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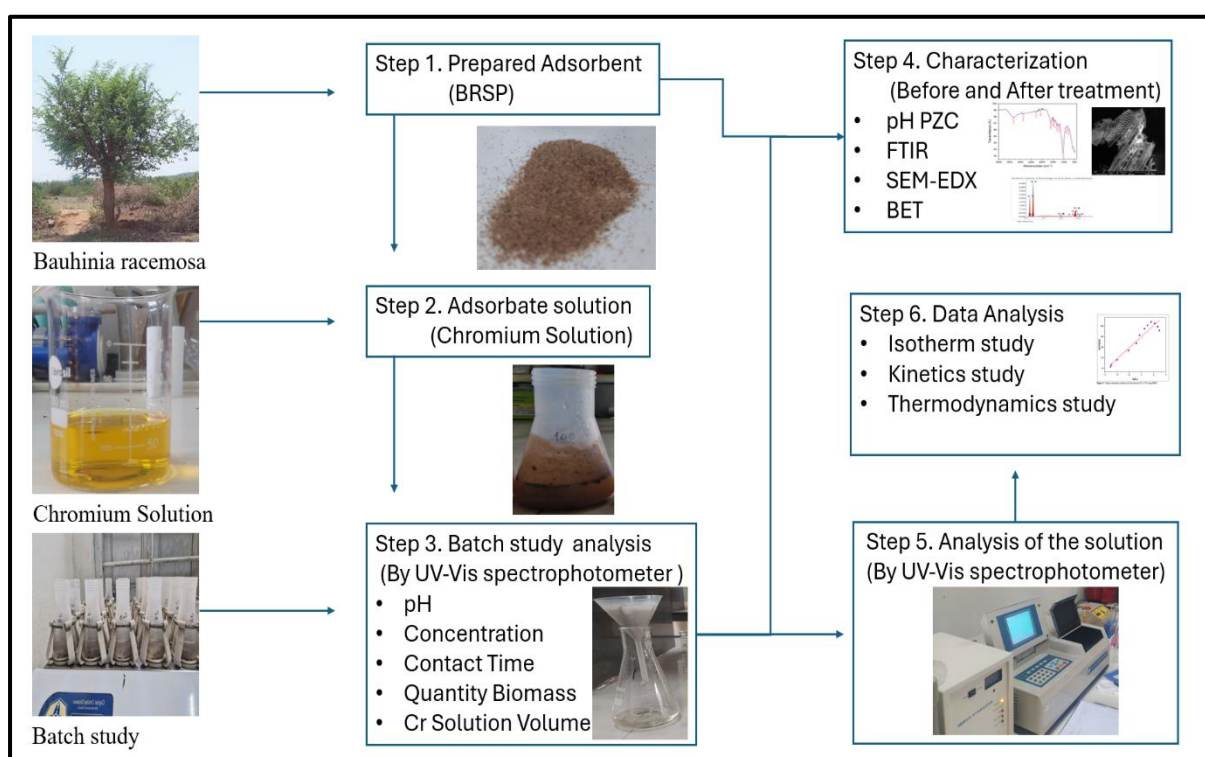
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Graphical Abstract



HIGHLIGHTS

- Bauhinia Racemosa sawdust powder (BRSP) demonstrates excellent biosorption of Cr (VI).
- FTIR, BET, and SEM-EDX analyses were performed for surface studies.
- The adsorption data fitted well to the Freundlich, Langmuir, Temkin, and D-R isotherms, whereas the kinetics adhered to a pseudo-first-order kinetic model.
- Thermodynamic investigations showed that the adsorption process was endothermic and spontaneous at ambient temperature.
- BRSP demonstrated a significant adsorption capability of 106.86 mg/g at an optimum pH of 4.0.

ABSTRACT

The purpose of the present study was to assess the effectiveness of *Bauhinia racemosa* sawdust powder (BRSP) for its potential use as a low-cost ligno-cellulosic adsorbent for the removal of hexavalent chromium [Cr(VI)] from aqueous solution. Adsorption study based batch experiments were conducted to study the various factors affecting adsorption, such as Cr(VI) concentration, initial pH, biosorbent particle size, contact time, and solution volume. The biosorbent was also characterized by FTIR, BET analysis, and SEM-EDX. The surface area, proximate analysis, Boehm titration, and point of zero charge estimation (pHPZC) were measured to determine the surface characteristics and functional group interactions. Maximum Cr(VI) removal was 99.78% and maximum Cr(VI) adsorption was 106.86 mg/g under optimal conditions (pH 4.0, dose of 0.4 g of grains in 100 mL of solution for a particle size of 75 μm with 100 mg/L concentration and a contact time of one h).

The Langmuir isotherm model effectively fits the adsorption equilibrium data, indicating monolayer adsorption. Nevertheless, kinetic runs based on the pseudo-second-order model indicated that chemisorption was the predominant process. Thermodynamic parameters (ΔG° , ΔH° , and ΔS°) suggested that the process was spontaneous and endothermic. These results indicated that BRSP is a promising sustainable biosorbent for removing Cr(VI) from polluted water, offering a green strategy for resource recycling and effluent treatment in diverse industries. The driving forces are van der Waals interaction, π - π stacking, hydrophobic, and electrostatic interactions.

