Abhi International Journal of
Chemical and Pharmaceutical Science
(A Peer Review Journal)

journal homepage: www.abhijournals.com/aijcps/

Volume 2, Issue 2, April 2026 ISSN : 3107-7153

Rice Husk Derived Activated Carbon for the Removal of Chromium (VI) from Wastewater

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ARTICLE INFO

Article History:
Received June 6, 2026
Revised June 8, 2026
Accepted June 16, 2026
Available online June 25, 2026

Keywords:
Biosorption
Rice Husk
Cr(VI)
Wastewater treatment
Adsorption

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ABSTRACT

Heavy metal contamination in wastewater poses a serious threat to environmental sustainability and human health due to the persistence and toxicity of metals such as lead (Pb), cadmium (Cd), chromium (Cr), and copper (Cu) (Jaishankar et al., 2014; Tchounwou et al., 2012). Conventional treatment methods, though effective, are often costly and generate secondary pollutants. This review critically evaluates the adsorption efficiency of biomass-derived adsorbents as sustainable alternatives. Emphasis is placed on adsorption mechanisms, kinetic and isotherm models, and operational parameters influencing performance. The applicability of models such as Langmuir, Freundlich, pseudo-first-order, and pseudo-second-order kinetics is discussed to understand adsorption behavior. The review concludes that biomass adsorbents exhibit high efficiency, with removal rates often exceeding 90%, and highlights pathways for optimization and large-scale implementation.

1.1 Background

Industrialization has significantly accelerated economic growth and technological advancement, but it has also intensified environmental degradation—particularly in the form of heavy metal contamination in aquatic systems. Industries such as mining, electroplating, battery manufacturing, textiles, leather tanning, and fertilizers discharge wastewater containing toxic metals like lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), and arsenic (As). These metals are of particular concern because they are non-biodegradable and persistent, meaning they do not undergo natural decomposition into harmless substances and can remain in ecosystems for extended periods (Fu & Wang, 2011).

Once released into water bodies, heavy metals tend to accumulate in sediments and enter the food chain through bioaccumulation and biomagnification. This results in progressively higher concentrations at higher trophic levels, posing serious ecological risks. Aquatic organisms are especially vulnerable; exposure to heavy metals can lead to enzyme inhibition, oxidative stress, impaired growth, and reproductive failure (Tchounwou et al., 2012). For example, mercury can disrupt neurological systems in fish, while cadmium affects kidney function and calcium metabolism.

From a human health perspective, the consequences are equally severe. Lead exposure is associated with neurological damage, particularly in children, causing cognitive impairment and developmental delays. Hexavalent chromium [Cr(VI)] is a known carcinogen, while arsenic exposure can lead to skin lesions, cardiovascular diseases, and cancer (Jaishankar et al., 2014). The contamination of drinking water sources with such metals thus represents a major global public health challenge. To address heavy metal pollution, several conventional wastewater treatment methods have been developed and widely applied. Among these, chemical precipitation, ion exchange, and membrane filtration are the most commonly used.

Chemical precipitation involves the addition of reagents such as lime ($Ca(OH)_2$), sodium hydroxide (NaOH), or sulfides to convert dissolved metal ions into insoluble hydroxides or sulfides, which can then be removed by sedimentation or filtration. While this method is simple and effective for treating wastewater with high metal concentrations, it has significant limitations. It produces large volumes of toxic sludge that require further handling and disposal, leading to secondary pollution. Additionally, its efficiency decreases at low metal concentrations, making it less suitable for polishing treatments (Fu & Wang, 2011).

Ion exchange is another widely used technique, where metal ions in solution are exchanged with innocuous ions (e.g., Na^+ or H^+) attached to synthetic resins. This method offers high selectivity and can achieve very low residual metal concentrations. However, ion exchange resins are expensive, and their regeneration requires the use of chemicals such as acids or bases, which generate secondary waste streams. The process is also sensitive to the presence of competing ions and organic matter, which can reduce efficiency (Barakat, 2011).

Membrane filtration technologies, including reverse osmosis, nanofiltration, and ultrafiltration, are highly effective in removing heavy metals even at trace levels. These processes use semi-permeable membranes to separate contaminants based on size and charge. Despite their high removal efficiency, membrane systems are associated with high capital and operational costs. Issues such as membrane fouling, high energy consumption, and the need for frequent replacement limit their widespread application. Moreover, the concentrated reject stream produced during filtration poses disposal challenges and may contribute to secondary pollution (Fu & Wang, 2011). While conventional treatment methods are technically effective, they suffer from drawbacks such as high cost, operational complexity, energy demand, and the generation of secondary pollutants. These limitations have prompted the search for alternative, sustainable, and cost-effective technologies for heavy metal removal.

