Volume 3, Issue 10, 2025

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

SYNTHESIS AND CHARACTERIZATION OF ACRYLIC ACID-MODIFIED *OCIMUM BASILICUM* HYDROGEL AS A SUSTAINABLE ADSORBENT FOR COBALT ION REMOVAL FROM AQUEOUS SOLUTIONS

Waqas Ahmad[1], Rashid Mahmood[2], Aiman Ishfaq[*3], Muhammad Ashraf Shaheen[*4], Shagufta Zayan[5], Aqsa Maqsood[6], Muhammad Azhar Abbas[7]

[1,2, * 3, *4]*Faculty of Sciences, Superior University Lahore, Lahore 54000, Pakistan*
[5, 6] *Institute of Chemistry, University of Sargodha, Sargodha 40100, Pakistan*
[7] *Government Ambala Muslim Graduate College, Sargodha 40100, Pakistan*

[*3]aiman.ishfaq.sgd@superior.edu.pk; [*4]*masaheen1964@gmail.com*

DOI: https://doi.org/10.5281/zenodo.18051231

Keywords
Ocimum basilicum hydrogel, polyacrylic acid copolymer, cobalt adsorption, bio-based adsorbent, wastewater treatment

Article History
Received: 11 October 2025
Accepted: 21 November 2025
Published: 22 December 2025

Copyright @Author
Corresponding Author: *
Aiman Ishfaq
Muhammad Ashraf Shaheen

Abstract

The growing discharge of cobalt ions to the aquatic environment is a major public health and environmental problem, so there is an urgent demand for inexpensive and sustainable remediation materials. In the present study, new bio-based adsorbents were prepared by free-radical copolymerization of Ocimum basilicum hydrogel with polyacrylic acid and an ammonia-cross-linked 3D hydrogel copolymer bearing carboxyl functional group was generated. The structure modification is beneficial to improve surface charge density, binding site accessories as well as adsorption affinity towards Co (II). The adsorption properties of the OBH-co-AA copolymer was systematically investigated by batch experiments and the effects of solution pH, contact time, initial Co (II) concentration, sorbent dosage, and temperature were determined. The optimum pH for the adsorption was found to be 6 and the process reached equilibrium within 60 min. The adsorption capacity of copolymer increased upon a shift towards alkaline range. The isotherm data could be well fitted by Langmuir, Temkin and Elovich isotherms presenting that the adsorption capacity in monolayer was 150.38 mg g^{-1} and surface was heterogeneous. Kinetics was found to be well described by the pseudo-second-order model, thus revealing chemisorption as the predominant adsorption process and diffusion models indicated that intra particle and pore diffusion took place in the end of uptake. Thermodynamics investigation indicated that the Co (II) adsorption on OBH-co-AA copolymer is a spontaneous, endothermic and entropy driven process. In conclusion, these results indicate that acrylic acid modified Ocimum basilicum hydrogel presents high effectiveness, environmental-friendly and economically competitive among other characteristics considered as an organic adsorbent and its potential for application in water treatment systems for removal of cobalt contamination.

1. INTRODUCTION

Pollution of world's water bodies by toxic heavy metal ions is an environmental challenge of major concern, due to accelerated industrial growth [1]. These pollutants are typically non-biodegradable,

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

environmentally persistent and bio accumulating, leading to serious long-term impacts on ecosystem health and human wellbeing [2]. Among various metallic contaminants cobalt ions are one of the metallic pollutants that draw much attentions owing to the wide discharge in mining, metallurgy and battery production or pigmentation [3]. Despite the fact that cobalt is a trace element, its high level is related to marked toxicological effects such as cardiac toxicity, neurotoxicity and potential carcinogenicity [4]. Therefore, the effective elimination of Co(II) from industrial effluents and well water sources is a very important issue to safeguard water quality and safety [5].

Conventional remediation technologies for removal of heavy metal from wastewater such as chemical precipitation, ion-exchange and membrane filtration, but are frequently hampered by substantial some drawbacks [6]. These drawbacks include high operating cost, high energy consumption, formation of hazardous sludge and particularly lower efficiency in treating dilute metal solutions [7-14]. Adsorption being one of the most successful and versatile separation processes that has been widely used for such separations [15-21]. Its popularity is due to the inherent benefits of operational simplicity, low cost, adsorbent regeneration possibility and high removal efficiency even when metal concentration is at trace levels [22]. The development of an efficient adsorption process begins with the design and synthesis of selective adsorbent material that has tailored surface chemistry, porous structures, and good population of binding sites [23].

To meet targets of sustainable development, a heavy amount of research interest is being directed towards employing renewable and hydrogel-based materials for environmental remediation. Natural biopolymers, particularly polysaccharides derived from plants, are very appealing for adsorbent supports because of their worldwide availability, biocompatibility, biodegradability, and cost effectiveness [24-27]. Importantly, their inherent molecular structures are also abundant with native functional groups such as hydroxyl and carboxylic acid groups which can be involved in metal ion binding [28]. But the direct application of native biopolymers is limited due to their lower adsorption capacity, inadequate mechanical property in water medium and nonspecific binding towards target contaminants [29]. To address these intrinsic limitations, indeed, a new paradigm has emerged based on the strategic chemical functionalization of the biopolymer backbone. This chemical modification e.g. by grafting, cross-carlinking or copolymerising is designed to introduce particular kinds of ligand groups which then significantly improve the material affinity and selectivity towards metal ions [30]. The attachment of carboxylic acid (-COOH) groups has emerged as an extraordinary effective form, due to the high chelating properties towards divalent and trivalent cations through ion exchange and complexation processes [31]. For example, it has been reported that the succinylation or maleation of polysaccharides can greatly increase their adsorption capability for Cd(II), Pb(II), and Cu(II) ions in aqueous solutions [32]. This concept of adding value to a natural substrate by controlled chemical synthesis is consistent with the overarching tenets of green chemistry and sustainable material development .

Basil (Ocimum basilicum) is an important culinary herb and the hydrogel of this plant was an unexploited source of structural polysaccharides including cellulose and hemicellulose [33]. It can be further studied by chemical modification to obtain novel and low-cost adsorbent using natural porous lignocellulosic matrix in the presence of hydroxyl groups which act as anchoring sites [34]. In the present work we introduce and carry out co polymerization of Ocimum basilicum hydrogel with acrylic acid. This method aims to densely graft a network of poly (acrylic acid) chains onto the plant substrate so as to form a three-dimensional hydrogel like polymer imbedded with numerous accessible carboxyl groups.

This article reports the potential use of the freshly synthesized Ocimum basilicum hydrogel-acrylic acid (OBH-co-AA) copolymer for Co(II) ion sequestration from aqueous media. The kinetics were examined on the basis of solution pH, contact time, initial dose of Co(II) adsorbent dosage and system temperature in a systematic manner. In addition, the obtained equilibrium data was fitted by isotherm models to interpret the adsorption behavior of copolymer. The rate controlling steps were determined following the kinetics studies and thermodynamic parameter was

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

computed to investigate whether the process is spontaneous of nature. The OBH-co-AA copolymer is expected to be an effective, environmentally-friendly and low-cost adsorbent to remediate cobalt pollution in aquatic resources with a high removal efficiency as well as propose a practical solution for the serious problem of cobalt contamination in water.

2. MATERIALS AND METHODS

2.1. Materials

Fresh leaves of Ocimum basilicum were procured from local source, washed and dried with distilled water to get rid of dust and impurities, shade dried and then oven dried. The functional monomer for copolymerization was the acrylic acid (AA). The free radical initiator was ammonium persulfate (APS) and crosslinking agent used was N,N′-methylenebisacrylamide (MBA). Co (II) stock solutions were prepared using cobalt (II) sulphate heptahydrate. All the chemicals employed were of analytical reagent grade and used as received. To remove any possible contamination, all of the glassware used in this study was thoroughly cleaned with distilled water, rinsed with a 2% nitric acid solution, and then dried in a vacuum oven. Distilled water was used for the preparation of all solutions. When necessary, diluted sodium hydroxide (NaOH) or hydrochloric acid (HCl) was used to adjust the pH of solutions.

2.2. Synthesis of Ocimum basilicum Hydrogel

Ocimum basilicum seeds were soaked in distilled water at room temperature to start the hydrogel extraction process. To guarantee full swelling and the development of a mucilaginous gel layer surrounding the seed coat, the seeds were left to hydrate for a full day. To ensure that all seed residues were removed, the swollen gel was carefully separated from the seeds using a fine muslin cloth after incubation. The collected gel was put into sterile petri dishes and left to dry overnight in a lab oven with temperature control. A clean stainless steel spatula was used to carefully remove the hydrogel film from the petri dishes after it had dried. A mortar and pestle were then used to grind the dried material into a fine powder. The bio polymeric component of the ensuing copolymer was this naturally extracted hydrogel.

