while the crosslinked network is intended to improve the material's stability in water relative to untreated chitosan. The earlier preparation study described the formation and characterization of the biobased chitosan/polyester spheres and assessed their properties and preliminary interactions with metal ions [6]. In the current study, the CTS–Polyester-Gly$_5$ formulation was selected for a more detailed assessment of Cd(II) uptake. This work extends the earlier material-focused investigation by examining the influence of

 Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

operating conditions and by applying kinetic, equilibrium, and thermodynamic analyses to the Cd(II) adsorption system [10] [11].
Adsorption performance is governed by several interacting variables, including pH, adsorbent dosage, contact time, solute concentration, and temperature. These factors can affect the protonation state of surface groups, the distribution of dissolved metal species, the number of accessible binding sites, and mass-transfer rates [8, 12]. Kinetic models are used to describe uptake as a function of time, whereas isotherm models relate equilibrium concentration to the amount adsorbed. Thermodynamic parameters provide additional information about the temperature dependence and energetic characteristics of the process [9, 7]. Accordingly, this study evaluates Cd(II) adsorption onto CTS–Polyester-Gly_5 by examining the effects of pH, adsorbent dosage, contact time, concentration, and temperature, followed by kinetic, isotherm, and thermodynamic modeling. The objective is to establish how these variables influence the measured adsorption response and to assess the material's potential for Cd(II) removal from aqueous solutions.

Material and methods

Materials

CTS–Polyester-Gly_5 crosslinked polymeric spheres, prepared and characterized in the previously published work [6], were used as the adsorbent. A certified Cd(II) standard solution (1000 mg L^{-1}) served as the source for preparing the test solutions. Hydrochloric acid (HCl) and sodium hydroxide (NaOH) were used to adjust solution pH. Deionized water was used throughout solution preparation and the adsorption experiments. All chemicals were of analytical grade and were used as received.

Adsorbent

Before the adsorption tests, the dry CTS–Polyester-Gly_5 spheres were washed thoroughly with deionized water. The washed material was then dried at 45 °C for 2–3 h and stored in a sealed container until use.

Preparation of Cd(II) Solutions

A working Cd(II) solution with an initial concentration of 80 mg L^{-1} was prepared by diluting the certified 1000 mg L^{-1} standard solution with deionized water. This solution was used in the batch experiments described below. Calibration solutions containing 0, 5, 10, and 15 mg L^{-1} Cd(II) were prepared by dilution and used to construct the calibration curve for flame atomic absorption spectrometric (FAAS) measurements. Dilution volumes were calculated using Equation (1):

$C_1V_1 = C_2V_2$ ……(1)

Where C_1 and V_1 are the concentration and volume of the stock solution, respectively, while C_2 and V_2 represent the required concentration and final volume of the diluted solution.

Batch Adsorption Experiments

Batch tests were performed to assess Cd(II) removal by CTS–Polyester-Gly_5. In a typical experiment, 0.05 g of dry adsorbent was added to a 50 mL conical flask containing 25 mL of Cd(II) solution at an initial concentration of 80 mg L^{-1}. The initial pH was adjusted to the required value using 1 M HCl or 0.5 M NaOH. The flasks were agitated at 160 rpm for 24 h at room temperature. At the end of each run, the adsorbent was separated from the liquid phase, and the residual Cd(II) concentration in the supernatant was measured by FAAS using the calibration curve. The equilibrium adsorption capacity (q_e) and removal percentage (R%) were calculated using Equations (2) and (3), respectively:

$$q_e = \frac{(C_0 - C_e)V}{m} \quad \text{……..(2)}$$

$$R(\%) = \frac{(C_0 - C_e)}{C_0} * 100 \quad \text{……..(3)}$$

where C_0 and C_e are the initial and equilibrium Cd(II) concentrations (mg L^{-1}), V is the solution volume (L), and m is the adsorbent mass (g).

Results and discussion

The chemical structure and principal functional groups of CTS–Polyester-Gly_5 were characterized by FTIR spectroscopy in the earlier study [6]. The present investigation therefore concentrates on the morphology of the prepared polymer and its adsorption response toward Cd(II).

Scanning Electron Microscopy (SEM) Analysis

SEM was used to examine the morphology of fractured CTS–Polyester-Gly_5 spheres before exposure to Cd(II), as shown in Figure 1. At lower magnification, the images show irregular polymer fragments with a range of particle sizes and some aggregation. The higher-magnification views reveal a non-uniform surface containing layered features, cavities, and depressions. These observations describe the surface morphology of the material

 Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

before adsorption; they do not, by themselves, establish the occurrence of Cd(II) binding or identify a specific adsorption mechanism.