1.2 Biomass as an Alternative

In response to the limitations of conventional methods, biomass-based adsorption, commonly known as biosorption, has emerged as a promising and sustainable alternative for the removal of heavy metals from wastewater. Biosorption utilizes natural materials derived from plants, agricultural residues, microorganisms, and algae to adsorb metal ions from aqueous solutions.

One of the most significant advantages of biosorption is its cost-effectiveness. Biomass materials such as rice husk, sawdust, coconut shells, sugarcane bagasse, and algae are abundant and often considered waste products. Their utilization in wastewater treatment not only reduces operational costs but also promotes waste valorization and resource recovery (Vijayaraghavan & Yun, 2008).

Biosorption is also environmentally friendly, as it relies on biodegradable and renewable materials. Unlike chemical treatments that introduce additional reagents into the environment, biosorption minimizes chemical usage and reduces the risk of secondary pollution. This makes it an attractive option for sustainable water management, particularly in developing countries where resources are limited.

In terms of performance, biomass-based adsorbents are highly efficient in removing heavy metals. The efficiency of biosorption is primarily attributed to the presence of various functional groups on the surface of biomass materials. These include hydroxyl (–OH), carboxyl (–COOH), amino ($–NH_2$), phosphate ($–PO_4^{3-}$), and sulfhydryl (–SH) groups, which can interact with metal ions through different mechanisms (Volesky, 2007).

Biosorption involves the passive binding of metal ions onto biological materials via physicochemical interactions, and it does not require metabolic activity. This distinguishes it from bioaccumulation, which depends on living organisms. The major mechanisms involved in biosorption include:

a) Ion exchange: Replacement of light metal ions (e.g., Na^+, Ca^{2+}) on the biomass surface with heavy metal ions

b) Complexation/chelation: Formation of stable complexes between metal ions and functional groups

c) Electrostatic attraction: Interaction between negatively charged biomass surfaces and positively charged metal ions

d) Physical adsorption: Weak interactions such as van der Waals forces

These mechanisms often occur simultaneously, contributing to high adsorption capacities.

Another advantage of biosorption is its flexibility and adaptability. It can be applied over a wide range of pH, temperature, and metal concentrations. Additionally, biomass materials can be chemically modified (e.g., acid or alkali treatment) or converted into activated carbon to enhance their adsorption properties. Such modifications increase surface area, porosity, and the number of active binding sites, thereby improving efficiency (Demirbas, 2008).

Despite these advantages, certain challenges remain. The regeneration and reuse of biomass adsorbents require further optimization, and large-scale applications demand better reactor design and process control. Nevertheless, ongoing research continues to address these issues through advanced material development and hybrid treatment systems.

2. LITERATURE REVIEW

2.1 Types of Biomass Adsorbents

The growing interest in sustainable wastewater treatment has led to extensive research on biomass-derived adsorbents. These materials are primarily classified into agricultural waste, plant biomass, microbial biomass, and algae/seaweed, each possessing unique structural and chemical characteristics that enhance heavy metal adsorption.

2.1.1. Agricultural Waste (Rice Husk, Bagasse)

Agricultural residues such as rice husk, wheat straw, and sugarcane bagasse are among the most widely studied biosorbents due to their abundance and low cost. Rice husk contains silica, cellulose, and lignin, which provide a porous structure and active binding sites for metal ions. Studies have demonstrated that rice husk can effectively remove heavy metals such as Pb^{2+}, Cd^{2+}, and Cr^{6+} from aqueous solutions (Demirbas, 2008). Similarly, sugarcane bagasse exhibits high adsorption capacity due to its fibrous structure and presence of hydroxyl and carboxyl groups (Foo & Hameed, 2010).

2.1.2. Plant Biomass (Prosopis juliflora)

Plant-based biomass such as Prosopis juliflora has been explored for its excellent adsorption properties. This invasive plant species contains lignocellulosic components with abundant functional groups capable of binding heavy metals. Research indicates that modified Prosopis juliflora biomass can significantly enhance the removal efficiency of metals like copper and lead due to increased surface area and functionalization (Sivakumar et al., 2012).

2.1.3. Microbial Biomass (Fungi, Bacteria)

Microorganisms such as fungi (e.g., Aspergillus niger) and bacteria (e.g., Bacillus subtilis) have demonstrated high biosorption potential. Their cell walls are rich in polysaccharides, proteins, and lipids containing functional groups such as –OH, –COOH, and $–NH_2$, which facilitate metal binding. Microbial biomass can be used in both live and dead forms, with dead biomass often preferred due to its stability and resistance to toxic environments (Vijayaraghavan & Yun, 2008).

2.1.4. Algae and Seaweed

Algae and seaweed are considered highly efficient biosorbents due to their high surface area and abundance of polysaccharides such as alginate, which contain carboxyl groups. Brown algae, in particular, have shown remarkable capacity in removing heavy metals like Pb, Cd, and Cu from wastewater (Volesky, 2007).