Keywords: Adsorption, hexavalent chromium, isotherm models, BET, SEM-EDX.

1. Introduction

Chromium, having atomic number 24, a d-block element, was discovered in 1797 by the French chemist Louis Nicolas Vauquelin, who identified it while studying lead(II) chromate (PbCrO_4). It is hard, steel-grey metal known for its bright lustre and brittle nature. The element gets its name from the Greek word chroma, meaning "colour", due to the wide range of colours seen in its compounds. Among transition metals, chromium is the sixth most abundant in the Earth's crust and ranks 21st among all elements, with an estimated concentration of about 122 parts per million (Barnhart, 1997). Its distinct chemical behavior and colourful oxidation states have made it important in both industrial and environmental contexts. Chromium (Cr) metal, specifically in its hexavalent ionic state, is a major environmental threat owing to its toxicity and is prevalent in the natural environment [1], [2]. Hexavalent chromium is highly soluble, mobile, and persistent, causing several health hazards. It is a known carcinogen and is linked to several diseases, such as respiratory diseases, kidney dysfunction, and genetic mutations [3]. The drinking water guidelines set by the World Health Organization (WHO, 2003) are ≤ 0.05 mg/L [4], [5]. As shown in Table 1, environmental legislation is regulated by various agencies. These criteria require treating industrial effluents or removing Cr (VI) before discharge into the environment. Traditional techniques for Cr (VI) treatment (e.g., photoreduction, chemical precipitation, ion exchange, and membrane filtration) are commonly used to eliminate other contaminants [4]–[6]. However, these approaches are limited by their high operational costs, secondary environmental pollution, and unsustainability. These problems have necessitated the development of cheaper, environmentally friendly, economical, and efficient alternatives that show enhanced Cr (VI) removal throughout the adsorption process. This technology has become one of the most promising methods for eliminating Cr (VI) from aquatic systems [7]. The use of sawdust as an efficient and environmentally friendly biosorbent for eliminating Cr (VI) from water bodies has also been investigated.[8].

Wood processing units generate many by-products, including sawdust, which is abundant, cheap, and does not cause environmental pollution [4]. Sawmilling operations are a significant source of lignocellulosic waste, with many timber-producing countries worldwide generating over 2 million m³ of sawdust annually [9]. In India, an estimated 23,000 sawmills were operational as of 2016, each producing an average of approximately 822.4 tonnes of sawdust per year. Based on these Figures, India's total annual sawdust generation is estimated to be around 18.91 million tonnes [10]. Considering the massive mass production of sawdust as timber industry waste, it was utilised for the study as it contains cellulose, hemicelluloses, and lignin. Owing to its porous structure and surface functional groups, sawdust has the potential for absorption processes. Sawdust has been found to adsorb significantly high concentrations of heavy metals, including lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn) [9]. This study investigated using *Bauhinia racemosa* sawdust, a low-cost biomass, to eliminate Cr (VI) from wastewater [11]. In the present study, sawdust was obtained from a sawmill in the Udgaon area of Maharashtra, India. Among the operational parameters, the pH of the adsorbate, quantity of biosorbent, initial concentration of adsorbate, contact time, particle size of the biosorbent, and volume of the Cr solution were optimized using batch adsorption study. Furthermore, adsorption isotherms, different kinetic models, and thermodynamic studies have been used to elucidate the adsorption process [12].

The equilibrium adsorption data were analyzed using four isotherm models: Langmuir, Freundlich, Temkin, and Dubinin–Radushkevich. The Freundlich adsorption isotherm model represents multilayer adsorption on a heterogeneous surface, whereas the Langmuir isotherm illustrates monolayer adsorption on a homogeneous surface. The Temkin isotherm accounts for the interaction between the adsorbate and adsorbent. At the same time, the Dubinin–Radushkevich model provides information on the energy of adsorption [13]–[16]. Pseudo-first-order and pseudo-second-order models were also tested to confirm the rate and mechanism of adsorption. The thermodynamic parameters [Gibbs free energy (ΔG°), enthalpy (ΔH°), and entropy (ΔS°)] were calculated for the spontaneity, feasibility, and nature of the adsorption mechanism [17]. To study the physicochemical aspects of BRSP techniques, such as Fourier-transform infrared spectroscopy (FTIR), Scanning electron microscopy with energy dispersive X-ray (SEM-EDX), Boehm titration, and proximate analysis were carried out. The functional groups involved in Cr (VI) uptake were identified using FTIR analysis. SEM-EDX elucidated the morphological/elemental composition data, while the surface functional groups were determined by Boehm titration.

The present study envisaged producing a cost-effective, environment-friendly adsorbent, BRSP, to sequester hazardous Cr (VI) from industrial effluent. This study contributes to developing strategies for sustainable wastewater treatment and offers green technologies for Cr (VI) removal. This study adopted this approach to address the menace of heavy metal pollution by utilizing sustainable, affordable, and readily available waste by-products with green chemistry, waste valorization, and environmental sustainability priorities.