2.3. Synthesis of Ocimum basilicum-Acrylic Acid Copolymer

To prepare the hydrogel-acrylic acid copolymer, 0.4g of the dry powder of the hydrogel of Ocimum basilicum was dissolved in beaker (20 mL) of a distilled water. The mixture was exposed to 70-80 °C to allow 40 min of continuous mixing under the magnetic stirring conditions to get full dissolution. Then, 0.9 g of ammonium persulfate was dripped into the solution as a free radical initiator, but stirring was furthered with 15-20 min more at the same temperature. Solution A was designating this solution. A crosslinking agent was present in a separate beaker whereby 4 mL of acrylic acid was mixed with 0.2 g of N,N 2-methylenebisacrylamide. This solution was referred to as Solution B. Solution B was added to Solution A at a low rate with constant stirring of the two solutions at the room temperature and allowed the two to react at least 40 min to initiate some pre-polymerization interactions. The resulting the homogeneous mixture was in turn transferred into clean test tubes and exposed to gradual thermal polymerization into a water bath. The initial hour was at temperatures of 60 °C, the second hour was 70 °C, the third hour was at temperatures of 80 °C, and the fourth hour was at temperatures of 90 °C. After polymerization was done, the resulting copolymer was taken out of the test tubes into petri dishes and washed completely using distilled water in order to remove any unreacted monomers. The solution was washed using a clean blade and dried the copolymer in an oven at 60 °C until it reached a constant weight. The dried samples were stored using airtight samples to ensure further characterization and adsorption research.

2.3. Preparation of Co (II) Solutions

To prepare Stock solution suspension of Co(II) ions, a measured quantity of cobalt (II) sulphate heptahydrate was dissolved in deionized water to form a stock solution of Co(II) ions. Suitable dilution from the stock solution resulted in working solutions of desired concentration. The pH of both solutions was regulated with diluted NaOH or HCl before adsorption studies.

2.4. Batch Adsorption Experiments

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

The removal efficiency of Co (II) by the newly copolymer was evaluated using a batch adsorption study. Specific 50 mg of adsorbent was added to a series of flasks containing Co(II) solutions with the predetermined concentration and pH. The flask agitated at a constant speed of about 1000rpm using a mechanical shaker for the predetermined contact times. The adsorbed coated particles were then filtered off and the remaining concentration of Co(II) was measured in the filtrate by a suitable analytical method. Equilibrium adsorption capacity (qe, mgg^{-1}) was estimated by the mass balance equation

$$q_e = \frac{(C_i - C_f)V}{m} \quad (1)$$

Where Ce (mg L−1) and Ci are the equilibrium and initial concentrations of Cu (II)or Co (II) , V (L) is the volume of the solution, and m (g) is the dry mass of hydrogel material added. The removal (%) can be calculated by the following Eq.

$$\%\,\mathrm{Re}moval = \frac{C_i - C_f}{C_i} \times 100 \quad (2)$$

Each measurement was repeated three times, and cell values are the average from three replicates to ensure reproducibility. The effect of pH on Co (II) adsorption was investigated over a wide range of pH values (2-8) with other parameters remaining each constant. To track adsorption kinetics and equilibrium time, the impact of contact time was investigated. The effects of temperature (258, 278, 298, 308, and 328 K) and initial Co(II) concentration and adsorbent dosage (10-100 mg) on the adsorption results were also systematically studied. Thermodynamic studies were performed in different temperatures to determine the spontaneous nature of phenol adsorption.

The experimental data were analyzed by using several isotherm models (Langmuir, Freundlich, Temkin, Dubinin-Radushkevich, Elovich) that are widely used for describing the interaction of Co(II) ion with a copolymer surface. The parameters of models were calculated by fitting the experimental data to the corresponding isotherms in order to simulate adsorption capacity and surface heterogeneity. The adsorption kinetics were studied by monitoring the time dependent Co(II) uptake with various kinetic models models (PFO, PSO, intra particle diffusion, elovich, pore diffusion). The suitability of the individual models was discussed by the correlation coefficients and agreement between experimental and calculated adsorption capacities.

2.5. Thermodynamic Analysis

The Gibbs free energy change, enthalpy change and entropy change were computed from the temperature dependent adsorption data. The spontaneity, feasibility and nature of adsorption process has also been evaluated using above mentioned parameters.

2.6. Reusability Study

The reusability of the resultant OBH-co-AA copolymer was examined by several cycles of adsorption desorption for Co (II) ions. After each adsorption experiment, the metal-loaded copolymer was isolated by filtration and washed with distilled water to eliminate unbound ions. Desorption was performed in dilute acidic solution (0.1 M HCl) and the metal ions bound to the copolymer were easily released from its surface. The regenerated copolymer was washed, dried, and used in upcoming cycles of adsorption under simply the same conditions. This process was repeated several times to check stability and the regeneration efficiency of the copolymer.

3. RESULTS AND DISCUSSIONS

3.1. Batch Adsorption Study

The amount of Co (II) ions in aqueous solution was measured by UV-Visible spectrophotometer and used to evaluate the adsorption properties of OBH-co-AA copolymer. A stock solution (500ml) of cobalt sulfate hepta hydrate was prepared, from which standard solutions of different concentrations (e.g. 1, 3, 5, 7, 9, 15, 20, 25, 30, 35, 50) were prepare for making the calibration curve. The absorbance of these standards were determined at their 511 λmax for Co (II) using 1 cm quartz cuvettes with distilled water as the reference. The combination of the absorbance-concentration (calibration curve) also has shown a linear relation by Beer-Lambert law. In adsorption experiments, 50 mg of copolymer was added to $CoSO_4.7H_2O$ solutions of various concentrations and then shaken under controlled conditions. The

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

absorbance of the supernatant was determined at equilibrium, and metal ion concentration in solution was held to be the residual one from analytic calibration graph. These parameters calculated provide the necessary information for assessing the effect of initial ion concentration, pH, adsorbent dosage, contact time and temperature on adsorption efficiency and capacity. Through this systematic methodology, a legitimate estimation of the copolymer effectiveness in Co (II) removal was accomplished and served as the stage for future investigation on kinetic and isothermal modeling.

3.2. Point of Zero Charge (pHpzc) and pH Effect

The surface charge properties of the Ocimum basilicum-acrylic acid copolymer and their impact on Co(II) adsorption was evaluated through pHpzc measurements and pH-dependent Co(II) adsorption studies. Such parameters are important for investigation of the electrostatic interactions between the surface of adsorbent and metal cations in aqueous solution.

Point of zero charge is the pH at which net surface charge on adsorbent is 0. It was observed by the pH_f versus pH_i diagram [33]. According to Fig. 1(a), the point where linear plot intersects with pHf = pHi line is at a value of pH = 5.5, representing the pHpzc of copolymer.

At pH < 5.5, the surface of the copolymer is preferentially positive charged owing to protonation of carboxyl and hydroxyl groups. Under such conditions, the electrostatic repulsion between positively charged surface and Co (II) ions prevents efficient adsorption. On the other hand, at pH values higher than 5.5 de protonation of carboxylic acid groups yields negatively charged sites, which contribute to increased electrostatic attraction towards Co(II) ions. The relatively small pH pzc is due to the presence of acidic functional groups introduced by acrylic acid grafting, proving that surface charge control is one of the key points in adsorption mechanism.

The influence of solution pH on the removal capacity for Co(II) was determined at various pH levels ranging from 2 to 10, as shown in Fig. 1(b). Such an adsorption capacity is highly pH dependent. The minimal adsorption capacity occurs at low pH values (pH 2-3). This is due to large amount of H^+ ions which competes with Co (II) ion for the available adsorption sites and the metal uptake occurs through surface protonation. At pH 3, which is probably due to the number of ionizable group on the adsorbent, carboxylic groups in the membrane still have positively charged surface and progressive increase de protonation to produce more negative binding site.