All biomass adsorbents share certain key features:

a) High porosity, which increases surface area for adsorption

b) Functional groups such as hydroxyl (–OH), carboxyl (–COOH), and amino ($–NH_2$), which play a crucial role in metal binding through chemical interactions

2.2 Adsorption Efficiency

Numerous studies have evaluated the efficiency of biomass-derived adsorbents in removing heavy metals from wastewater. Reported removal efficiencies are often remarkably high under optimized conditions. For instance, lead (Pb^{2+}) removal efficiencies of up to 95%, cadmium (Cd^{2+}) up to 90%, and copper (Cu^{2+}) around 90% have been documented (Babel & Kurniawan, 2003; Global NEST Journal, 2025).

The efficiency of biosorption depends on several factors, including:

a) Initial metal concentration

b) pH of the solution

c) Contact time

d) Temperature

e) Surface properties of the adsorbent

Studies consistently show that adsorption capacity increases with pH due to reduced competition from hydrogen ions and enhanced availability of binding sites (Foo & Hameed, 2010).

2.3 Mechanisms of Biosorption

Biosorption is governed by a combination of physical and chemical processes that facilitate the removal of metal ions from aqueous solutions. The primary mechanisms include:

2.3.1. Ion Exchange

In this process, metal ions in solution replace lighter ions (such as H^+, Na^+, or Ca^{2+}) present on the surface of the biomass. This mechanism is particularly important in materials rich in carboxyl and hydroxyl groups (Volesky, 2007).

2.3.2. Complexation

Metal ions form coordination complexes with functional groups such as –COOH and – NH_2 present on the biomass surface. This leads to strong and stable binding of metals.

2.3.3. Electrostatic Attraction

Negatively charged biomass surfaces attract positively charged metal ions through Coulombic forces, especially at higher pH levels.

2.3.4. Surface Adsorption

Physical adsorption occurs through weak van der Waals forces, contributing to the overall uptake of metals.

2.3.5. Kinetic Models

The adsorption process is commonly described using kinetic models, which help in understanding the rate and mechanism of adsorption.

a) Pseudo-first-order model: Assumes that the rate of adsorption is proportional to the number of unoccupied sites.

b) Pseudo-second-order model: Assumes that chemisorption is the rate-limiting step involving electron sharing or exchange.

Experimental studies have shown that the pseudo-second-order model provides a better fit for most biosorption systems, indicating that chemical interactions dominate the process (Ho & McKay, 1999; SAGE Journals, 2021).

2.4 Advantages of Biomass Adsorbents

Biomass-based adsorbents offer several advantages over conventional treatment methods:

a) Low cost: Derived from waste materials, reducing overall treatment expenses

b) Renewable and sustainable: Easily available and environmentally friendly

c) High efficiency: Capable of removing heavy metals even at low concentrations

d) Minimal sludge formation: Unlike chemical precipitation, biosorption produces little to no secondary waste

These advantages make biosorption a promising alternative for wastewater treatment, particularly in resource-limited settings (Demirbas, 2008).

2.5 Limitations of Biomass Adsorbents

Despite their advantages, biomass adsorbents have certain limitations that must be addressed for large-scale application:

a) Low selectivity: Biomass materials may adsorb multiple ions simultaneously, reducing efficiency in complex wastewater systems

b) Regeneration challenges: Desorption and reuse of biomass can be difficult and may reduce adsorption capacity over time

c) Scale-up issues: Laboratory-scale success does not always translate to industrialscale feasibility

Additionally, variability in biomass composition and lack of standardization pose challenges for consistent performance (Fu & Wang, 2011; ScienceDirect, 2024).

3. RESEARCH GAP and OBJECTIVES

3.1 Research Gap:

1. Lack of large-scale industrial application models
2. Limited research on multi-metal competitive adsorption

3. Poor understanding of regeneration and reuse efficiency
4. Insufficient mathematical modelling integration
5. Lack of standardized biomass modification techniques

3.2 Objectives:

1. To investigate the adsorption efficiency of Rice husk derived activated carbon for the removal of Cr(VI) from wastewater.
2. To develop a kinetic and thermodynamic model for biosorption processes.

4. MATERIALS AND METHODS

The systematic methodology adopted for the preparation of biomass-derived adsorbents, experimental procedures for heavy metal removal, and analytical techniques used for characterization and evaluation. The methodology is designed to ensure reproducibility, accuracy, and scientific rigor.

4.1 Biomass Preparation

The preparation of biomass adsorbents is a crucial step that significantly influences adsorption efficiency. Proper treatment enhances surface area, porosity, and availability of active binding sites.