Table 1: Regulatory limits of hexavalent and trivalent chromium in drinking water in major countries

Authority/Country	Cr (VI) limit (mg/L)	Cr (III) limit (mg/L)	Total Cr (mg/L)	Reference
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World Health Organization (WHO)	0.05	Not specified	-	[18]
Bureau of India Standards (BIS)	0.05	Not specified	-	[19]
India Central Pollution Control Board (CPCB)	0.1	2.0	2.0	[20]
United States (USEPA)	0.01 (as total Cr)	-	0.1	[21]
European Union (EU)	0.05 (as total Cr)	-	0.05	[22]
Canada (Health Canada)	0.05	Not specified	-	[23]
Australia (ADWG)	0.05 (as total Cr)	-	0.05	[24]
South Africa (SANS 241)	0.05	Not specified	-	[25]
Japan (JWWA)	0.05	Not specified	-	[26]
Malaysia (MOH)	0.05 (as total Cr)	-	0.05	[27]
Germany (UBA)	0.05	Not specified	-	[28]

2. Materials and Methods

2.1. Preparation of adsorbate

All biosorption experiments were carried out using analytical-grade (AR) reagents, which were mainly provided by Merck (Germany), and through the use of borosilicate laboratory wares. Deionized water was used throughout the work during the preparation of all reagents and aqueous solutions without further purification. [Cr(VI)] Stock solution was obtained through the dissolution of 2.828 g of anhydrous potassium dichromate ($K_2Cr_2O_7$) into 1000 mL of deionized water. For full dissolution and stabilization of the Cr(VI), 1.5 mL of 1 M nitric acid (HNO_3) was added to the aqueous medium [29,30]. Working solutions were freshly made as needed, starting from the above-mentioned stock. The concentration of the aqueous sample and effluent of Cr(VI) was analyzed by the 1,5-diphenylcarbazide (DPC) colorimetric method, as per standard procedures given by the American Public Health Association (APHA) [38]. The UV-Visible spectrophotometer (Model CB-104, Chem Biotech, India) at a 540 nm wavelength was utilized to measure the absorbance of the aqueous solutions, which was monitored and controlled using a digital pH meter (Model EQ618, Equitronics, India). Batch adsorption tests were conducted using a rotary shaker (Model B11-054, Biotechnics, India; ISO 9001:2008 certified) set to varying speeds ranging from 20 to 500 rpm. A hot air oven (Model BIT28, Bio-Tech) and a muffle furnace (Model BIT36, Chem Bio-Tech) were used for proximate analysis. All the work involving adsorption was done at ambient room temperature ($25 \pm 2^\circ C$). The initial pH of the aqueous solutions was adjusted to the desired level by HCl or NaOH, as required.

2.1.1. Biomass: Source, collection, and processing

Plant Material (Source and Collection)

The wood was collected from a sawmill near Udgaon, Maharashtra, India. Sawdust was thoroughly washed with distilled water to eliminate contaminants and dust. Once cleaned, the sawdust was left to dry in the sun for 1-2 days, followed by drying in an oven (Bio-technics India; BTI-29) at 150 °C for six hours per day over 3 days to remove excess moisture. The drying and cooling processes were performed multiple times until a stable weight was achieved. The sawdust was sieved to obtain a desired particle size of 75 μm and stored in an airtight container. The process for preparing the biosorbent is shown in Fig. 1.