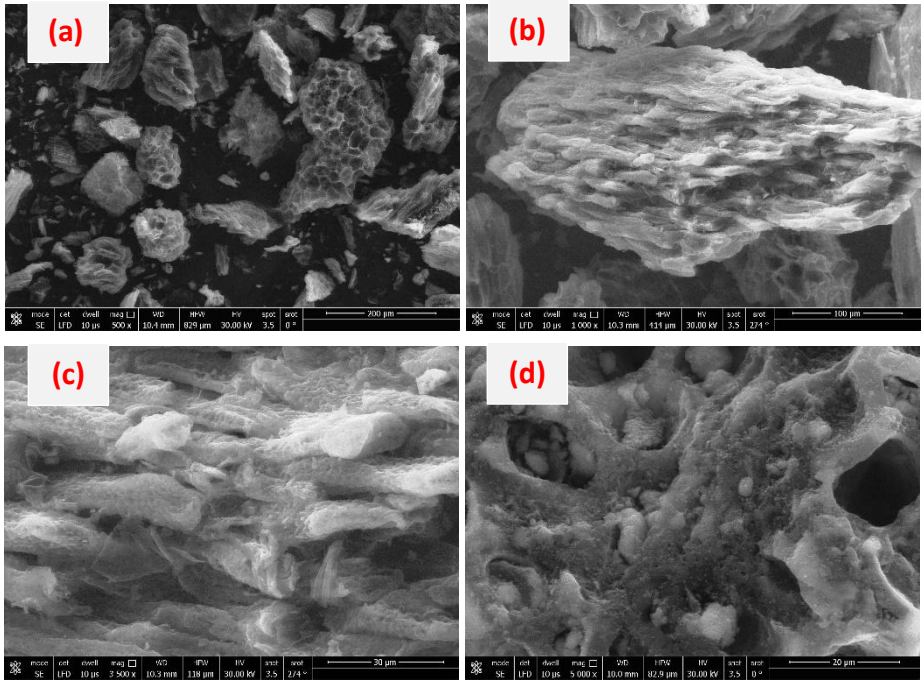


Figure 1: SEM micrographs of CTS–Polyester-Gly_5 before Cd(II) adsorption at magnifications of (a) 500×, (b) 1000×, (c) 3500×, and (d) 5000×.

The roughness and surface cavities may increase the area of the polymer that is accessible to the aqueous phase and may facilitate contact between dissolved Cd(II) and the functional groups present in the material. The heterogeneous surface may also provide chemically distinct interfacial environments. These features are consistent with the potential use of the spheres as an adsorbent, although confirmation of changes caused by metal uptake would require comparative characterization before and after adsorption [13, 14].

Effect of Contact Time on Cd(II) Adsorption

Figure 2 shows the change in Cd(II) adsorption capacity with contact time at 25 °C, an initial Cd(II) concentration of 80 mg L^{-1}, and an adsorbent dosage of 2 g L^{-1}. Uptake was rapid at the beginning of the experiment: q_t increased from about 4 mg g^{-1} at 15 min to approximately 10.5 mg g^{-1} at 60 min and 14 mg g^{-1} at 120 min. The rate then declined, with the capacity reaching approximately 23–24 mg g^{-1} at 300 min and 25.3 mg g^{-1} at 540 min. At longer times, the increase was smaller; values of about 28 mg g^{-1} at 720 min and 28.5–29 mg g^{-1} at 840 min were recorded. The curve therefore approaches a plateau over approximately 720–840 min, indicating that the system was nearing equilibrium within this interval [15].

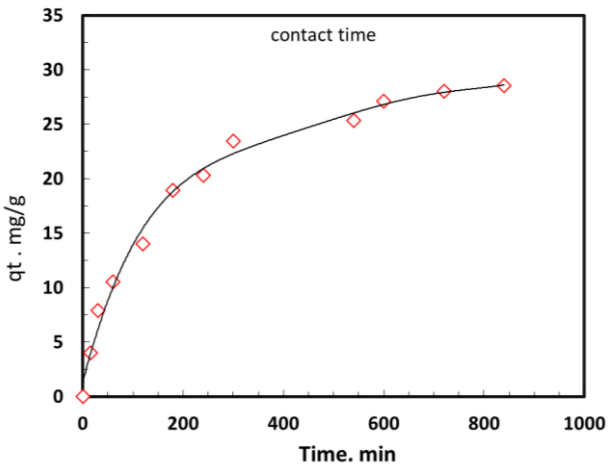


Figure 2: Effect of contact time on Cd(II) adsorption onto CTS–Polyester-Gly_5 at 25 °C (initial Cd(II) concentration = 80 mg L^{-1}; adsorbent dosage = 2 g L^{-1}).

 Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

The initial high uptake rate is consistent with the availability of unoccupied adsorption sites and a relatively large concentration difference between the bulk solution and the adsorbent surface. As adsorption proceeds, progressive occupation of these sites and a reduction in the concentration driving force can account for the slower increase in q_t. Although the curve begins to level off at about 720 min, the highest measured capacity in the reported time series was obtained at 840 min (approximately 28.5–29 mg g^{-1}).

Effect of Adsorbent Dosage

The influence of adsorbent dosage on Cd(II) removal is presented in Figure 3. Increasing the dosage from 0.5 to 4.0 g L^{-1} raised the removal efficiency from approximately 61% to 90%. The increase was more pronounced at the lower dosages: removal reached about 74% at 1.0 g L^{-1} and 85% at 2.0 g L^{-1}. A further increase from 2.0 to 4.0 g L^{-1} improved removal by only about five percentage points. This diminishing increment is consistent with the greater availability of adsorption sites at higher dosages, combined with a progressively lower amount of dissolved Cd(II) remaining in the solution [11].