The pHpzc value is slightly lower to the point (6), where the maximum adsorption capacity was found. This in turn, indicates that electrostatic attraction and surface complexation become more favorable for slightly acid to near neutral pH. At this pH, Co(II) ions are capable of coordinately binding with the carboxylate and hydroxy groups on the copolymer surface. At pH over 6, a slow decline in adsorption capacity is found at higher pH. This decrease could be due to the initiation of Co(II) hydrolysis and partial precipitation as cobalt hydroxide species, thereby lowering free Co(II) ion concentration for adsorption. Also, over deprotonation can alter surface chemistry and hinder uptake.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

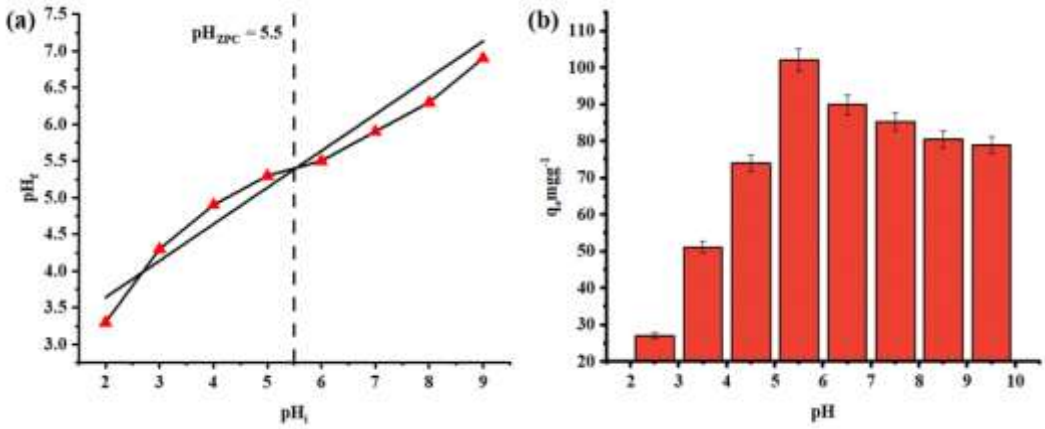


Fig.1. (a) Point of zero charge (pHzpc) of the copolymer at pH 5.0 showing surface charge transition (b) Effect of pH on Co (II) sorption, with maximum uptake at pH 6.

3.3. Effect of Sorbent Dose

Influence of sorbent dose on the adsorption capacity of Co(II) ions using the Ocimum basilicum-acrylic acid copolymer is presented in Fig. 2(a). the value of qe increased rapidly between 20 and 50 mg sorbent dose with a maximum value of about 108 mg/g. This enhancement can be ascribed to the more active adsorption sites, such as carboxyl and hydroxyl functional groups, facilitating further interaction with and complexation of Co(II) ions. Nevertheless, an additional increase of sorbent dose above 50 mg led to a slight decrease in adsorption yield. The decrease may be attributed to the clustering and superposition of adsorptive sites at high dosages, which apparently reduces the effective surface area as well as unoccupied binding sites. Moreover, an excessive amount of sorbent could lead to active sites being partially blocked and the metal uptake per unit mass decreases. These findings suggest that the best sorbent dose under investigation is 50 mg for effective adsorption of Co(II).

3.4. Effect of Initial Co(II) Concentration

Fig. 2(b) shows the effect of Co(II) initial concentration on copolymer adsorption capacity. The dosage presented a positive impact on the adsorption and the maximum adsorption capacity increased markedly when Co(II) concentration was raised from 20 to 60 mg L^{-1}, which can be interpreted as higher driving force for mass transfer at high concentrations. A smaller number of active sites get occupied at low concentrations due to less availability of Co(II) ions present in the solution, leading to lower adsorptive capacity. With an increase in the concentration, the possibility of Co(II) ion collision with sorbent surface was much higher and improved adsorption. At 60 mg L^{-1} and higher, the adsorption capacity saturated due to saturation of the available adsorption sites on the surface of copolymer. This indicates that copolymer coverage of Co(II) ions is achieved and verifies the limited number of available binding sites present in the co polymer frame work. The plateau corresponds to the equilibrium adsorption where uptake does not change with metal ion concentration.

3.5. Effect of Contact Time

The impact of contact time on Co(II) adsorption by the Ocimum basilicum–acrylic acid copolymer was shown in Fig. 2(c). An immediate rise in adsorption capacity was observed within the early period of the process, in particular during the first 60 min that evidences a rapid Co(II) ion uptake. This fast initial adsorption is due to the existence of many available and accessible surface active sites on the sorbent. Then, adsorption rate decreases with the increasing of time, the adsorption equilibrium is reached after about 60 min (105 mg g^{-1}). The decline in adsorption rate at the later stages may be attributed to the progressive coverage of active sites and increased resistance to mass transfer as Co(II) ions diffuse into the internal regions of polymer. The attainment of equilibrium suggests that the adsorption process

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

consists of both surface adsorption and intra particle diffusion.

3.6. Effect of Temperature

The effect of temperature on Co(II) adsorption by the copolymer is shown in Fig. 2(d). The adsorption ability was enhanced as the temperature went from 280 to 310 K, maximum at about 92 mg g^{-1}. This phenomenon suggests that the adsorption is an endothermic process, because higher thermal energy will provide great mobility to Co(II) ions and form stronger ion-adsorbent phase interaction via contact with the metal ions and functional groups in copolymer structure. Increased temperature could also promote pore size and Co(II) penetration into the polymer matrix. However upon further increase in temperature above 310 K, there is a slight reduction in adsorption capacity that could be assigned to the partial disruption of the intermolecular forces between absorbent-absorbate or structural modification within polymer network at higher temperatures. This tendency indicates the existence of an optimum temperature that is obtained at the maximum adsorption of Co(II).

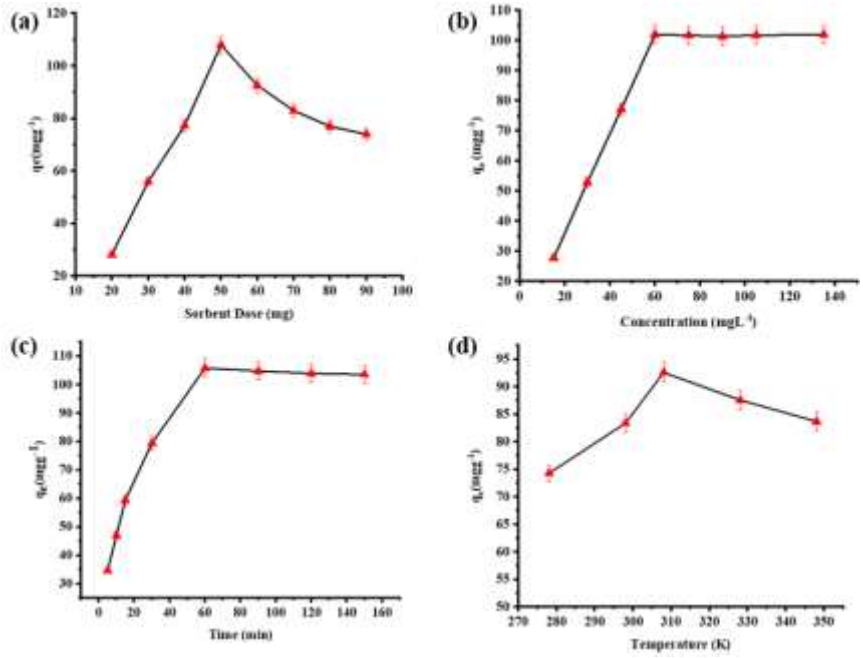


Fig. 2. Effect of experimental conditions on adsorption of Co (II) onto OBH-co-AA: (a) Effect of sorbent dose, (b) Effect of the initial concentration, (c) Effect of contact time and (d) Effect of temperature.

3.7. Isotherm Models

The isotherm models used to analyze the suitability of various theoretical models in explaining the equilibrium adsorption behavior of Co(II) ions on the Ocimum basilicum-acrylic acid copolymer was the adsorption isotherm modeling. The linearity in the individual isotherm plots is a measure of the goodness of the corresponding model to the experimental data of the adsorptions.

3.7.1. Freundlich Isotherm Model

Freundlich isotherm model explains the adsorption on non-homogeneous surfaces and it assumes that there are multiple layers through which adsorption occurs and the energies of adsorption are non-uniformly distributed [34]. The linear form of the Freundlich equation takes the form:

$$\log q_e = \log K_F + \frac{1}{n}\log C_e \qquad (3)$$

in which, qe (mg g^{-1}) is the quantity of Co(II) adsorbed at equilibrium, Ce (mg L^{-1}) is the concentration of Co(II) at equilibrium in solution, K_F (mmg^{-1})is Freundlich constant which shows the adsorption capacity as well as sorption maxima and n is is a dimensionless constant associated with this model for explaining the sorption intensity and favorable (0.1 <

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

1/n < 1) or unfavorable (1/n > 2) of sorption process and 1/n, is the heterogeneity factor.