4.1.1. Collection of Agricultural Waste

Biomass materials such as rice husk, wheat straw, and sugarcane bagasse were collected from local agricultural fields and processing units. These materials were chosen due to their abundance, low cost, and high lignocellulosic content. Care was taken to ensure that the collected biomass was free from visible contamination such as soil, plastics, or oils.

4.1.2. Washing and Drying

The collected biomass was thoroughly washed with distilled water to remove dust, soluble impurities, and adhering particles. In some cases, mild detergents were used followed by repeated rinsing with deionized water. After washing, the biomass was dried:

a) Initially under sunlight for 24–48 hours
b) Followed by oven drying at 60–80°C until constant weight was achieved

Drying ensures removal of moisture, which can otherwise interfere with adsorption and reduce efficiency.

4.1.3. Grinding and Sieving

The dried biomass was mechanically ground using a grinder or milling machine to reduce particle size. The powdered material was then sieved using standard mesh sizes (e.g., 100–200 µm) to obtain uniform particle distribution. Smaller particle sizes increase surface area and improve adsorption kinetics.

4.1.4. Chemical Activation (HCl, NaOH)

To enhance adsorption capacity, chemical activation was performed using acids and bases:

a) Acid treatment (HCl):

   Biomass was soaked in dilute hydrochloric acid (0.1–1 M) for several hours. This process removes impurities, increases surface roughness, and exposes functional groups such as –COOH.

b) Alkali treatment (NaOH):

   Treatment with sodium hydroxide modifies lignin structure and increases the number of negatively charged sites, enhancing metal ion binding.

After chemical treatment, the biomass was washed repeatedly until neutral pH was achieved and then dried again. The activated biomass was stored in airtight containers for further use.

4.2 Experimental Setup

Batch Adsorption Experiments

Batch adsorption studies were conducted to evaluate the removal efficiency of heavy metals under controlled conditions. In a typical experiment:

a) A known mass of biomass adsorbent (e.g., 0.5–2 g) was added to a fixed volume of metal ion solution (e.g., 100 mL).
b) The solution was placed in conical flasks and agitated using a mechanical shaker at constant speed (120–200 rpm).
c) After a predetermined time, samples were filtered or centrifuged, and the residual metal concentration was analyzed.

Batch experiments are widely used due to their simplicity and ability to study multiple parameters simultaneously.

Parameters Studied

i. pH

pH is one of the most critical factors affecting biosorption. Experiments were conducted across a pH range (typically 2–10) using dilute HCl or NaOH for adjustment. At low pH, competition from H^+ ions reduces adsorption, while at higher pH, metal uptake increases due to enhanced electrostatic attraction.

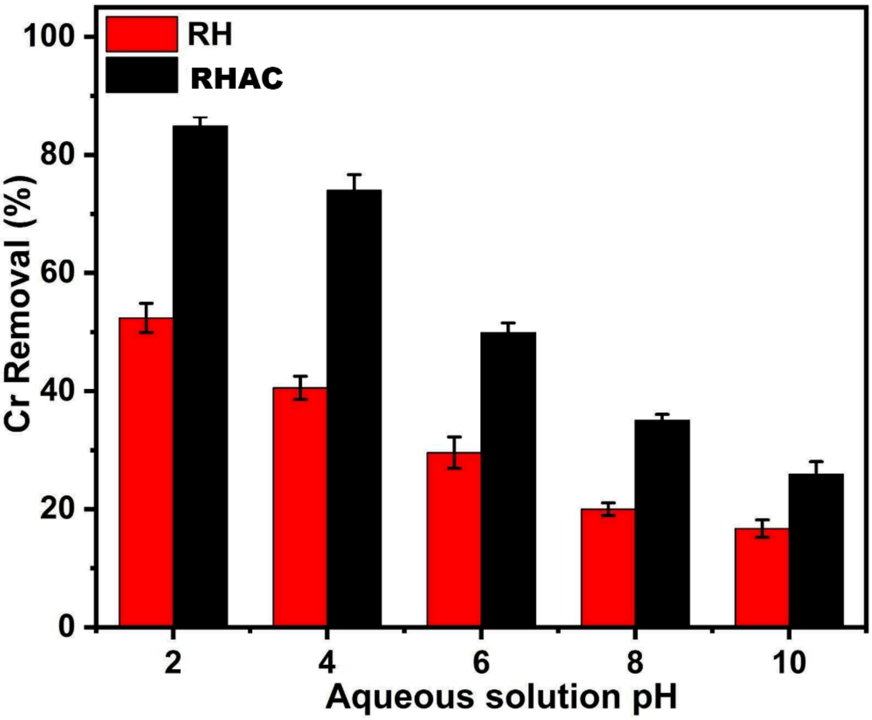

Figure 1. Effect of pH (2 to 10) on the removal efficiency of Cr.

ii. Temperature

Experiments were carried out at different temperatures (e.g., 25°C, 35°C, 45°C) to study thermodynamic behavior. Temperature influences adsorption capacity, reaction kinetics, and diffusion rates.

iii. Contact Time

The effect of contact time was studied by sampling at different intervals (e.g., 10, 30, 60, 120 minutes). This helps determine equilibrium time and adsorption rate.

iv. Initial Metal Concentration

Different initial concentrations (e.g., 10–200 mg/L) were used to evaluate adsorption capacity and isotherm behavior. Higher concentrations increase driving force for mass transfer but may lead to saturation of adsorption sites.