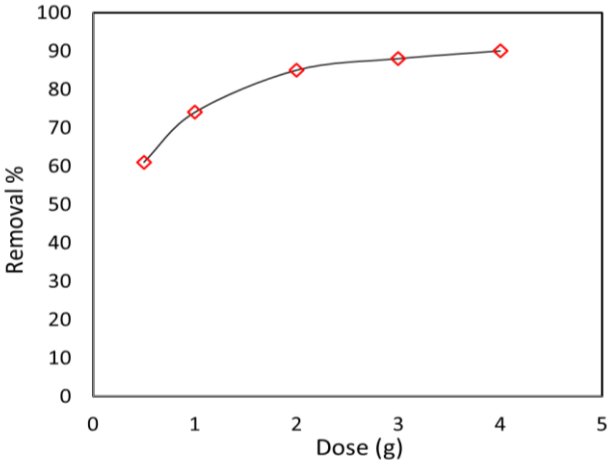


Figure 3: Effect of CTS–Polyester-Gly_5 dosage on the removal efficiency of Cd(II).

At higher adsorbent loadings, the additional removal may become limited because a larger fraction of the available Cd(II) has already been removed. Particle aggregation or partial overlap of accessible sites may also contribute, depending on the suspension characteristics. Under the conditions examined, 2.0 g L^{-1} achieved approximately 85% removal at 4.0 g and may therefore represent a practical dosage for subsequent experiments, while the higher dosage produced only a modest additional improvement [16].

Effect of Solution pH

The effect of initial solution pH on Cd(II) adsorption was evaluated at an initial concentration of 80 mg L^{-1} (Figure 4). The adsorption capacity increased as pH rose from 2 to 6. The measured values were approximately 5 mg g^{-1} at pH 2, 9.5 mg g^{-1} at pH 3, 19.5 mg g^{-1} at pH 4, and 26 mg g^{-1} at pH 5. The maximum capacity, approximately 28.5–29 mg g^{-1}, was obtained at pH 6. Under strongly acidic conditions, competition between H^+ and Cd(II) for available binding sites is a plausible explanation for the lower uptake.

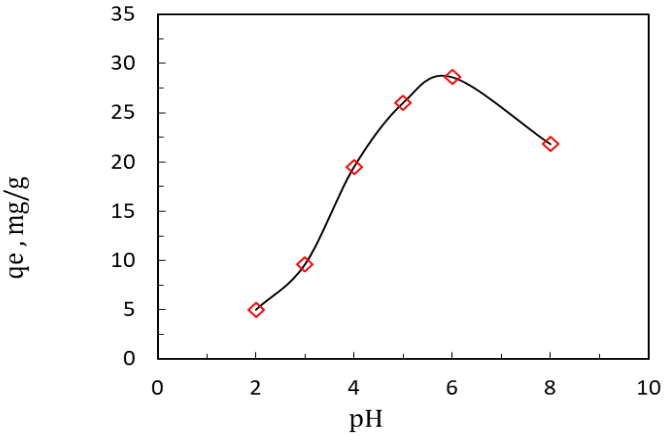


Figure 4: Effect of solution pH on the adsorption capacity of Cd(II) onto CTS–Polyester-Gly_5 (initial Cd(II) concentration = 80 mg L^{-1}).

 Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

As pH increases, the concentration of competing H^+ ions decreases, which can favor interaction of Cd(II) with amino and hydroxyl groups in the chitosan -containing adsorbent [17, 18]. At pH 8, however, the measured capacity declined to approximately 21.5 mg g^{-1}. Changes in surface-group ionization and possible changes in dissolved cadmium speciation, including hydroxide formation at higher pH, should be considered when interpreting this decrease. Because precipitation was not independently quantified in the reported experiments, the decline should not be attributed exclusively to adsorption-site effects. Within the pH range tested, pH 6 gave the highest measured adsorption capacity.

Effect of Initial Cd(II) Concentration

The relationship between equilibrium Cd(II) concentration (C_o) and adsorption capacity (q_e) is shown in Figure 5. The capacity increased from approximately 17.8 to 28.5 mg g^{-1} as C_o rose from 50 to 200 mg L^{-1}. A higher concentration gradient between the liquid phase and the adsorbent can increase the driving force for mass transfer and promote Cd(II) transport toward available sites. The observed increase in q_e is consistent with greater uptake at higher equilibrium concentrations over the range examined. Because the plotted data do not show a distinct plateau, the onset of complete site saturation cannot be established from this concentration interval alone. The data were therefore used for subsequent equilibrium-isotherm analysis [19, 20].

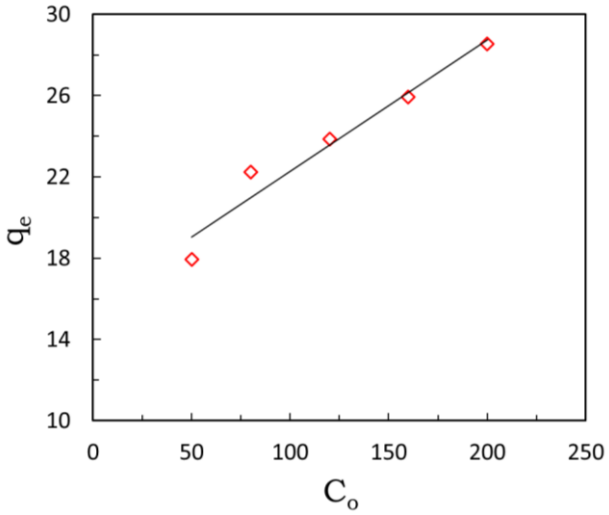


Figure 5: Effect of initial Cd(II) concentration on the adsorption capacity of CTS–Polyester-Gly_5 at 25 °C (adsorbent dosage = 2 g L^{-1}).