From graph Fig. 3(a), Co(II) adsorption result is 0.6112 which falls within the range of favorable adsorption (0 < 1/n). It means that the copolymer surface has energetically diverse sites of adsorption and Co(II) ions have a tendency to adsorb at low concentrations. The Freundlich constant K_F = 6.4881 mg g^{-1} indicates the adsorption capacity of the copolymer and proves the positive affinity of the copolymer towards Co (II) ions. Nonetheless, the correlation coefficient (R^2 = 0.8672) is a little less than the correlation coefficient of other models and indicates that surface heterogeneity is indeed an important variable, but the Freundlich model cannot fully explain the adsorption equilibrium. The implication of this deviation is that adsorption is not strictly multilayer and saturation of sites is important at high concentrations.

3.7.2. Langmuir Isotherm Model

The Langmuir isotherm operates on the basis of monolayer adsorption on a homogeneous surface and has a fixed number of binding sites of the same type and in the absence of an interaction between the adsorbed species [35]. The Langmuir equation is linearized and is presented as:

$$\frac{C_e}{q_e} = \frac{1}{Q_{\max} \times b} + \frac{C_e}{Q_{\max}} \quad (4)$$

Qmax is the maximum adsorption capacity (mgg^{-1}), b is the Langmuir isotherm constant related to the adsorption energy (Lmg^{-1}) and Ceis the equilibrium concentration of Cu (II)in solution (mgL^{-1}).

Maximum monolayer adsorption capacity of the present model in Fig. 3(b) is Qmax =150.38 mg g^{-1} which means that the number of active sites is high to bind Co(II). This value is high, and it indicates high adsorption performance of the grafted copolymer that is made out of acrylic acid. The Langmuir affinity constant b =0.0201mg L^{-1} indicates intense contacts between Co(II) ions and functional groups accessible on the copolymer surface. The sorption of the Co (II) was found to be favorable in nature onto the copolymer (acrylic acid copolymer system) and was compared by the dimensionless separation factor R_L derived from the Langmuir model is defined as:

$$R_L = \frac{1}{1 + bC_i} \quad (5)$$

Where b is the Langmuir constant and Ci represent the initial Co (II) concentration. The value of the separation factor RL = 1.3109 indicates that the adsorption characteristics will be favorable in the studied concentration. Such a large regression coefficient (R^2 = 0.9012) proves that the mono-layered adsorption is one of the most prominent properties of the system.

These findings reveal that Co(II) ions favor selectively binding energetically compatible binding sites, which are probably related to deprotonated carboxylate moieties added to acrylic acid through modification. When these locations become occupied, no more adsorption can take place in agreement with Langmuir assumptions.

3.7.3. Temkin Isotherm Model

Temkin isotherm model takes the interaction of adsorbent and adsorbate into consideration and that the heat of adsorption will reduce linearly with the surface coverage [36]. The Temkin Linear equation will be given as:

$$q_e = B \ln A + B \ln C_e \quad (6)$$

The linear plot of qe vs. lnCe indicates a desirable fit to the model of Temkin as shown in Fig. 3(c). Interaction energy is an important parameter in the adsorption mechanism by the powerful correlation of the Temkin model with the experimental data (R^2 = 0.9323). The heat of adsorption is associated with the Temkin constant B = 42.151. The balance binding value A=0.1569 is yet another affirmation of Co(II) ions affinity on the copolymer surface. The parameter bT=58.778 denotes that the adsorption energy is found to decrease gradually with increasing surface coverage which is characteristic in chemisorption processes.

The reason why Co (II) adsorption is not simply physical as the good agreement with the Temkin model reveals that because of the adsorption of the Co(II) ion must contain chemical interaction with the surface functional groups including electrostatic attraction and coordination bonding.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

3.7.4. Dubinin -Radushkevich Isotherm Model

Dubinin-Radushkevich (D-R) isotherm model is model that is applied to differentiate between physical and chemical adsorption and assess the mechanisms of pore-filling [37] . The linearized D-R equation is:

$$\ln q_e = \ln X_m - \beta\varepsilon^2 \quad (7)$$

$$\varepsilon^2 = RT \ln\left(1+\frac{1}{C_e}\right) \quad (8)$$

$$E = \frac{1}{\sqrt{-2\beta}} \quad (9)$$

Where Xm is the maximum adsorption capacity (mgg^{-1}), β is the constant related to the adsorption energy (mol^2/J^2), ε is Polanyi potential calculated through ε = RT ln(1+1/Ce).

The linear relation between lnqe and ε^2, as shown in Fig. 3(d). Theoretical saturation capacity of this model (Xm = 132.77 mg g^{-1}) is similar with Langmuir model (Qmax), which implies that the two models are consistent with each other and the adsorption capacity of the copolymer was high.

The average energy of adsorption E=7.0951 kcal mol^{-1} is in the regime established as being chemisorption and ion-exchange, as opposed to weak physical adsorption. This energy range is indicative of the strong interaction of Co(II) ions and the functional groups of the copolymer by way of coordination and/or an electrostatic interaction. The large correlation coefficient (R^2 = 0.9229) demonstrates that the contribution of pore filling and the interactions between chemicals to the adsorption process is significant which is predictable in an absorber based on a porous and functionalized polymer.

3.7.5. Elovich Isotherm Model

Elovich isotherm Elovich isotherm model is usually used on surfaces that are very heterogeneous and where adsorption energy varies exponentially with respect to the site. Elovich isotherm linearized equation can be formulated as following:

$$\ln\frac{q_e}{C_e} = \ln K_E Q_{\max} - \frac{q_e}{Q_{\max}} \quad (10)$$

K_E is the equilibrium constant of the Elovich reaction and qm is the maximum adsorption capacity.

The Elovich isotherm was used to describe Co (II) adsorption onto acid copolymer, by plotting ln(qe/Ce) against qe as shown in Fig. 3(e). The Elovich model has the largest correlation coefficient (R^2 = 0.9333), which is with the highest confidence to the experimental data. Strong surface heterogeneity is indicated by the Elovich parameters with the changes in activity of the surface sites being progressive. This is an indication that adsorption is not uniform but site rather tapping sites with varying activation energies which changes as the adsorption continues. The fact that the Elovich model fits very well substantially points into the conclusion that Co(II) adsorption to the Ocimum basilicum-acrylic acid copolymer is regulated mainly by chemisorption, on energetically heterogeneous sites.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

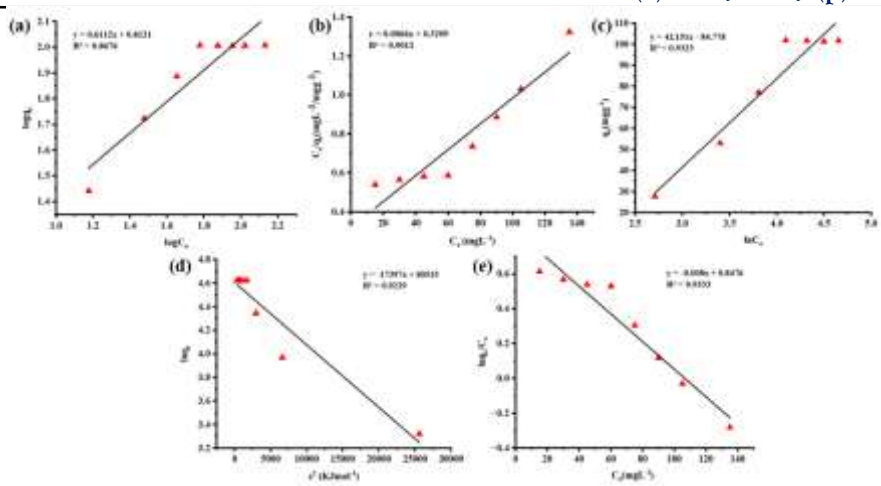


Fig. 3. (a) Freundlich, (b) Langmiur, (c) Temkin, (d) D-R models and (e) Elovich isotherm models are explain Co II adsorption onto the OBH-co-AA.

Table 1 Various isothermal parameters obtained from isothermal modelling on Co (II) adsorption on OBH-co-AA.