4.3 Analytical Techniques

Accurate characterization and quantification of adsorption processes require advanced analytical techniques.

4.3.1. Atomic Absorption Spectroscopy (AAS)

AAS was used to determine the concentration of heavy metals before and after adsorption. It is a highly sensitive and precise technique based on the absorption of light by free metal ions.

Principle:

a) Metal atoms absorb specific wavelengths of light.

b) The absorbance is proportional to the concentration of the metal.

Applications:

a) Measurement of Pb, Cd, Cu, Cr concentrations

b) Determination of removal efficiency

AAS is preferred due to its high accuracy and ability to detect trace metal concentrations.

4.3.2. Scanning Electron Microscopy (SEM)

SEM was employed to analyze the surface morphology of biomass before and after adsorption.

Key Observations:

a) Surface texture and porosity

b) Changes in structure after metal adsorption

c) Distribution of adsorbed particles

SEM images typically show rough, porous surfaces before adsorption and smoother surfaces after metal binding, indicating successful adsorption.

4.3.4. Fourier Transform Infrared Spectroscopy (FTIR)

FTIR analysis was used to identify functional groups involved in adsorption.

Principle:

a) Molecules absorb infrared radiation at specific frequencies corresponding to vibrational modes.

Applications:

a) Identification of functional groups such as –OH, –COOH, $–NH_2$

b) Detection of shifts in peak positions after adsorption, indicating metal binding

For example, a shift in the –OH stretching frequency suggests involvement in metal complexation.

5. ADSORPTION ISOTHERMS

Adsorption isotherms describe how heavy metal ions interact with biomass adsorbents at equilibrium. They provide a quantitative relationship between the amount of metal adsorbed per unit mass of adsorbent and its equilibrium concentration in solution at a constant temperature. Isotherm models are essential for understanding adsorption capacity, surface properties, and designing treatment systems. Among the most widely used models in biosorption studies are the Langmuir and Freundlich isotherms.

5.1 Langmuir Isotherm

$$q_e = \frac{q_{max}\, bC_e}{1 + bC_e}$$

The Langmuir isotherm is based on the assumption of monolayer adsorption onto a homogeneous surface with a finite number of identical adsorption sites.

Assumptions of Langmuir Model

a) Adsorption occurs at specific homogeneous sites on the adsorbent

b) Each site can hold only one metal ion (monolayer coverage)

c) No interaction between adsorbed molecules

d) All adsorption sites have equal energy

Parameters Explanation

a) q_e: Amount of metal adsorbed at equilibrium (mg/g)

b) q_{max}: Maximum adsorption capacity (mg/g)

c) C_e: Equilibrium concentration of metal ions (mg/L)

d) b: Langmuir constant related to adsorption affinity (L/mg)

Scientific Interpretation

The Langmuir model implies that once a site is occupied, no further adsorption can occur at that site. It is particularly suitable for systems where adsorption is uniform and involves strong chemical bonding (chemisorption).

Separation Factor (Feasibility Indicator)

A key feature of the Langmuir model is the dimensionless separation factor R_L, defined as:

$$R_L = \frac{1}{1 + bC_e}$$

a) R_L: Unfavorable adsorption

b) $0 < R_L < 1$: Favorable adsorption

c) $R_L = 1$: Linear adsorption

d) $R_L = 0$: Irreversible adsorption

Application in Biomass Adsorption

The Langmuir model is widely used to describe heavy metal adsorption onto chemically modified biomass, where surface uniformity is enhanced. It provides an estimate of maximum adsorption capacity, which is crucial for reactor design.

5.2 Freundlich Isotherm

$$q_e = K_f C_e^{1/n}$$

The Freundlich isotherm is an empirical model that describes adsorption on heterogeneous surfaces with varying energy levels.