Effect of Temperature

The combined influence of temperature and contact time on Cd(II) removal is illustrated in Figure 6 for 25, 35, and 45 °C. At each temperature, removal increased rapidly at early contact times and then approached a more gradual region. At 25 °C, the removal efficiency rose from approximately 10% at 15 min to about 60% at 300 min and 78% at 840 min. At 35 °C, the final removal efficiency was approximately 85%, while the corresponding value at 45 °C reached about 89%. At the highest temperature, removal increased from approximately 27% at 15 min to about 70% at 300 min before reaching the final value at 840 min.

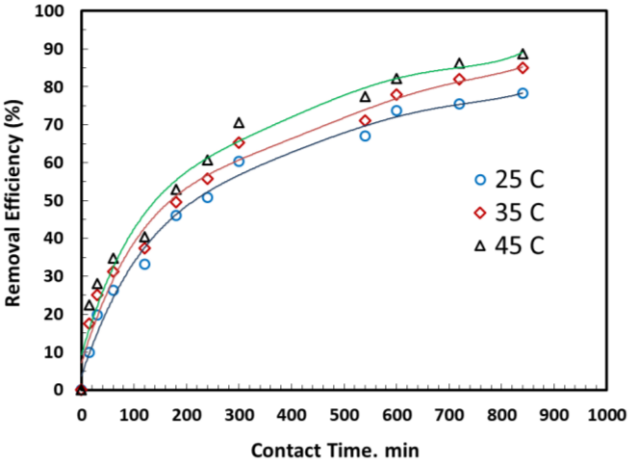


Figure 6: Effect of contact time on Cd(II) removal efficiency by CTS–Polyester-Gly_5 at 25, 35, and 45 °C.

 Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

The higher removal observed at elevated temperature indicates that temperature enhanced Cd(II) uptake under the conditions investigated [21]. Increased temperature may improve solute mobility and facilitate transport toward accessible sites within the polymer matrix; however, the precise contribution of diffusion and surface interactions cannot be isolated from these data alone. At 840 min, removal increased from approximately 78% at 25 °C to 85% at 35 °C and 89% at 45 °C. The flattening of the curves at longer contact times is consistent with the approach toward equilibrium [22, 23].

Adsorption Kinetics

The kinetic experiments were conducted at a fixed initial Cd(II) concentration of 80 mg L^{-1}. The time-dependent data were analyzed using the pseudo-first-order (PFO) and pseudo-second-order (PSO) models. Their linear forms are given in Equations (4) and (5), respectively [24, 21]:

$$\ln(q_e - q_t) = \ln q_e - k_1 t \quad \text{(4)}$$

$$\frac{t}{q_t} = \frac{1}{K_2 q_e^2} + \frac{t}{q_e} \quad \text{(5)}$$

Here, q_e and q_t are the amounts of Cd(II) adsorbed at equilibrium and at time t, respectively (mg g^{-1}); k_1 is the PFO rate constant (min^{-1}); k_2 is the PSO rate constant (g mg^{-1} min^{-1}); and t is the contact time (min). The linear plots are presented in Figure 7, and the corresponding fitted parameters are summarized in Table 1.

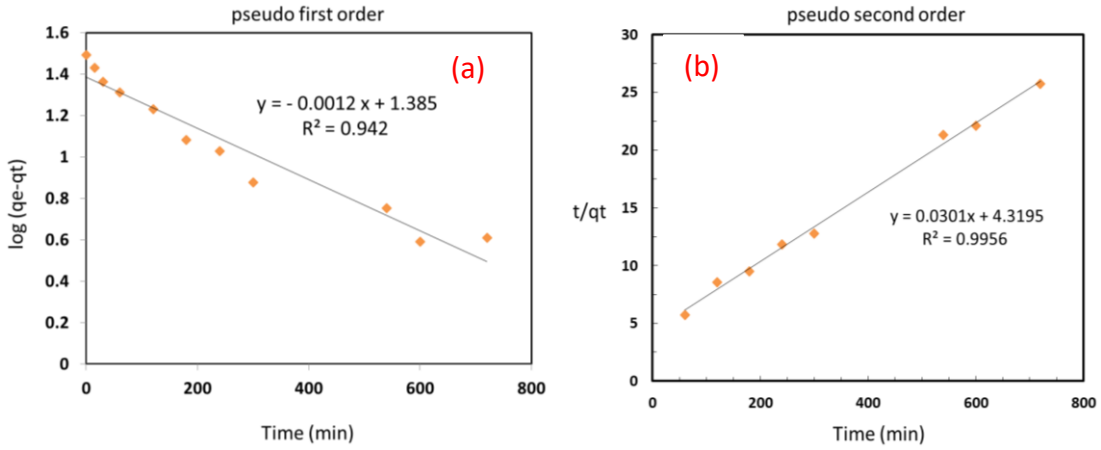


Figure 7: Linearized kinetic plots for Cd(II) adsorption onto CTS–Polyester-Gly_5: (a) pseudo-first-order model and (b) pseudo-second-order model.

Table 1: Kinetic parameters obtained from the PFO and PSO models for Cd(II) adsorption onto CTS–Polyester-Gly_5.