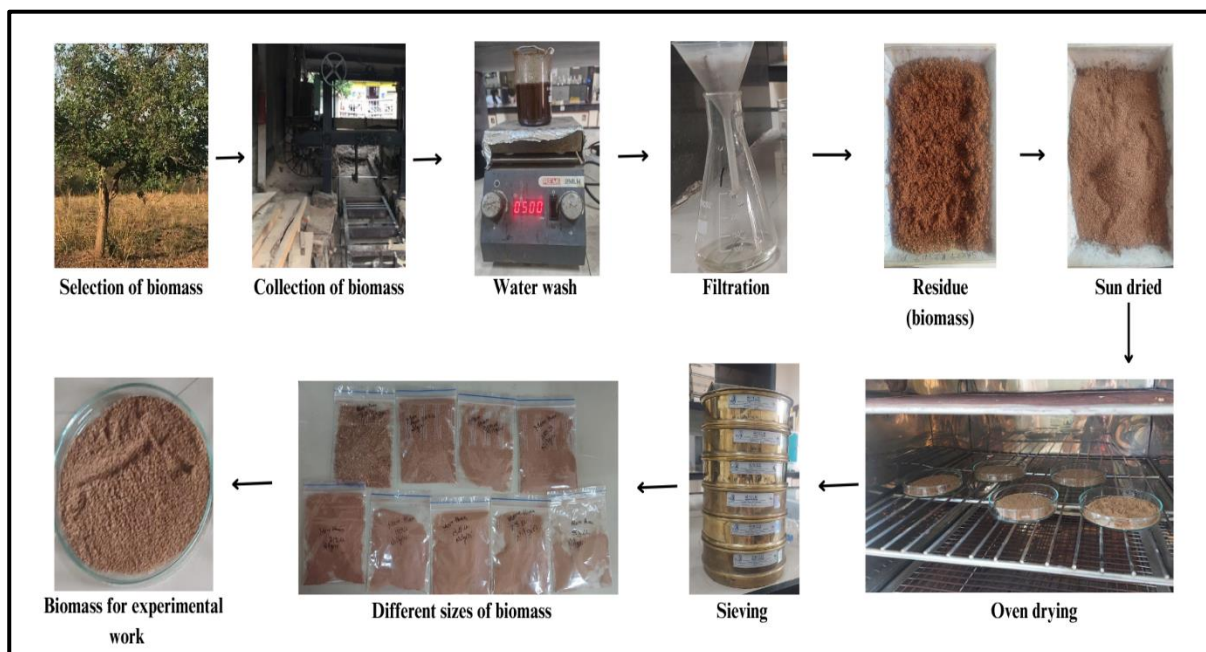


Fig. 1. Preparation of Biomass (BRSP) for Cr (VI) removal

2.1.2. Batch adsorption studies

All adsorption experiments were conducted on a rotary shaker at 150 rpm using 250 mL Erlenmeyer flasks at room temperature (25°C). The first experiment investigated the effects of adsorbent contact time and equilibrium time. For this purpose, Cr (VI) solution (100 mL, 50 mg/L) and 0.5 g of BRSP with pH 4.0 were added to the flasks. The mixtures were then agitated at 150 rpm for contact times ranging from 5 to 200 min until equilibrium was attained. A contact time of 60 min was determined to be sufficient for achieving equilibrium based on the preliminary experiments. The second experiment focused on the pH of the adsorbate solution. The pH values of the Cr (VI) solutions were adjusted to 1.0–12.0 using 1 M HNO_3 or 1 M NaOH solutions. Subsequently, 100 mL of Cr (VI) (50 mg/L) solution (90 mg/L) and 0.5 g of BRSP were added to 250-mL Erlenmeyer flasks and agitated for 60 min at 150 rpm. The third experiment examined the effect of adsorbent dosage. BRSP at different doses (0.1–1.0 g) was added to the flasks containing 100 mL of Cr (VI) solutions with a concentration of 50 mg/L, pH of 4.0, and contact time of 60 min at 120 rpm. The fourth experiment was conducted for different concentrations of Cr (VI), ranging from 5 to 300 mg/L, with a pH of 4.0, BRSP dosage of 0.5 g, and 100 mL of Cr (VI) solution at room temperature. The 5th parameter, with different Cr (VI) solution volumes varying from 25 mL to 250 mL with a 4.0 pH dosage, is 0.5 g of BRSP for 60 min of agitation at 150 rpm with a 50 mg/L concentration. Once metal adsorption was completed in each experiment, the supernatant was filtered using pre-washed Whatman

No. 2 filter paper with 2% nitric acid for 1 min. The filtrate was then analyzed for residual Cr (VI) content using UV-Vis spectrophotometry. The adsorption experiments were performed in triplicate. As a control, 50 mL of a solution containing Cr (VI) was placed in a 250-mL Erlenmeyer flask without adding biomass. The removal efficiency (%) measures the effectiveness of the adsorbent material in eliminating heavy metal ions from an aqueous solution. It was calculated using the initial and final concentrations of heavy metals, based on Eq. No. (1) and Eq. No. (2), as described by Phaenark et al [36].

$$\text{Biosorption (\%)} = \frac{C_i - C_f}{C_i} \times 100 \quad \text{Eq. No. 1}$$

$$Q = \frac{V (C_0 - C_e)}{m} \quad \text{Eq. No. 2}$$

Where

C_i = initial concentration of Cr(VI) solution (mg/L)

C_f = final concentration of Cr(VI) solution (mg/L)

V = solution volume (L),

C_0 = initial concentration of Cr(VI) solution (mg/L)

C_e = concentration of Cr(VI) solution at equilibrium (mg/L)

m = biomass quantity (g),

Q = metal uptake or adsorption ability (mg/g) [29][30].

2.1.3. Elemental and compositional analysis of the BRSP

Proximate analysis of BRSP

Proximate analysis was performed according to the guidelines established by the American Society for Testing and Materials (ASTM) standard. [23]–[24]. The moisture content (MC) was measured using the oven-drying technique described in the ASTM standard (D2867-09). A 1 g biomass sample was placed in a crucible and dried for three hours at 105 °C, after which it was allowed to cool in a desiccator. Weights were obtained using an analytical balance (Wensar ISO 9001:2001, India). An analytical balance was used to weigh the samples before and after heating them. The moisture percentage in the biomass was calculated using Equation 3 as follows:

$$MC(\%) = \left(\frac{B-C}{B-A} \right) \times 100 \quad \text{Eq. No. 3}$$

In this scenario, A refers to the weight of the crucible (g), B represents the total weight of the crucible with the BRSP sample (g), C signifies the weight of the crucible containing the sample (g), and (MC) denotes the percentage of moisture content (%).