Assumptions of Freundlich Model

a) Adsorption occurs on a heterogeneous surface
b) Sites have different energies and affinities
c) Multilayer adsorption is possible
d) Adsorption strength decreases with increasing surface coverage

Parameters Explanation

a) q_e: Amount of adsorbate adsorbed (mg/g)
b) C_e: Equilibrium concentration (mg/L)
c) K_f: Freundlich constant indicating adsorption capacity
d) n: Intensity factor indicating adsorption favorability

Scientific Interpretation

a) If $1/n < 1$: Adsorption is favorable
b) If $1/n = 1$: Linear adsorption
c) If $1/n > 1$: Cooperative adsorption

Higher values of K_f indicate greater adsorption capacity, while n reflects surface heterogeneity.

5.3. Redlich–Peterson isotherm model

The Redlich–Peterson isotherm model is a three-parameter adsorption model that combines features of both the Langmuir and Freundlich isotherms. It is useful for describing adsorption on both homogeneous and heterogeneous surfaces.

Equation

$$q_e = \frac{K_R C_e}{1 + a_R C_e^g}$$

5.4. Temkin isotherm model

The Temkin isotherm model assumes that the heat of adsorption decreases linearly with increasing surface coverage due to adsorbent–adsorbate interactions.

Equation

$$q_e = BlnA + BlnC_e$$

Where:

$$B = \frac{RT}{b}$$

- q_e= amount adsorbed at equilibrium (mg/g)
- C_e= equilibrium concentration (mg/L)
- A= Temkin equilibrium binding constant (L/g)
- B= Temkin constant related to adsorption heat
- R= universal gas constant (8.314 J mol^{-1} K^{-1})
- T= absolute temperature (K)
- b= Temkin constant related to adsorption energy

Application in Biomass Adsorption

The Freundlich model is more suitable for natural biomass materials, which typically have heterogeneous surfaces with diverse functional groups. It accounts for multilayer adsorption and variable binding energies.

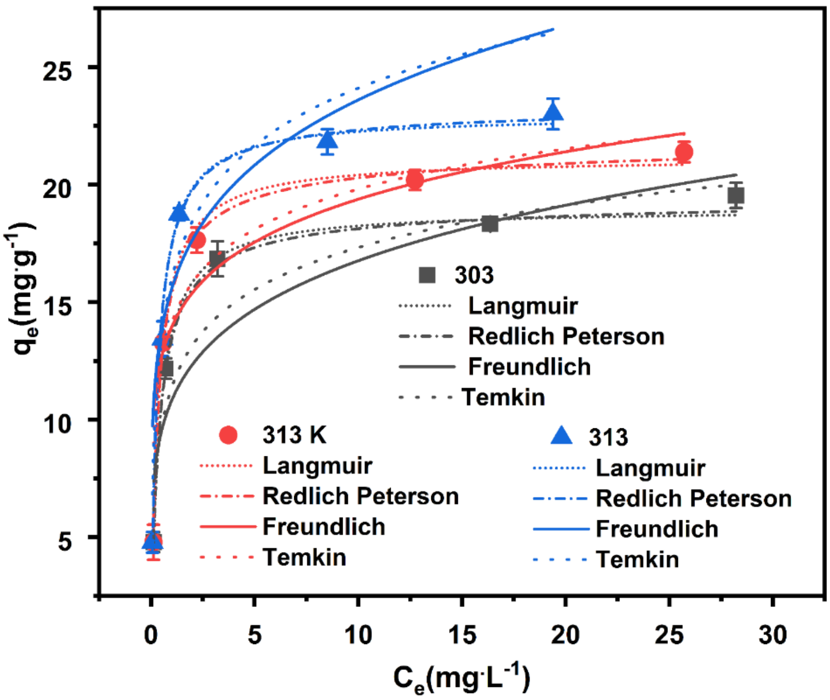

Figure 2.
Non-linear fit of Langmuir, Freundlich, and Temkin isotherms for Cr adsorption

Both Langmuir and Freundlich isotherms play a crucial role in understanding biosorption behavior. The Langmuir model is ideal for estimating maximum adsorption capacity and designing treatment systems, while the Freundlich model provides insights into surface heterogeneity and adsorption intensity. In practical biomass-based systems, experimental data are often fitted to both models, and the best fit determines the dominant adsorption mechanism. Understanding these isotherms is essential for optimizing biosorption processes and integrating them into large-scale wastewater treatment applications.

6.KINETIC MODELS

Kinetic models are fundamental for understanding the rate and mechanism of biosorption of heavy metals onto biomass-derived adsorbents. While isotherms describe equilibrium behavior, kinetic models explain how fast adsorption occurs and identify the controlling steps—whether diffusion, surface reaction, or chemisorption. Among the most widely applied models in biosorption studies are the pseudo-first-order and pseudo-second-order kinetic models.

6.1 Pseudo First Order Kinetic Model

$$\frac{dq_t}{dt} = k_1(q_e - q_e)$$

The pseudo-first-order model, also known as the Lagergren model, assumes that the rate of occupation of adsorption sites is proportional to the number of unoccupied sites.