Isothermal models	Parameters	Units	Co (II)
Freundlich Isotherm	1/n	~~~	0.6112
	$k_F = Q_{max}$	mgg^{-1}	6.4881
	R^2	~~~	0.8676
Langmuir Isotherm	Q_{max}	mgg^{-1}	150.38
	b	mgL^{-1}	0.0201
	R_L	~~~	1.3109
	R^2	~~~	0.9012
Temkin Isotherm	B	~~~	42.151
	A	~~~	0.1569
	b_T	~~~	58.778
	R^2	~~~	0.9323
Dubinin-Radushkevich Isotherm	β	kJ^2mol^2	-7.0218
	$X_m = Q_{max}$	mgg^{-1}	132.77
	E	$kcalmol^{-1}$	7.0951
	R^2	~~~	0.9229
Elovich Isotherm	β	~~~	-125
	α	~~~	$-7.755*10^{-49}$
	R^2	~~~	0.9333

3.8. Kinetic Models

The kinetic modeling of adsorption was conducted to explain the rate-limiting processes and the chemical mechanism involved in Co(II) adsorption to the chemically modified Ocimum basilicum-acrylic acid copolymer. Experimental kinetic data were modeled using various popular kinetic models and the quality of the model was determined using the linear regression coefficients as well as consistency between the calculated and experimental adsorption capacities.

3.8.1. Pseudo-First-Order Kinetic Model

The pseudo-first-order (PFO) kinetic model was initially suggested by Lagergren, which suggests the rate of adsorption is proportional to the amount of unoccupied adsorption sites [38]. The PFO model in the linearized form is represented by the following:

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

$$\log(q_e - q_t) = \log q_e - \frac{k_1}{2.303} t \qquad (11)$$

Where qt and qe are the adsorption capacities (mgg^{-1}) at time t and equilibrium respectively and k_1(min^{-1}) is the PFO rate constant

The PFO model Fig. 4(a) also provided a comparatively low equilibrium adsorption capacity (qe = 17.426 mgg^{-1}) and a small rate constant (k_1= 0.0166) and this determined a slow adsorption rate. The correlation coefficient (R^2 = 0.7123) is not very strong which indicates a loose agreement between the model predictions and the experimental data. This difference indicates that adsorption of Co(II) is not a one-step process under the regulation of physisorption and that the PFO approach can be not applied to explain the average adsorption characteristics of the copolymer.

3.8.2. Pseudo-Second-Order Kinetic Model

The pseudo-second-order (PSO) kinetic model supposes that the adsorption process is a chemisorption, i.e. a valence force or a sharing of electrons or an ion exchange between the adsorbent and the adsorbate [39]. The PSO equation in the linearized form is as follows:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \qquad (12)$$

Where k_2 ($gmg^{-1}min^{-1}$) is the PSO rate constant. Fig. 4(b) shows that, the PSOmodel is characterized by a very high correlation coefficient (R^2 = 0.9958) and a very good fit to experimental data. The estimated equilibrium adsorption capacity (qe=114.32 mg^{-1}) is remarkably similar to the observed one, which proves the validity of this model. The rate constant (k_2 = 0.0007 g $mg^{-1}min^{-1}$) indicates kinetic strength of the interaction between Co(II) ions and the surface of the copolymer. The overall high fitness of the PSO model suggests that the process of adsorption is dominated by chemisorption, whereby exchange of electrons or sharing these electrons takes place between Co(II) ions and functional groups, e.g., carboxylate functional group that is added by acrylic acid modification.

3.8.3. Intraparticle Diffusion Model

To examine the rate-limiting step of the process, intraparticle diffusion (WeberMorris) model was utilised in order to determine whether diffusion through the polymer matrix is the rate-limiting step [39] . The model is expressed as in linear form:

$$q_t = k_{idm} t^{1/2} + C \qquad (13)$$

Where k_{idm} ($mgg^{-1}min^{-1/2}$) is the intra particle diffusion constant and C represents thickness of boundary layer. The plot of intraparticle diffusion for Co (II) adsorption Fig. 4(c). indicates that two-stage adsorption process occurs and is seen by two different diffusion rate constants. At the first stage, the rate constant of diffusion is highly correlated with the diffusion rate constant (R^2 = 0.9961) confirming the fast rate of external surface adsorption and boundary layer diffusion. Intercept value (C = 7.2115mgg^{-1}) presents a huge boundary layer influence at this phase. The diffusion rate constant of the second stage is actually much lower and its correlation coefficient (R^2 = 0.9863) is somewhat less, although quite large. This increase in the value of the intercept (C=109.74 mg g^{-1}) indicates that the mass transfer into the internal pores of the copolymer matrix becomes more resistant. It is verified by the fact that the intraparticle diffusion plots are not going through the origin meaning that the intraparticle diffusion is not the only rate-limiting step.

3.8.4. Elovich Kinetic Model

Elovich kinetic model is usually applied to those systems wherein adsorption is controlled by chemisorption and where surfaces are heterogeneous [40]. Elovich linearized equation is given as:

$$q_t = \frac{1}{\beta}\ln(\alpha\beta) + \frac{1}{\beta}\ln t \qquad (14)$$

Where α (mgg^{-1} min^{-1}) is the initial adsorption rate and β (gmg^{-1})-which is related to the desorption. The slope (1/β) is moderate in plot of qt versus t lnt as shown in Fig. 4(d). There was moderate correlation with the experimental data to the Elovich model as shown with the correlation coefficient of R^2 = 0.8379. The adsorption rate indicates that Co(II) ions are rapidly adsorbed in the early stage of the adsorption

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

process, whereas the Elovich constant indicates heterogeneity and the distribution of activation energy. The fact that this model is applicable and shows that adsorption is occurring on an irregular surface, and those processes are the chemisorption processes, although this model is not detailed enough to explain the adsorption kinetics like the PSO one.

3.8.5. Pore Diffusion Model

The effect of internal diffusion resistance on the adsorption of Co(II) ions onto Ocucaje basilicum-acrylic acid copolymer has been determined by the pore diffusion model [41]. The linear form of this model is expressed as:

$$q_t = \ln k_B + \alpha_B \ln t \quad (15)$$

Where K_B (mgg^{-1}) denoted the Bangham Constant whose value described the sorbtion maxima, α is constant for pore diffisuin whose value should be less that unity, (qt / q = 1) is the film diffusion constant (min^{-1}). The film/pore diffusion plot in Fig. 4(e).

The linearity between the pore-diffusion model indicates a correlation coefficient of R^2 = 0.9298indicating the relevance of internal diffusion in the adsorption process. The determined parameter (KB = 1321.6 mgg^{-1}) represents a large adsorption capacity due to fluid movement pore within the pore structure, and the diffusion constant explains slow movement of Co(II) ions to the inside pore structure. These findings affirm that pore diffusion plays a major part in adsorption at the later stages, but should occur concomitant to surface adsorption and chemisorption as opposed to playing a controlling role exclusively.