Volatile matter (VM) was measured using the ASTM standard (D5832-98) by placing a 1 g biomass sample into a crucible and heating it for 7 min in a muffle furnace (Bio-Technics India BTI-2008) at 950°C[33]. Subsequently, the samples were transferred to a desiccator and weighed using an electronic balance. The equation (Eq. no. 4) is as follows.

$$VM(\%) = \left(\frac{D-B}{C-B} \right) \times 100 \quad \text{Eq. No. 4}$$

In this context, VM represents the percentage of volatile matter in the biomass, while C denotes the combined weight of the crucible and the initial sample (in grams). B refers to the weight of the empty crucible (g), and D indicates the weight of the crucible with ignited sample (g).

The ash content (AC) was determined following the ASTM standard (D2866-94): a 1 g BRSP sample was placed in a crucible and combusted for four hours at a temperature of 500°C in a muffle furnace. The samples were cooled in a desiccator and weighed using an electronic scale. To calculate the ash content of the sample, mass-balance (Eq. No. 5) was used:

$$AC(\%) = \left(\frac{D-B}{C-B} \right) \times 100 \quad \text{Eq. No. 5}$$

Where B is the weight of the crucible (g), C is the weight of the crucible plus the initial biomass sample (g), and D is the weight of the crucible plus the ash sample (g)[34].

The following equation (Eq. No. 6) was used to determine the fixed carbon (FC) content.

$$FC(\%) = 100 - [MC(\%) + VM(\%) + AC(\%)] \quad \text{Eq. No. 7}$$

FC, MC, VM, and AC are the percentages of fixed carbon, moisture, volatile matter, and ash [40], [41].

Boehm titration of BRSP

Boehm titration was employed to identify the functional groups on the biomass surface, including carboxyl, lactone, carbonyl, and basic groups. Three fundamental reagents were used to determine the acidic functional groups: sodium hydroxide (NaOH), sodium carbonate (Na₂CO₃), and sodium bicarbonate (NaHCO₃). The number of bases in the biomass sample was determined by hydrochloric acid (HCl) titration [35], [36].

Approximately 0.1 g of each sample and 50 ml of one type of 0.01 M solution of NaOH, Na₂CO₃, NaHCO₃, or HCl were mixed for the test. The reaction mixture was placed in a conical flask and shaken at 150 rpm for 24 h at room temperature. The suspensions were subsequently filtered using a 0.45 µm filter. The filtrate (10 ml) was back titrated against a 0.01 M HCl standard solution to determine the hydroxyl group content. The content of the basic groups was determined by back titration of the filtrate with 0.01 M NaOH. This was performed by agitating 0.1 g of biomass in a solution of 0.01 M HCl for 24 h.

pHPZC

Adding 0.1 g of BRSP to a 0.01 M NaCl solution enabled the measurement of the pH point of zero charge (pHpzc) of the BRSP. NaCl solutions with different pH levels were prepared. The pH levels of 1 to 12 (± 0.1 pH unit) were obtained using 0.1 M HNO₃ and 0.1 M NaOH to adjust the pH. The mixtures were placed on a rotary shaker at 150 rpm and shaken for 72 h. The pH_r(pH after settling) was then measured. The PZC was determined by plotting the differences in pH (ΔpH = pH_r – pH_i) versus the initial pH (pH_i) [29].

2.1.3. Structural and physicochemical characterization of Bauhinia Racemosa Sawdust

The synthesized adsorbents' surface morphology, elemental composition, chemical structure, and textural properties were fully characterized using SEM-EDX, FT-IR, and BET analyses. The surface morphology of the adsorbents was studied using Scanning Electron Microscopy (SEM) (Quanta 200-EDX, India) conducted as per standard procedures, at an accelerating voltage of 5.00 kV. The elemental composition and atomic distribution were measured using EDX (Quanta 200F-EDS system). Fourier-transform infrared (FT-IR) spectroscopy (Shimadzu IR Spirit) was employed to determine the functional groups of the biosorbents before and after Cr(VI) adsorption in the scanning range of 4000–400 cm⁻¹, and key vibrational modes related to the functional group interaction were noted. The surface area

was evaluated using the Brunauer–Emmett–Teller (BET) method (BELSORP Mini X, India); nitrogen gas adsorption–desorption at 700 mm (atmospheric) was performed after degassing the sample at 350°C for five hours. The BET surface area and pore size were measured to determine the porous structure of the biosorbents.

2.1.4. Adsorption Isotherms, Kinetics, and Thermodynamic Analysis

Adsorption isotherms, kinetics, and thermodynamics provide in-depth insights into the adsorption process, which assists in generating effective techniques for removing heavy metals. The adsorption isotherms of several models, including the Langmuir, Freundlich, Temkin, and Dubin-Radushkevich (D-R), were examined. Based on these isotherms, the applicable factors of the adsorbent surface properties, adsorption mechanism, and adsorbate-adsorbent interactions were defined [37]. The Freundlich model is appropriate for multilayer adsorption on heterogeneous surfaces with varying adsorption energies [38]. In contrast, the Langmuir isotherm is employed for monolayer adsorption on a uniform surface [39], [40]. The Temkin isotherm illustrates the impact of indirect interactions between the adsorbate and adsorbent [41], [42]. Whereas the D-R model offers insights into the energy of adsorption, whether it involves physical or chemical adsorption [43], [44].