Initial concentration C_0 (mg/L)	Kinetic model	q_e (mg/g)	k_1 (min^{-1})	k_2 (g/mg·min)	R^2
80	Pseudo-first-order	24.26	2.764×10^{-3}	—	0.9420
80	Pseudo-second-order	33.22	—	2.10×10^{-4}	0.9956

The PFO regression gave R^2 = 0.9420, whereas the PSO regression yielded R^2 = 0.9956. Thus, among the two linearized models considered, the PSO plot showed the stronger correlation with the experimental kinetic data [25]. The PSO-calculated equilibrium capacity was 33.22 mg g^{-1}, compared with an experimental value of approximately 28.5 mg g^{-1}. The difference is 4.72 mg g^{-1}, with the model estimate exceeding the measured capacity. Consequently, the higher PSO R^2 should not be interpreted on its own as proof that the PSO model fully represents the adsorption mechanism; the discrepancy between calculated and experimental capacities must also be considered. The fitted PSO rate constant was 2.10×10^{-4} g mg^{-1} min^{-1}. Overall, the PSO model provided the higher linear-fit coefficient for the dataset, but its calculated q_e did not coincide with the experimental value. Model selection should therefore consider both the regression statistics and the agreement between calculated and measured adsorption capacities [26].

Adsorption Isotherms

The equilibrium data were analyzed using the Langmuir, Freundlich, and Temkin models to examine the relationship between C_e and q_e [27]. The fitted linear relationships and coefficients of determination are shown

 Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

in Figure 8. For the Freundlich model, the regression was $ln(q_e) = 0.3131\, ln(C_e) + 1.6851$, with R^2 = 0.9751. The slope, 1/n = 0.3131, is within the range commonly interpreted as favorable adsorption. The Langmuir plot gave $C_e/q_e = 0.0289\, C_e + 1.3858$ and R^2 = 0.9923. From the slope, the calculated maximum monolayer capacity is approximately 1/0.0289 = 34.6 mg g^{-1}. The Temkin relationship was $q_e = 7.1266\, ln(C_e) - 9.7209$, with R^2 = 0.978 [28].

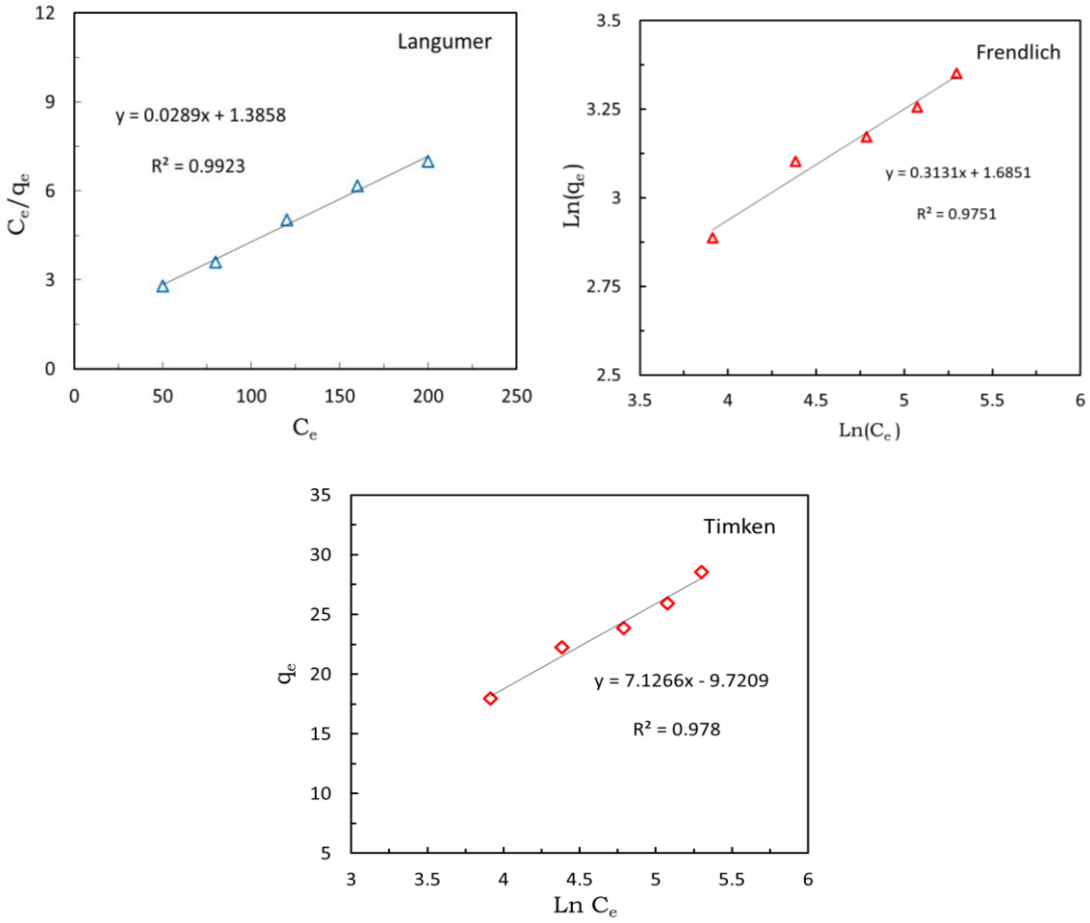


Figure 8: Linearized adsorption isotherms for Cd(II) on CTS–Polyester-Gly_5: Langmuir, Freundlich, and Temkin models.