Integrated Form

Upon integration (with boundary conditions $q_t = 0$ at $t = 0$:

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

a) q_t: Amount adsorbed at time (t) (mg/g)

b) q_e: Amount adsorbed at equilibrium (mg/g)

c) k_1: Rate constant of pseudo-first-order adsorption (min^{-1})

d) t: Time (min)

Scientific Interpretation

a) The model suggests that adsorption is primarily controlled by physical adsorption (physisorption).

b) It is most applicable during the initial stages of adsorption.

c) A plot of $\ln(q_e - q_t)$ vs. t should yield a straight line if the model is valid.

Limitations

a) Often fails to accurately predict adsorption behavior over the entire time range

b) Experimental q_e values may differ significantly from calculated values

6.2 Pseudo Second Order Kinetic Model

$$\frac{dq_t}{dt} = k_2(q_e - q_e)^2$$

The pseudo-second-order model assumes that adsorption follows chemisorption, involving valence forces through sharing or exchange of electrons between adsorbent and adsorbate.

Integrated Form

$$\frac{t}{q_t} = \frac{1}{k_2 {q_e}^2} + \frac{t}{q_e}$$

Parameters

a) k_2: Rate constant of pseudo-second-order adsorption (g/mg·min)

b) Other parameters as defined earlier

Scientific Interpretation

a) The rate-limiting step is chemical interaction between metal ions and functional groups

b) Provides a better fit for most biosorption systems

c) A plot of $\frac{t}{q_t}$ vs. t gives a straight line Initial Adsorption Rate

$$h = k_2 {q_e}^2$$

where h is the initial adsorption rate (mg/g·min)

6.3 Elovich kinetic model

The Elovich kinetic model is commonly used to describe the adsorption of gases or solutes onto heterogeneous solid surfaces, especially in chemisorption processes where the adsorption rate decreases with time.

Elovich Equation

$$\frac{dq_t}{dt} = \alpha e^{-\beta q_t}$$

Where:

- q_t = amount adsorbed at time t(mg/g)
- α= initial adsorption rate (mg g^{-1} min^{-1})
- β= desorption or surface coverage constant (g mg^{-1})

The linearized form is:

$$q_t = \frac{1}{\beta} ln(\alpha\beta) + \frac{1}{\beta} lnt$$

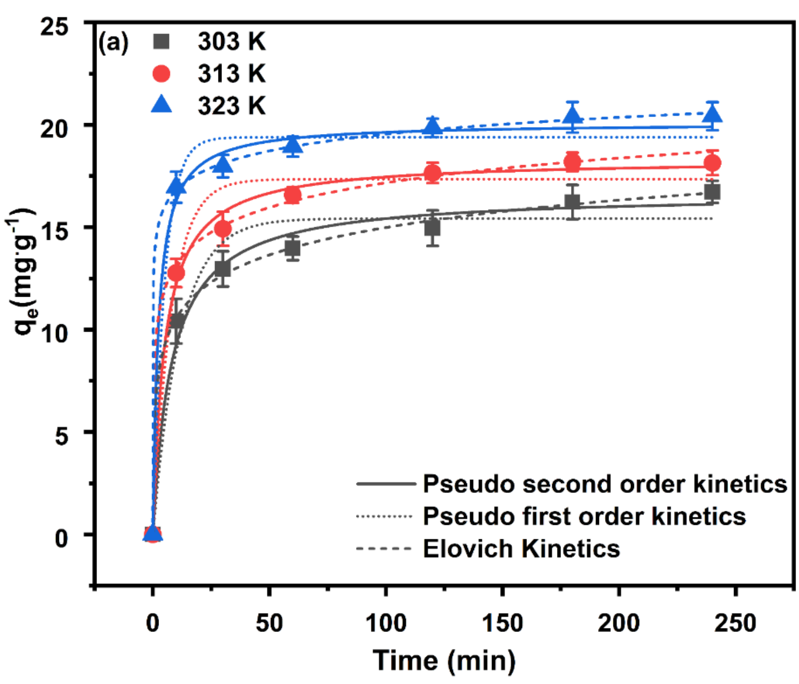

Figure 3. Adsorption kinetic of Cr (40 mg·L^{-1}) for different Kinetics models (a) pseudo first order; pseudo-second order and Elovich

Kinetic models are essential tools for analyzing biosorption processes and designing efficient wastewater treatment systems. While the pseudo-first-order model provides insights into early-stage adsorption, the pseudo-second-order model is more reliable for describing the overall mechanism of heavy metal uptake in biomass systems. Accurate kinetic analysis enables optimization of contact time, adsorbent dosage, and reactor design for large-scale applications.