The adsorption kinetics study examines the adsorption of heavy metals onto adsorbents. According to Lagergren's formula, the pseudo-first-order model states that the adsorption rate depends on the difference between the equilibrium adsorption capacity [42], [45]. The pseudo-second-order model suggests a chemisorption process, with the overall rate proportional to the number of available adsorption sites [46], [47]. Efficient adsorption systems are planned based on kinetic models, which provide adsorption rates, equilibrium capacities, and adsorption patterns. In addition, the adsorption process is primarily governed by thermodynamics, owing to its feasibility and spontaneity. By analyzing thermodynamic parameters such as Gibbs free energy (ΔG), enthalpy (ΔH), and entropy (ΔS), the endothermic or exothermic nature of adsorption can be determined, and the predominant parameter in the adsorption process can be identified [45], [48], [49].

3. Results and Discussion

3.1. Adsorption behaviour and batch study findings

3.1.1. Influence of Biosorbent Size

A range of 75–425 μm was selected to examine the impact of the adsorbent particle size. As the biomass particle size decreased, Cr (VI) removal increased from 40 to 99%. Smaller adsorbent particles lead to increased adsorption rates. Reducing the particle size of biomass

can increase its surface area, which in turn enhances its capacity to adsorb heavy metals [50]. The minimum biomass size of 75 μm resulted in a maximum removal percentage of $\sim 99\%$. This indicates that the effectiveness of Cr removal peaked at this specific biomass size, as shown in Fig... 2 (A). The percentage of Cr (VI) reduction decreased significantly with increasing biomass size. This suggests that larger particle sizes are less effective in eliminating Cr (VI) from the system. The last data point on the graph shows that as the biomass size neared 425 μm , the percentage of Cr (VI) removal decreased to approximately 41%, much lower than the removal efficiency observed at the smallest biomass size. The analysis revealed a negative association between biomass size and Cr (VI) elimination capacity. The reduced biomass sizes

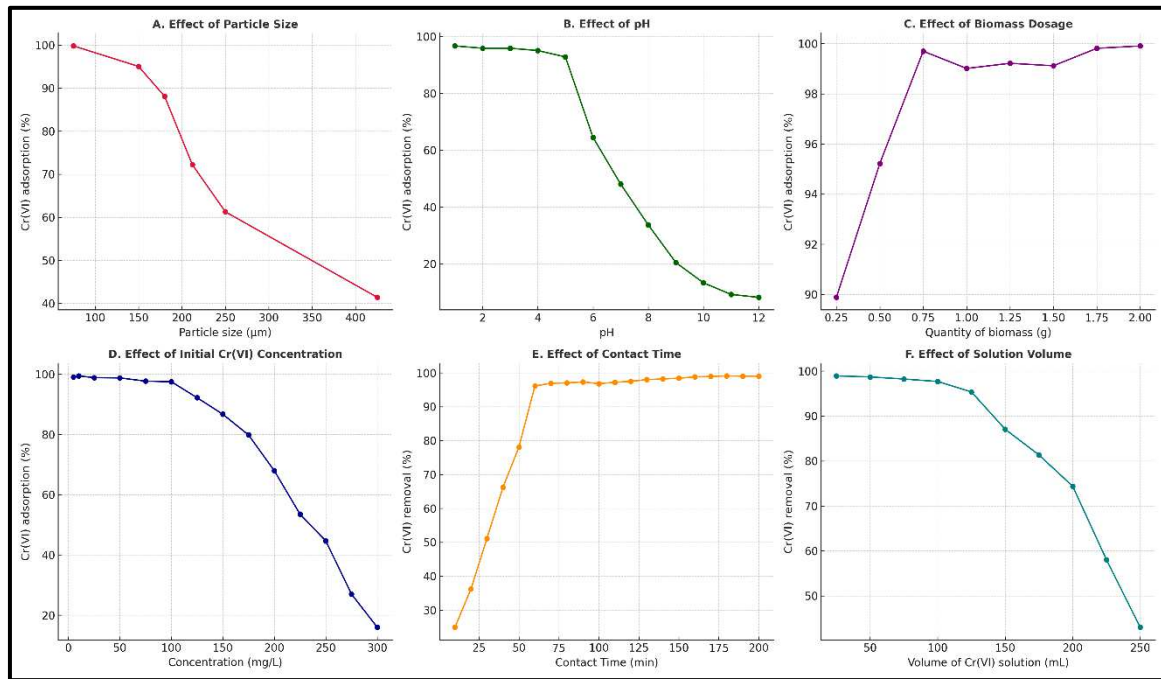


Fig. 2. Batch study: (A) Particle size, (B) pH, (C) Biomass dosage, (D) Initial Cr (VI) concentration, (E) Contact time, and (F) Solution volume of Cr (VI)

showed greater efficiency in adsorbing Cr (VI).