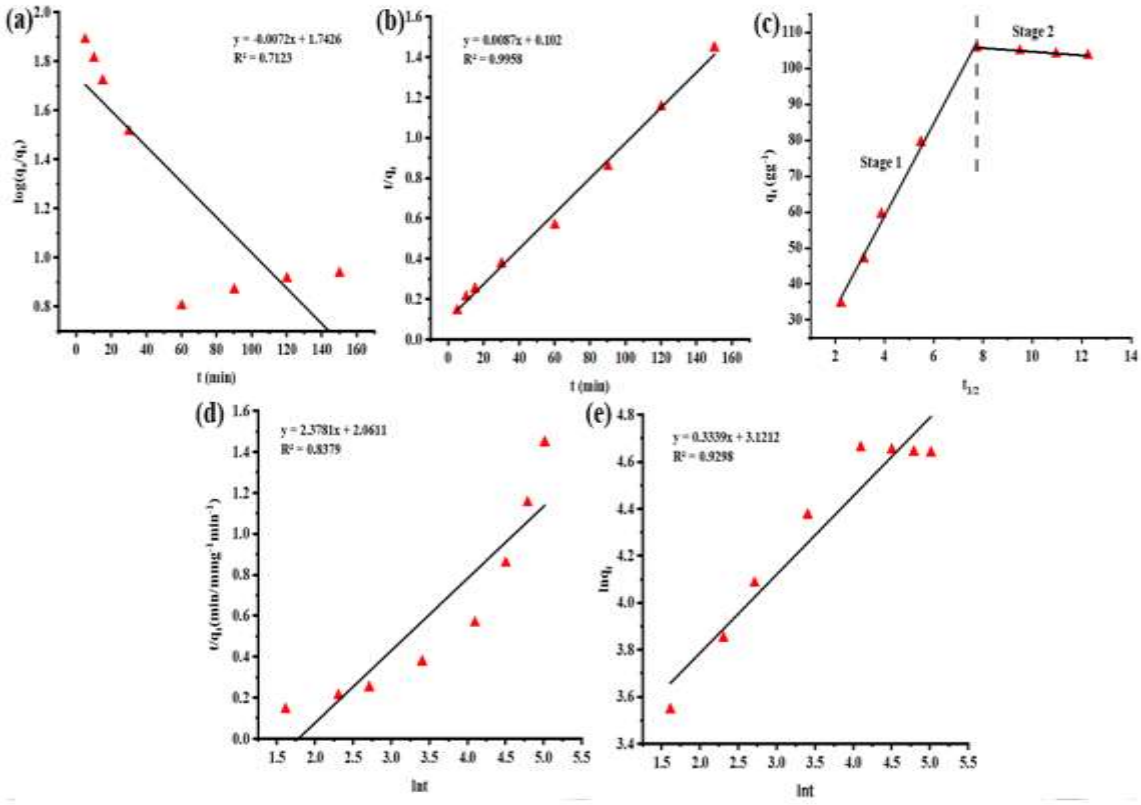


Fig. 4. Kinetic model plots for Co (II) adsorption onto OBH-co-AA (a) PFO, (b) PSO, (c) intraparticle diffusion, (d) Elovich and (e) pore diffusion models

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

Table 2. Various kinetics parameters obtained from kinetic modelling on Co (II) adsorption on OBH-co-AA.

Kinetic Models	Parameters	Units	Co (II)
Pseudo-first-order	$q_e = Q_{max}$	mgg^{-1}	17.426
	k_1	$gmg^{-1}min^{-1}$	0.0166
	R^2	~~~	0.7123
Pseudo-second-order	$q_e = Q_{max}$	mgg^{-1}	114.32
	k_2	$gmg^{-1}min^{-1}$	0.0007
	R^2	~~~	0.9958
Intraparticle diffusion	$k_{idm,1}$	$mgg^{-1}min^{-0.5}$	12.911
	$R^2{}_{,1}$	~~~	0.9961
	C	mgg^{-1}	7.2115
	$k_{idm,2}$	$mgg^{-1}min^{-0.5}$	-0.5133
	$R^{2,}{}_2$	~~~	0.9863
	C	mgg^{-1}	109.74
Elovich	α	~~~	5.6576
	β	$mgg^{-1}min^{-1}gmg^{-1}$	0.4205
	R^2	~~~	0.8379
Pore-Diffusion	$K_B = Q_{max}$	mgg^{-1}	1321.6
	α_B	~~~	0.3339
	R^2	~~~	0.9298

3.9. Thermodynamic study

The major thermodynamic parameters that controlled the adsorption of the Co(II) ions on Ocimum basilicum-acrylic acid copolymer were measured to clarify the spontaneity, energy profile and the nature of the process mechanistic. The distribution coefficient (Kc) was obtained by the ratio of adsorption capacity to balance concentration:

$$K_c = \frac{q_e}{C_e} \quad (16)$$

The van't Hoff equation was used to analyze the temperature dependent equilibrium constant (Kc) based on the standard enthalpy change (ΔH°) and entropy change (ΔS°) and was expressed as follows:

$$\ln K_c = \frac{\Delta S^o}{R} - \frac{\Delta H^o}{RT} \quad (17)$$

Where R is the gas constant which has 8.314 $J \cdot mol^{-1} \cdot K^{-1}$ value, T is temperature and Kc is equilibrium constant. Adsorption isotherms at various temperatures (298, 308, 318 K) were used to determine the values of Kc. Fig. 5 of a plot of lnKc/1/T gave a very linear behavior with a high correlation coefficient (R^2 = 0.9955) which validates the validity of the van't Hoff model to describe this system. Based on the slope and intercept of this plot, the thermodynamic parameters were derived as summarized in Table 3.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

Table 3. Thermodynamic values of Co (II) adsorbed onto OBH-co-AA.

Model	Parameters	Units	Co (II)
Thermodynamic	$\Delta H°$	($kJmol^{-1}$)	14.03
	$\Delta S°$	($Jmol^{-1}K^{-1}$)	61.01
	$\Delta G°$	($kJmol^{-1}$)	4.146
	R^2		0.9955

The endothermic nature of the adsorption process is demonstrated by the positive figure of ΔH° (+14.03kJ /mol). This implies that energy is drawn in the environment to facilitate Co (II) ions binding with the active sites of the copolymer. The designation of such endothermicity may be in reference to particular chemical interactions like the dehydration of hydrated metallic cation before adsorption or the formation of the strong inner-sphere complexes with the functional groups on the surface of adsorbents. At the same time, the positive number 61.01 J mol^{-1} K^{-1} as 83.9877 -101 JK^{-1} indicates a substantial rise in entropy in the solid liquid interface adsorption process. The more random contribution can be ascribed either to the removal of several, highly ordered, water molecules in the hydration shell of the Co(II) ions when they are moved out of the bulk aqueous phase into the copolymer side. The fact that these water molecules are emitted into the solution makes the system in the line of greater disorder, which is one of the major driving forces behind the adsorption process. The spontaneity and viability of adsorption reaction were evaluated through the calculation of the standard Gibbs free energy change (ΔG°) based on the following equation:

$$\Delta G^o = -RT \ln K_c \quad (18)$$

Negative values of ΔG° of temperatures considered during the study of the phenomenon of adsorption (e.g., -4.146 kJ /mol^{-1} at 298 K) prove that adsorption process under investigation is spontaneous and thermodynamically advantageous. The magnitude of ΔG° allows on average of physisorption, implying that the adsorption process can be accompanied by a part of physical forces (electrostatic attraction), and a relatively weak chemical interaction. In addition, the thermodynamic findings suggested by the van't Hoff analysis are supported with the help of the observed rise in adsorption capacity under an increase in temperature, which is characteristic of the endothermic character of the process.

To conclude, considering the results of the thermodynamic analysis presented in this paper, adsorption of Co(II) onto the Ocimum basilicum-acrylic acid copolymer is spontaneous (ΔG°), endothermic (ΔH°) and entropy-driven (Δ°S). The positive change in the entropy is the dominant one that facilitates the spontaneity of the reaction overcoming the endothermicity of enthalpy change. The insights can be used to scale the process because they indicate that slightly higher temperatures can increase efficiency in the removal.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

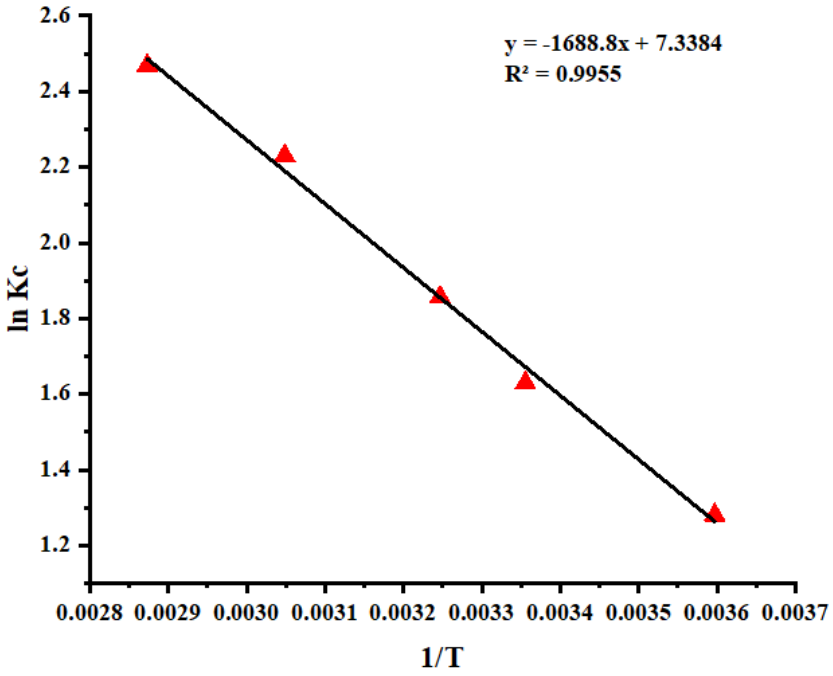


Fig.5. Van't Hoff plot of Co (II) adsorption onto OBH-co-AA

3.10. Re-Regeneration and Reuse Investigation.

In the practice of water treatment, regeneration and reusability of an adsorbent are parameters crucial in cost-effectiveness and ecological friendliness of an adsorbent. The regeneration performance of chemically modified Ocimum basilicum-acrylic acid copolymer in the current study was determined using the assessment of the capability of the de-contamination agent to repeately remove Co(II) ions in aqueous solutions. Recycleability of the copolymer was studied by adsorption-desorption cycle. The Co (II) loaded copolymer was regenerated after every adsorption step with the help of a suitable desorbing agent and then it was washed with distilled water before being reused in consequent adsorption experiments under the same conditions.