Based on the reported R^2 values, the order of linear fit was Langmuir (0.9923) > Temkin (0.978) > Freundlich (0.9751). The Langmuir equation therefore provided the highest coefficient of determination among the three models over the concentration range examined. This result indicates that the Langmuir representation describes the measured equilibrium data more closely than the alternative linearized forms tested. The model fit is consistent with a monolayer description, although a high R^2 alone does not establish that the surface is physically uniform or that adsorption occurs through a single molecular mechanism [22, 28].

Thermodynamic Analysis

The thermodynamic behavior of Cd(II) adsorption onto the optimized CTS-Polyester-Gly_5 was investigated at 298, 308, and 318 K using an initial Cd(II) concentration of 80 mg L^{-1}. The standard Gibbs free-energy change was calculated using Equation (6), while the enthalpy and entropy changes were obtained from the van't Hoff relationship in Equation (7) [29]:

$$\Delta G^\circ = -RT ln\, Kc \quad \ldots\ldots (6)$$

$$ln\, Kc = (-\Delta H^o / RT) + (\Delta S^o / R) \quad \ldots\ldots (7)$$

In these equations, R is the universal gas constant (8.314 J mol^{-1} K^{-1}), T is the absolute temperature (K), and Kc is the equilibrium constant used in the thermodynamic calculations. A plot of ln Kc against 1/T was used to obtain ΔH° and ΔS° from the slope and intercept, respectively (Figure 9).

 Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

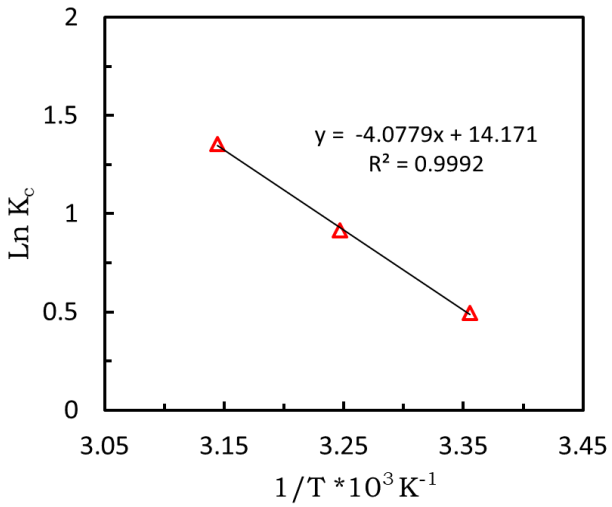


Figure 9: Van't Hoff plot for the adsorption of Cd(II) onto the CTS-Polyester-Gly$_5$.

The van't Hoff analysis yielded ΔH° = +33.90 kJ mol^{-1} and ΔS° = +117.79 J mol^{-1} K^{-1}. The positive enthalpy change is consistent with an **endothermic** adsorption process and agrees with the increase in removal observed as temperature rose from 25 to 45 °C [23, 30, 31, 32]. The calculated Gibbs free-energy changes were −1.22, −2.35, and −3.58 kJ mol^{-1} at 298, 308, and 318 K, respectively. Their negative values indicate thermodynamic favorability under the adopted equilibrium-constant convention, while the increasingly negative values suggest that favorability increased over the investigated temperature range [33, 34, 35].

Table 2: Thermodynamic parameters for the adsorption of Cd(II) onto the CTS-Polyester-Gly$_5$ at different temperatures.

Sample Code	*Temperature (K)*	K_c	ΔG° (kJ.mol^{-1})	Δ*H°* (KJ. mol^{-1})	Δ*S°* (J. mol^{-1} K^{-1})
CTS-Polyester-Gly$_5$	298	1.637	−1.22		
	308	2.5	−2.35	33.90	117.79
	318	3.875	−3.58		

The positive entropy change suggests an increase in the overall entropy associated with the solid–solution interface during adsorption. One possible explanation is the release of water molecules or other species previously associated with the adsorbent surface as Cd(II) interacts with available sites. This interpretation is plausible but is not directly demonstrated by the present measurements. Taken together, the thermodynamic parameters indicate an endothermic process with negative calculated ΔG° values under the conditions studied. The results support further assessment of CTS–Polyester-Gly$_5$ for aqueous Cd(II) treatment; practical suitability will also depend on regeneration, reuse, and performance in real wastewater [36, 29].

Conclusion and Recommendations

CTS–Polyester-Gly$_5$ crosslinked Polymeric spheres were evaluated as an adsorbent for Cd(II) removal from aqueous solution. The adsorption response depended on pH, adsorbent dosage, contact time, concentration, and temperature. The highest measured adsorption capacity, approximately 28.5–29 mg g^{-1}, was obtained at pH 6. A dosage of 2 g L^{-1} produced about 85% removal, while extending contact time to 840 min gave a capacity of approximately 28.5–29 mg g^{-1}. Increasing the temperature from 25 to 45 °C raised the removal efficiency from about 78% to 89%. Among the kinetic models, PSO gave the higher R², although its calculated equilibrium capacity exceeded the experimental value. For the equilibrium data, the Langmuir model gave the highest R² among the three isotherms examined; the original conclusion reported R² = 0.9989, while the Results section and Figure 8 report R² = 0.9923. The calculated maximum capacity was approximately 34.6 mg g^{-1}. The thermodynamic results (positive ΔH° and negative calculated ΔG° values) were consistent with endothermic and thermodynamically favorable uptake over the investigated Temperature range. Further work should examine adsorption mechanisms using comparative SEM and FTIR measurements before and after Cd(II) exposure, assess regeneration and reuse, test the material in real wastewater, and evaluate its performance in continuous-flow systems.