3.1.2. Influence of pH

The influence of pH on Cr (VI) adsorption efficiency using BRSP was studied in the range of 1-12. Under acidic conditions, the removal percentage was approximately 90-99%, particularly between pH 1 and 5. As we move beyond the basic pH of > 6 , the adsorption efficiency drops abruptly, and almost no removal occurs at alkaline pH values greater than 9. These patterns suggest that the pH of the solution plays a crucial role in adsorption because of alterations in surface charge interactions. These findings highlight the significance of optimizing the pH to achieve maximum Cr (VI) removal efficiency [51][52].

The graph in Fig. 2 (B), showing the percentage removal of Cr (VI) against pH, indicates that adsorption favors acidic conditions. This can be attributed to the excess hydrogen ions (H^+) at low pH, which protonate the adsorbent surface and give it a positive charge. The electrostatic interaction of these positively charged functional groups with negatively charged Cr (VI) oxyanions (e.g., HCrO_4^- and $\text{Cr}_2\text{O}_7^{2-}$) increases adsorption, which is termed ion exchange or ion adsorption.

However, with an increase in pH, the surface of the adsorbent becomes negatively charged, and there is electrostatic repulsion between the adsorbent and Cr (VI) oxyanion, resulting in a decrease in the adsorption rate. Furthermore, Cr (VI) species can precipitate as hydroxides because of higher pH values and limitations of the removal process.

At low pH, the following reaction occurs:



At moderate pH, the following reaction occurs:



At lower pH levels, the high concentration of H^+ ions on the surface of the adsorbent enhanced the reduction of dichromate ions ($Cr_2O_7^{2-}$). However, when the pH exceeded 6.0, the adsorption decreased significantly. This reduction is due to the interference between chromate ions (CrO_4^{2-}) and hydroxide ions (OH^-), as the adsorption of OH^- ions takes precedence. Biosorption is favorable at lower pH levels. BRSP demonstrated the most effective Cr (VI) removal at a pH of 4.0. Therefore, pH 4 (optimal pH) was identified for further research.

3.1.3. Influence of the Quantity of biomass

As shown in Fig. 2 (C), the biomass quantity impacts Cr(VI) percentage removal, which depends on the availability of binding sites for metal ions and the surface area of the BRSP. Increasing the quantity can improve the interaction between the biomass surface and the metal ions [53]. At a particular intersection, stability in the removal % or reduction may occur because of the aggregation of biosorption sites, which diminishes the availability of the surface area for metal ions. The adsorption capacity of Cr (VI) changed with the adsorbent dosage. Increasing the adsorbent dosage led to more significant metal removal [54], [55]. Simultaneously, the adsorption percentage significantly improved with increasing biomass dosage from 0.25 g to approximately 1.0 g and was close to 99% adsorption efficiency. This rapid increase indicates that Cr (VI) uptake is improved by more adsorption sites to adsorb Cr (VI). The saturation of active sites explains the phenomenon that causes higher amounts of adsorbent not to improve removal efficiency because the Cr (VI) ions in the solution become limited. These results highlight the need to optimize the adsorbent dosage to achieve higher reductions while avoiding the use of excessive resources, which is especially important for the cost-effectiveness and sustainability of large-scale processes.

For Cr (VI), concentrations exceeding the peak biosorption showed no significant increase in the biosorption rate. The existence of active sites for biosorption was confirmed by observing that the percentage removal increased with an increase in biomass. BRSP biomass at a 0.5–2.0 g dosage exhibited a higher removal percentage. This pattern is consistent with the results of a previous study. For further analysis, 0.5 g of biomass was used.

3.1.4. Influence of Concentration

The capacity and efficiency of the biosorption process were affected by the concentration of Cr (VI) during the initial phase of the cycle, as shown in Fig.2 (D). Lower concentrations resulted in a higher removal efficiency. When the Cr (VI) concentration was 5 mg/L and 10 mg/L, the highest removal rates were 99.87% and 99.75%, respectively. In each phase of this experiment, an increased concentration decreased the amount of Cr (VI) removed. The pH was 4.0, the volume of the chromium solution was 100 mL, and the temperature was ambient. The Cr (VI) solution concentrations varied from 5 to 300 mg/L, with a biomass of 0.5 g throughout the experiment. When metal ions cross vacant biomass sites, they push the lead-fit metals to the active binding sites of biomass. If this occurs, the adsorbent and adsorbate may

eventually reach an equilibrium. Furthermore, the saturated state obstructs metal adhesion to the biomass surface, where it typically resides. The main reason for this phenomenon is the gradual decrease in Cr (VI) as the concentration of metal ions increases. This attribute underpins their evolution.

3.1.5. Influence of Contact Time

Contact duration is pivotal in determining the efficiency of many chemical and physical processes, particularly in adsorption and pollutant removal systems. As the time increased, the rate of Cr (VI) uptake by the adsorbent also increased. This experiment optimized the contact time required for the biomass to reach equilibrium with the heavy metal solutions. Cr (VI) showed sudden biosorption during the initial stage, reaching equilibrium between 60 and 200 minutes. Fig. 2 (E) shows that 24.92% was eliminated after 10 min of contact time. The ability to remove gradually increased with time, reaching equilibrium after 60 min, with a removal rate of ~99%. The elimination of chromium increased with increasing contact time (10 to 50 minutes); however, after 60 minutes, the removal rate reached a saturated state within minutes and remained constant. This rapid elimination was due to the rapid interaction between the metal ions and the functional groups of the biomass. This saturation point often arises from the accumulation of metals at binding sites [56]. The rapid adsorption was attributed to the active binding sites on the biomass surface.