The outcomes revealed that the copolymer exhibited a high Co(II) uptake capacity in several cycles with minimal variation in the adsorption capacity occurring after repeated usage. The stability observed depicts that active functional groups that have been added to the acrylic acid modification namely the carboxylate functional groups that cause ion exchange and surface complexation are intact in structure and are actively involved in the reversible Co(II) adsorption. The FTIR analysis used in the results of pre and post regeneration indicated no notable changes in the characteristic functional group peaks which justifies this conclusion. The slight reduction in adsorption efficiency could be explained by the active sites occupying part of the active sites or to minor structural pressure within the polymer network in repetitive adsorption desorption exchanges. Altogether, the great regeneration potential, and long-term adsorption activity prove that the Ocimum basilicum-acrylic acid copolymer is a cost-effective, long-lasting, and eco-friendly adsorbent. These properties render it a prospective substance in the process of practical treatment ofedulctic contaminated water.

4. Conclusion

Grafting of acrylic acid on Ocimum basilicum hydrogel with free-radical copolymerization resulted in the preparation of a sustainable and efficient bio-based adsorbent. The bifunctional carboxyl functional groups incorporated into it substantially increased the negativity and adsorption strength of the copolymer with Co(II) ions. The point of zero charge analysis indicated 5.5 as the pHzc, whereas the pH-dependent uptake of the metal indicated the maximum uptake at slightly acidic to near-neutral pHs. One of the studies

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

examining batch adsorption indicated that the removal of Co(II) was highly affected by the operational parameters with maximum adsorption capacities reported at a sorbent dose of 50 mg, an initial concentration of Co(II) of 60mg L– 1 and a contact time with 60 min. The Langmuir, Temkin and Elovich isotherm models were the most appropriate ones in representing the equilibrium adsorption characteristics, which implies a major monolayer adsorption to the energetically heterogeneous surfaces. The Langmuir adsorption capacity (150.38 mg g -1) is high and this indicates that the copolymer has a high metal-binding capacity. The adsorption process was proved to be chemisorption as supported by kinetic studies that demonstrated a great deal of agreement with PSO model. Analysis of intraparticle and pore diffusion showed internal diffusion at later stages to be associated with adsorption but not the only rate limiting step. Thermodynamic analysis has shown that Co(II) adsorption on the OBAA copolymer is spontaneous, endothermic and entropy-driven, which may improve the adsorption process under relatively high temperatures. In general, the obtained results predetermine Ocimum basilicum-acrylic acid copolymer as an efficient, ecologically safe, and cost-efficient adsorbent in cobalt ion adsorption in a liquid environment. The study is a positive contribution to the creation of the green material in the case of heavy-metal remediation and also emphasize on the prospects of agricultural hydrogel based polymers in realistic water treatment.

REFERENCES

[1] Irfan, J., Ali, A., Hussain, M.A., Abbas, A., Haseeb, M.T., Naeem-ul-Hassan, M., Azhar, I., Hussain, S.Z. and Hussain, I., 2024. Chemical modification of Aloe vera leaf hydrogel for efficient cadmium-removal from spiked high-hardness groundwater. *International Journal of Biological Macromolecules*, *259*, 128879.

[2] Abbas, A., Siddique, A.B., Batool, R., Sher, M., Irfan, M.I. and Abbas, M.A., 2023. Isothermal and kinetic modeling for uptake of heavy metal ion from aqueous solution using succinylated polysaccharide. *Starch-Stärke*, *75*(5-6), 2200191.

[3] Adsorptive removal of Ni (II) and Co (II) from aqueous solution using succinate-bonded polysaccharide isolated from Artemisia vulgaris seed mucilage

[4] Abbas, A., Hussain, M.A., Sher, M., Abbas, N.S. and Ali, M., 2017. Modified hydroxyethylcellulose: a regenerable super-sorbent for Cd2+ uptake from spiked high-hardness groundwater. *Cellulose Chem. Technol*, *51*, 167-174.

[5] Khan, F., Siddique, A.B., Irfan, M.I., Hassan, M.N.U., Sher, M., Alhazmi, H.A., Qramish, A.N., Amin, H.M., Qadir, R. and Abbas, A., 2024. Maleated hydroxyethyl cellulose for the efficient removal of Cd (II) ions from an aqueous solution: isothermal, kinetic and regeneration studies. *Water, Air, & Soil Pollution*, *235*(8), 536.

[6] Ali, A., Hussain, M.A., Abbas, A., Haseeb, M.T., Azhar, I., Muhammad, G., Hussain, S.Z., Hussain, I. and Alotaibi, N.F., 2023. Succinylated Salvia spinosa hydrogel: Modification, characterization, cadmium-uptake from spiked high-hardness groundwater and statistical analysis of sorption data. *Journal of Molecular Liquids*, *376*, 121438.

[7] Hussain, M.A., Abbas, A., Yameen, E., Ali, A., Muhammad, G., Hussain, M. and Shafiq, Z., 2022. Adsorptive removal of Pb2+ and Cu2+ from aqueous solution using an acid modified glucuronoxylan-based adsorbent. *Desalination and Water Treatment*, *248*, 163-175.

[8] Ali, A., Hussain, M.A., Abbas, A., Khan, T.A., Muhammad, G., Haseeb, M.T. and Azhar, I., 2022. Comparative isoconversional thermal analysis and degradation kinetics of Salvia spinosa (Kanocha) seed hydrogel and its acetates: a potential matrix for sustained drug release. *Cellul. Chem. Technol*, *56*(3-4), 239-250.

[9] Ali, A., Akram, A., Bakar, M.A., Amin, H.M., Zohra, L., Abbas, A., Sher, M., Hussain, M.A., Haseeb, M.T. and Imran, M., 2025. A model batch and column study for Cd (II) uptake using citric acid cross-linked Salvia spinosa hydrogel: Optimization through Box-Behnken design. Journal of Industrial and Engineering Chemistry, 151, 746-761.

[10] Hussain, A., Fatima, S., Abbas, A., Ali, A., Amin, M., Muhammad, G. and Sher, M., 2023. Removal of Cr (III) and Ni (II) from aqueous

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

solution using a mixed cellulose ether-ester hydroxyethylcellulose adipate. Desalination and Water Treatment, 283, 153-163.

[11] Hussain, M.A., Gul, S., Abbas, A., Ali, A. and Alotaibi, N.F., 2021. Chemically modified rhamnogalacturonans from linseed: a supersorbent for Cd2+ and Pb2+ uptake from aqueous solution. Desalination and Water Treatment, 221, 163-175.

[12] Shehzad, M.K., Ali, A., Qasim, S., Mumtaz, A., Hussain, M.A., Fawy, K.F., Nishan, U., Azhar, I., Abbas, M.A. and Abba, A., 2025. Sustainable remediation of cadmium using succinate-functionalized glucoxylan from chia (Salvia hispanica) seeds hydrogel. Journal of Industrial and Engineering Chemistry. https://doi.org/10.1016/j.jiec.2025.10.034

[13] Ali, A., Haseeb, M.T., Hussain, M.A., Tulain, U.R., Muhammad, G., Azhar, I., Hussain, S.Z., Hussain, I. and Ahmad, N., 2023. A pH responsive and superporous biocomposite hydrogel of Salvia spinosa polysaccharide-co-methacrylic acid for intelligent drug delivery. RSC Advances, 13(8), 4932-4948.

[14] Ali, A., Hussain, M.A., Haseeb, M.T., Farid-Ul-Haq, M., Erum, A. and Hussain, M., 2024. Acute toxicity studies of methacrylic acid based composite hydrogel of Salvia spinosa seed mucilage: a potential non-toxic candidate for drug delivery. Cellulose Chemistry and Technology, 58(1-2), 45-53.

[15] Ali, A., Hussain, M.A., Haseeb, M.T., Tulain, U.R., Farid-ul-Haq, M., Tabassum, T., Muhammad, G., Hussain, S.Z., Hussain, I. and Erum, A., 2023. Synthesis, characterization, and acute toxicity of pH-responsive Salvia spinosa mucilage-co-acrylic acid hydrogel: A smart excipient for drug release applications. Reactive and Functional Polymers, 182, 105466.