Declaration of Competing Interest

The authors say they don't have any known personal relationships or financial interests that could have seemed to affect the work in this paper.

 Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

References

[1] N. A. A. Qasem, R. H. Mohammed, and D. U. Lawal, "Removal of heavy metal ions from wastewater: A comprehensive and critical review.," npj Clean Water, pp. vol. 4, Art. no. 36, 2021.

[2] Y. Fei and Y. H. Hu, "Recent progress in removal of heavy metals from wastewater: A comprehensive review," Chemosphere, pp. vol. 335, Art. no. 139077, 2023.

[3] World Health Organization, "Exposure to cadmium: A major public health concern.," World Health Organization, 2019.

[4] U. Upadhyay, I. Sreedhar, S. A. Singh, C. M. Patel, and K. L. Anitha, "Recent advances in heavy metal removal by chitosan based adsorbents.," Carbohydrate Polymers, pp. vol. 251, Art. no. 117000, 2021.

[5] Y. Dong, T. Ma, P. Zhang, and H. Lin, "Preparation of modified chitosan and its application to remove cadmium ions in wastewater: A review," Journal of Environmental Chemical Engineering, pp. vol. 12, no. 1, Art. no. 111626, 2024.

[6] N. A. Krayem, A. A. Alhwaige, W. Elhrari, and M. Amer,, "Biobased chitosan/polyester crosslinked polymer: Preparation and characterization of novel polymeric spheres," in ICCPGE 2016 Proceedings, p. pp. 675–682, 2016.

[7] Y. Zhang, M. Zhao, Q. Cheng, C. Wang, H. Li, X. Han, Z. Fan, G. Su, D. Pan, and Z. Li,, "Research progress of adsorption and removal of heavy metals by chitosan and its derivatives: A review," Chemosphere, pp. vol. 279, Art. no. 130927, 2021.

[8] A. Ashraf, J. Dutta, A. Farooq, M. Rafatullah, K. Pal, and G. Z. Kyzas, "Chitosan-based materials for heavy metal adsorption: Recent advancements, challenges and limitations," Journal of Molecular Structure, pp. 1309, Art. no. 138225, 2024.

[9] I. O. Saheed, W. D. Oh, and F. B. M. Suah, "Chitosan modifications for adsorption of pollutants – A review.," Journal of Hazardous Materials, pp. vol. 408, Art. no. 124889, 2021.

[10] F. da S. Bruckmann, J. O. Gonçalves, L. F. O. Silva, M. L. S. Oliveira, G. L. Dotto, and C. R. B. Rhoden, "Chitosan-based adsorbents for wastewater treatment: A comprehensive review.," International Journal of Biological Macromolecules, pp. vol. 309, Art. no. 143173, 2025.

[11] G. T. Tee, X. Y. Gok, and W. F. Yong, "Adsorption of pollutants in wastewater via biosorbents, nanoparticles and magnetic biosorbents: A review.," Environmental Research, pp. vol. 212, Art. no. 113248, 2022.

[12] G. Z. Kyzas and D. N. Bikiaris, "Recent Modifications of Chitosan for Adsorption Applications: A Critical and Systematic Review," Marine Drugs, pp. vol. 13, no. 1, 312–337, 2015.

[13] V. M. Gun'ko, "Polymer adsorbents vs. functionalized oxides and carbons: Particulate morphology and textural and surface characteristics," Polymers, pp. vol. 13, no. 8, Art. no. 1249, 2021.

[14] Q. Kong, B. Xie, S. Preis, Y. Hu, H. Wu, and C. Wei, "Adsorption of Cd^{2+} by an ion-imprinted thiol-functionalized polymer in competition with heavy metal ions and organic acids," RSC Advances, pp. vol. 8, 8950–8960, 2018.

[15] W. Abd El-Fattah, A. Guesmi, N. Ben Hamadi, R. Yahya, T. S. Alraddadi, A. Shahat, and R. F. M. Elshaarawy, "A sustainable approach to the development and characterization of chitosan thiomer beads for the efficient removal of Cd(II) ions from aqueous effluents," RSC Advances, pp. vol. 15, no. 40, pp. 33695–33707, 2025.

[16] D. Somashekara and L. Mulky, "Sequestration of Contaminants from Wastewater: A Review of Adsorption Processes," ChemBioEng Reviews, pp. vol. 10, no. 4, 491–509, 2023.

[17] E. A. Alabbad, "Estimation the Sorption Capacity of Chemically Modified Chitosan Toward Cadmium Ion in Wastewater Effluents," Oriental Journal of Chemistry, pp. vol. 35, no. 2, 757–765, 2019.

[18] Z. A. Sutirman, M. M. Sanagi, K. J. Abd Karim, W. A. Wan Ibrahim, and B. H. Jume, "Equilibrium, kinetic and mechanism studies of Cu(II) and Cd(II) ions adsorption by modified chitosan beads," International Journal of Biological Macromolecules, pp. vol. 116, 255–263, 2018.

[19] J. Montalvo-Andía, W. Reátegui-Romero, A. D. Peña-Contreras, W. F. Zaldivar Alvarez, M. E. King-Santos, V. Fernández-Guzmán, J. L. Guerrero-Guevara, and J. E. Puris-Naupay, "Adsorption of Cd (II) Using Chemically Modified Rice Husk: Characterization, Equilibrium, and Kinetic Studies," Adsorption Science & Technology, pp. Art. no. 3688155, 17 , 2022.

 Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

[20] C. H. Giles, T. H. MacEwan, S. N. Nakhwa, and D. Smith, "Studies in adsorption. Part XI. A system of classification of solution adsorption isotherms, and its use in diagnosis of adsorption mechanisms and in measurement of specific surface areas of solids," Journal of the Chemical Society (Resumed), p. 3973–3993, 1960.

[21] C. Duran, D. Ozdes, A. Gundogdu, H.B. Senturk, "Kinetics and isotherm analysis of basic dyes adsorption on to almond shell (Prunusdulcis) as a low cost adsorbent,," J. Chem. Eng, p. 2136–2147, 2011.

[22] N,A,Ekrayem . A,A,Alhwaige. W,Elhrari. M, Amer, "Removal of lead (II) ions from water using chitosan/polyester crosslinked spheres derived from chitosan and glycerol-based polyester," Journal of Environmental Chemical Engineering, pp. 9 - 106628, 2021.

[23] J. S. Algethami, A. A. Alqadami, S. Melhi, M. A. M. Alhamami, A. M. Fallatah, and M. A. Rizk, "Sulfhydryl functionalized magnetic chitosan as an efficient adsorbent for high-performance removal of Cd(II) from water: Adsorption isotherms, kinetic, and reusability studies," Adsorption Science & Technology, p. Art no 2248249, 2022.

[24] L. Liu, S. Liu, Q. Zhang, C. Li, C. Bao, X. Liu, P. Xiao,, "Adsorption of Au(III), Pd(II), and Pt(IV) from aqueous solution onto graphene oxide," J. Chem. Eng., p. 209–216, 2013.

[25] Q. Zhang, R. Chu, Y. Wei, and L. Cai, "Cadmium adsorption onto aluminum hydroxide-modified attapulgite prepared with basic aluminum acetate," Scientific Reports, pp. 14, 31428, 2024.

[26] S. Wang, and D. Yu, "Adsorption of Cd(II), Pb(II), and Ag(I) in aqueous solution on hollow chitosan microspheres," Journal of Applied Polymer Science, pp. vol. 118, no. 2, pp. 733–739, 2010.

[27] K. Vijayaraghavan, T.V.N. Padmesh, K. Palanivelu, M. Velan,, "Biosorption of nickel(II) ions onto Sargassum wightii: application of two-parameter and three parameter isotherm models," J. Hazard. Mater. , p. 304–308, 2006.

[28] L. Lu & C. Na, "Gibbsian interpretation of Langmuir, Freundlich and Temkin isotherms for adsorption in solution," Philosophical Magazine Letters, pp. 102(7), 239–253, 2022.

[29] C. Ardean, M. Ciopec, C. M. Davidescu, P. Negrea, and R. Voda, "Kinetics and thermodynamics studies for cadmium (II) adsorption onto functionalized chitosan with hexa-decyl-trimethyl-ammonium chloride," Materials, pp. 13(23), 5552, 2020.

[30] S. A. S. A. Shah, S. Shukrullah, Y. Khan, M. U. Saleem, and M. Shoaib, "Synthesis and Study of Kinetics of $CoFe_2O_4$@SiO_2-Chitosan Adsorbents for Removal of Cadmium and Lead From Water," International Journal of Chemical Engineering, p. no. 6198054, 2025.

[31] S. U. Din, K. M. Al-Ahmary, S. R. Al-Mhyawi, H. AlMohamadi, N. Y. Elamin, I. F. Alshdoukhi, F. A. Imohiosen, E. A. Ofudje, and J. S. Al-Otaibi, "Sustainable removal of Cd(II) and Cr(VI) from aqueous solution via agro-waste derived biochar," Scientific Reports, pp. vol. 16, Art. no. 9792, 2026.

[32] I. A. Baba, S. Mustapha, B. J. Ismail, J. O. Tijani, and A. S. Abdulkareem, "Engineered hierarchical WO_3/activated carbon nanocomposite for sequestration of some heavy metals in mining wastewater," Next Materials, pp. vol. 11, Art. no. 101897, 2026.

[33] T. Shahwan., "Critical insights into the limitations and interpretations of the determination of ΔG°, ΔH°, and ΔS° of sorption of aqueous pollutants on different sorbents," Communications, pp. 41, 100369, 2021.

[34] N. A. Ekrayem, H. E. Eshtiwi, A. A. Benour, and A. M. Abugoffa, "Removal of Methyl Orange Dye Using Chemically Activated Carbon Derived from Commercial Pine Charcoal," Albahit Journal of Applied Sciences, pp. 85-100, 2026.

[35] N. A. Ekrayem, F. S. Keelany, A. M. Abdulhalim, and M. S. Alkoum., "Methylene Blue Removal from Aqueous Solutions Using a Low-Cost Bentonite–Eggshell Waste Adsorbent: Equilibrium, Kinetic, and Thermodynamic Studies," Journal of Alasmarya University, 2026.

[36] A. Kumar, T. Das, R. S. Thakur, Z. Fatima, S. Prasad, N. G. Ansari, and D. K. Patel, "Synthesis of biomass-derived activated carbons and their immobilization on alginate gels for the simultaneous removal of Cr(VI), Cd(II), Pb(II), As(III), and Hg(II) from water," ACS Omega, pp. 7(46), 41997–42011, 2022.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of **AJAPAS** and/or the editor(s). **AJAPAS** and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

 Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).