7.RESULTS AND DISCUSSION

This chapter presents and interprets the experimental findings on the performance of biomass-derived adsorbents for heavy metal removal. The discussion integrates adsorption capacity, kinetic behavior, and thermodynamic feasibility to provide a comprehensive understanding of the biosorption process.

7.1 Adsorption Capacity

The adsorption capacity of the prepared biomass adsorbents was evaluated for different heavy metals, with particular emphasis on lead (Pb^{2+}) and copper (Cu^{2+}). Experimental results revealed high removal efficiencies, often exceeding 90% under optimized conditions of pH, contact time, and dosage.

Key Observations

a) Lead (Pb^{2+}) exhibited the highest adsorption capacity among the tested metals. This can be attributed to its larger ionic radius and higher affinity toward functional groups such as –COOH and –OH present on the biomass surface.

b) Copper (Cu^{2+}) also showed significant adsorption, though slightly lower than Pb^{2+} due to differences in ionic characteristics and hydration energy.

Effect of Biomass Modification

Chemical activation of biomass using acids (HCl) and bases (NaOH) resulted in a marked improvement in adsorption performance:

a) Increased surface area and porosity

b) Enhanced exposure of functional groups

c) Greater availability of active binding sites

Modified biomass demonstrated higher adsorption capacities compared to raw biomass, confirming that surface treatment plays a crucial role in improving biosorption efficiency.

7.2 Kinetic Analysis

Kinetic studies were conducted to evaluate the rate of adsorption and to identify the controlling mechanism. Experimental data were fitted to both pseudo-first-order and pseudo-second-order models.

Key Findings

a) The pseudo-second-order kinetic model showed excellent agreement with experimental data, as indicated by higher correlation coefficients (R^2 values).

b) The calculated equilibrium adsorption capacity (q_e) from this model closely matched experimental values.

Interpretation

The dominance of the pseudo-second-order model suggests that:

a) Chemisorption is the rate-limiting step, involving electron sharing or exchange between metal ions and biomass functional groups.

b) Functional groups such as –COOH, –OH, and $–NH_2$ actively participate in binding metal ions.

Adsorption Behavior

a) Rapid adsorption occurred during the initial phase due to abundant vacant sites

b) Gradual slowing down followed as sites became occupied

c) Equilibrium was achieved within a finite time period

These results confirm that biosorption is not merely a physical process but involves significant chemical interactions.

7.3 Thermodynamic Study

Thermodynamic parameters were evaluated to determine the feasibility and nature of the adsorption process. The key parameters analyzed include Gibbs free energy change (ΔG), enthalpy change (ΔH), and entropy change (ΔS).

Gibbs Free Energy (ΔG)

a) The values of ΔG were negative across the studied temperature range.

b) This indicates that the adsorption process is spontaneous and thermodynamically favorable.

Enthalpy Change (ΔH)

a) The positive values of ΔH confirm that the process is endothermic.

b) This implies that adsorption capacity increases with temperature, as higher thermal energy facilitates interaction between metal ions and adsorbent.

Entropy Change (ΔS)

a) Positive ΔS values suggest increased randomness at the solid–solution interface during adsorption.

b) This reflects structural changes and greater disorder as metal ions are transferred from solution to the adsorbent surface.

The combined results from adsorption capacity, kinetics, and thermodynamics provide a coherent understanding of the biosorption process: High adsorption capacity demonstrates the effectiveness of biomass adsorbents, especially after chemical modification. Kinetic analysis confirms chemisorption, indicating strong and stable interactions between adsorbent and metal ions. Thermodynamic parameters validate feasibility, showing that the process is spontaneous and enhanced at higher temperatures.

8. CONCLUSION and FUTURE SCOPE

8.1 CONCLUSION

Biomass-derived adsorbents present a highly promising solution for the removal of heavy metals from wastewater due to their sustainability, low cost, and high adsorption efficiency. Their abundant availability and environmentally friendly nature make them suitable for large-scale applications. However, challenges such as regeneration, selectivity, and scalability need to be carefully addressed to ensure consistent performance and economic feasibility. Further research focusing on material modification, process optimization, and system integration is essential. With continued advancements, biomass-based biosorption can become a viable and sustainable technology for effective wastewater treatment and long-term environmental protection.

8.2 FUTURE SCOPE

The advancement of biomass-based biosorption technology demands innovative strategies to improve efficiency, scalability, and real-world applicability. Future research should emphasize the development of advanced materials such as nano-biomass composites, along with the integration of computational tools like artificial intelligence for process optimization. Combining biosorption with hybrid treatment systems and smart monitoring technologies can further enhance performance and reliability. Addressing challenges related to regeneration, selectivity, and large-scale implementation is essential. These coordinated efforts will enable the effective transition of biosorption from laboratory investigations to industrial-scale applications, ensuring sustainable and cost-effective solutions for wastewater treatment and environmental protection.

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