[16] Ali, A., Hussain, M.A., Haseeb, M.T., Ashraf, M.U., Farid-ul-Haq, M., Tabassum, T., Muhammad, G. and Abbas, A., 2023. pH-responsive, hemocompatible, and non-toxic polysaccharide-based hydrogel from seeds of Salvia spinosa L. for sustained release of febuxostat. Journal of the Brazilian Chemical Society, 34, 906-917.

[17] Ali, A., Hussain, M.A., Haseeb, M.T., Bukhari, S.N.A., Tabassum, T., Farid-ul-Haq, M. and Sheikh, F.A., 2022a. A pH-responsive, biocompatible, and non-toxic citric acid cross-linked polysaccharide-based hydrogel from Salvia spinosa L. offering zero-order drug release. Journal of Drug Delivery Science and Technology, 69, 103144.

[18] Amjad, F., Ali, A., Hussain, M.A., Haseeb, M.T., Ajaz, I., Farid-ul-Haq, M., Hussain, S. Z. and Hussain, I., 2025. A superabsorbent and pH-responsive copolymer-hydrogel based on glucomannans from Ocimum basilicum (sweet basil): A smart and non-toxic material for intelligent drug delivery. International Journal of Biological Macromolecules, 315(2), 144452.

[19] Ali, A., Haseeb, M.T., Hussain, M.A., Muhammad, T., Muhammad, G., Ahmad, N., Alotaibi, N.F., Hussain, S.Z. and Hussain, I., 2022. Extraction optimization of a superporous polysaccharide-based mucilage from Salvia spinosa L. Cellulose Chemistry and Technology, 56, 957-969.

[20] Hussain, M.A., Shahzad, K., Ali, A., Haseeb, M.T. and Hussain, S.Z., 2025. Development of a novel smart bio-composite hydrogel based on dextran, citric acid, and glucoxylan for pH-dependent drug delivery and stimuli-responsive swelling and release. Polymers and Polymer Composites, 33, p.09673911251350240.

[21] Khatoon, M., Ali, A., Hussain, M.A., Haseeb, M.T., Muhammad, G., Sher, M., Hussain, S.Z., Hussain, I. and Iqbal, M., 2025. A chia (Salvia hispanica L.) seed mucilage-based glucoxylan-grafted-acrylic acid hydrogel: a smart material for pH-responsive drug delivery systems. Materials Advances, 6(8), 2636-2647.

[22] Hussain, M.A., Raees, N., Ali, A., Tayyab, M., Muhammd, G., Uroos, M. and Batool, M., 2025. Optimization of rhamnogalacturonan extraction from linseed using RSM and designing a pH-responsive tablet formulation for sustained release of ciprofloxacin. Cellulose Chemistry and Technology, 59, 547-558.

[23] Hussain, M.A., Taj, T., Ali, A., Haseeb, M.T., Hussain, S.Z., Muhammad, G. and Bukhari, S.N.A., 2025. Cross-Linking of Hydroxypropylcellulose With Flaxseed

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

Rhamnogalacturonans Using Citric Acid Produces a Hemocompatible Biocomposite for pH-Responsive Rifaximin Delivery. Journal of Applied Polymer Science, e57486.

[24] Hussain, M.A., Abbas, A., Yameen, E., Ali, A., Muhammad, G., Hussain, M. and Shafiq, Z., 2022. Adsorptive removal of Pb2+ and Cu2+ from aqueous solution using an acid modified glucuronoxylan-based adsorbent. Desalination and Water Treatment, 248, 163-175.

[25] Crini, G., 2005. Recent developments in polysaccharide-based materials used as adsorbents in wastewater treatment. *Progress in polymer science*, *30*(1), 38-70.

[26] Abbas, M.A., Hameed, S., Farman, M., Kressler, J. and Mahmood, N., 2015. Conjugates of degraded and oxidized hydroxyethyl starch and sulfonylureas: Synthesis, characterization, and in vivo antidiabetic activity. *Bioconjugate Chemistry*, *26*(1), 120-127.

[27] Russo, T., Fucile, P., Giacometti, R. and Sannino, F., 2021. Sustainable removal of contaminants by biopolymers: a novel approach for wastewater treatment. Current state and future perspectives. *Processes*, *9*(4), 719.

[28] Alharbi, H.M., 2024. Exploring the Frontier of Biopolymer-Assisted Drug Delivery: Advancements, Clinical Applications, and Future Perspectives in Cancer Nanomedicine. *Drug Design, Development and Therapy*, 2063-2087.

[29] Zabiszak, M., Nowak, M., Taras-Goslinska, K., Kaczmarek, M.T., Hnatejko, Z. and Jastrzab, R., 2018. Carboxyl groups of citric acid in the process of complex formation with bivalent and trivalent metal ions in biological systems. *Journal of inorganic biochemistry*, *182*, 37-47.

[30] Siddique, A.B., Shaheen, M.A., Abbas, A., Zaman, Y., Amin, H.M., Alam, M.M., Alharbi, N.K., Alshehri, F., Shami, A., Al-Joufi, F.A. and Ali, A., 2025. Sunlight-assisted greenly synthesised silver nanoparticles for highly selective mercury ion sensing, biomedical and photocatalytic applications. *International Journal of Environmental Analytical Chemistry*, 1-23.

[31] Waqar, I., Ahmad, N., Massey, S., Rehman, A.U., Ejaz, H. and Alsaidan, O.A., 2025. Preparation, characterization, and biological evaluation of Ocimum basilicum hemicellulose-based composites for wound healing. *Journal of Biomaterials Science, Polymer Edition*, 1-24.

[32] Al-Gethami, W., Qamar, M.A., Shariq, M., Alaghaz, A.N.M., Farhan, A., Areshi, A.A. and Alnasir, M.H., 2024. Emerging environmentally friendly bio-based nanocomposites for the efficient removal of dyes and micropollutants from wastewater by adsorption: a comprehensive review. *RSC advances*, *14*(4), 2804-2834.

[33] Al-Maliky, E.A., Gzar, H.A. and Al-Azawy, M.G., 2021, September. Determination of point of zero charge (PZC) of concrete particles adsorbents. In *IOP conference series: materials science and engineering* (Vol. 1184, No. 1, p. 012004). IOP Publishing.

[34] Demir, Ö., Gök, A. and Kırbaşlar, Ş.İ., 2023. Optimization of protocatechuic acid adsorption onto weak basic anion exchange resins: Kinetic, mass transfer, isotherm, and thermodynamic study. *Biomass Conversion and Biorefinery*, *13*(17), 16131-16147.

[35] Kumari, P., Tripathi, K.M., Awasthi, K. and Gupta, R., 2023. Sustainable carbon nano-onions as an adsorbent for the efficient removal of oxo-anions. *Environmental Science and Pollution Research*, *30*(6), 15480-15489.

[36] Musah, M., Azeh, Y., Mathew, J., Umar, M., Abdulhamid, Z. and Muhammad, A., 2022. Adsorption kinetics and isotherm models: a review. *Caliphate Journal of Science and Technology*, *4*(1), 20-26.

[37] Nguyen, C. and Do, D.D., 2001. The Dubinin–Radushkevich equation and the underlying microscopic adsorption description. *Carbon*, *39*(9), 1327-1336.

[38] Tseng, R.L., Wu, F.C. and Juang, R.S., 2010. Characteristics and applications of the Lagergren's first-order equation for adsorption kinetics. *Journal of the Taiwan Institute of Chemical Engineers*, *41*(6), pp.661-669.

[39] Bullen, J.C., Saleesongsom, S., Gallagher, K. and Weiss, D.J., 2021. A revised pseudo-second-order kinetic model for adsorption, sensitive to changes in adsorbate and adsorbent concentrations. *Langmuir*, *37*(10), 3189-3201.

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

[40] Peers, A.M., 1965. Elovich adsorption kinetics and the heterogeneous surface. *Journal of Catalysis*, 4(4), 499-503.

[41] Fatima, S., Taj, M.B. and Carabineiro, S.A.C., 2025. Ocimum Species as Multifunctional Green Adsorbents for the Removal of Dyes and Heavy Metals and Corrosion Inhibition. In *Advances in Nanomaterials for Detection, Control, and Removal of Environmental Pollutants* (pp. 357-391). Cham: Springer Nature Switzerland.