3.1.6. Influence of Volume of Solution

The adsorption activity of the biosorbent in response to Cr (VI) solution volume was more significant than that of other factors, showing a distinct decreasing trend when Cr (VI) solution volume gradually increased beyond a specific volume. As shown in Fig. 2(F), the removal of Cr (VI) was still quite efficient, with more than 95% Cr(VI) removed at the solution volume of 125 mL. With a higher volume being added (higher than 150 mL), the removal efficiency decreased progressively and significantly (43% at 250 mL). This decrease is mainly due to the saturation of the adsorbent surface with Cr (VI) ion concentrations higher than the number of adsorption sites. Furthermore, in high flow rates, the contact time between Cr (VI) ions and the adsorbent is insufficient to allow equilibrium adsorption, and the driving force for mass transfer decreases. The larger volume of solution could also lead to the dilution of the concentration gradient and a decrease in the adsorption rate. The results further indicate that the optimal volume should be kept, utilizing the adsorbent's effectiveness fully. In practical terms, this emphasizes the necessity to scale the amount of adsorbent added and the treatment conditions with volume to prevent the loss of efficiency. Thus, the study also confirms that the optimal solution volume ranges from 25 to 125 mL for efficiently removing the maximum Cr(VI) under the present experimental conditions. For further study, 100 mL of solution is considered.

3.2. Analysis of the elemental composition of the adsorbent

3.2.1. Proximate analysis

Table 2. Physicochemical properties of BRSP:

Parameters	Values (%)
Moisture (%)	4.56
Ash (%)	7.04

The results of the proximate analysis of the biomass are presented in Table 2. The results show a low moisture level in the sample, which is advantageous because it enhances the availability of active sites for adsorption without the need for considerable drying. Moderate ash concentrations indicate the presence of inorganic elements that may require management and positively affect the adsorption [57]. The significant amount of volatile matter suggests creating a porous structure by subjecting the material to heat or chemical treatment. This increases the available surface area for the adsorption [58]. A substantial amount of fixed carbon guarantees a robust framework with several active sites, essential for the efficient adsorption of heavy metal ions. This investigation shows that subjecting biomass to suitable pre-treatment and activation may be an efficient and environmentally friendly method for heavy metal removal from wastewater.

Volatile matter (%)	60.31
Fixed carbon (%)	28.09

3.2.2. Surface chemistry sorbent

The examination of the surface chemistry of BRSP indicated the presence of functional groups crucial for its action as a biosorbent. The carboxyl groups were measured to be 0.164 meq/g, indicating their acidic properties, capacity to bond with metal ions, and proton donation ability. Phenolic groups provide an extra level of acidity at a rate of 0.056 meq/g, which increases the possibility of hydrogen bonding interactions with pollutants. The most prevalent groups in the biomass, with a concentration of 0.680 meq/g, were lactonic groups, namely, lactones and lactols. These groups enhance the reactivity of biomass owing to their cyclic nature [59]. The sawdust surface exhibited a collective concentration of acidic groups of 0.900 meq/g and a concentration of fundamental groups of 0.465 meq/g, respectively.

Table 3. Surface chemistry of BRSP

Functional groups	Values (meq /g)
Carboxyl	0.164
Phenolic	0.056
Lactonic (lactones & lactols)	0.680
Total acidic	0.900
Total basic	0.465
pH PZC	2.7

This suggests the presence of fundamental functional groups that may interact with anions or act as exchange sites. The chemical composition of sawdust powder renders it suitable for applications that require contaminant elimination. Their acidic functional groups facilitate effective adsorption, particularly for eliminating heavy metals from aqueous environments. The specific concentrations of the functional groups are presented in Table 3.

3.2.3. Point Zero Charge (pHPZC)

Fig. 3 shows the relationship between pH and pHPzc values. From the graph, it is clear that the pHPzc values are lower than the pH values. The adsorbent developed positive charges, which enhanced its effectiveness in eliminating Cr (VI) anions. Likewise, when the pH exceeds the pHPzc ($7 > 2.7$), as shown in Table 3, the adsorbent acquires positive charges that greatly enhance the removal of Cr ions. This phenomenon can be explained by the intense electrostatic attraction between the positively charged surface of the adsorbent and dichromate ions.

In an acidic environment, the predominance of the chromate anion (HCrO_4^-) over the dichromate anion ($\text{Cr}_2\text{O}_7^{2-}$) enhances the adsorption efficiency of these species.[60]. These findings are consistent with those reported by Mancilla et al. [61]. Owing to the strong electrostatic interactions, the BRSP surface chemistry, characterized by substantial acidic functional groups and pH PZC, enhances its effectiveness as a biosorbent for Cr ions. This material is effective for removing heavy metals from wastewater.

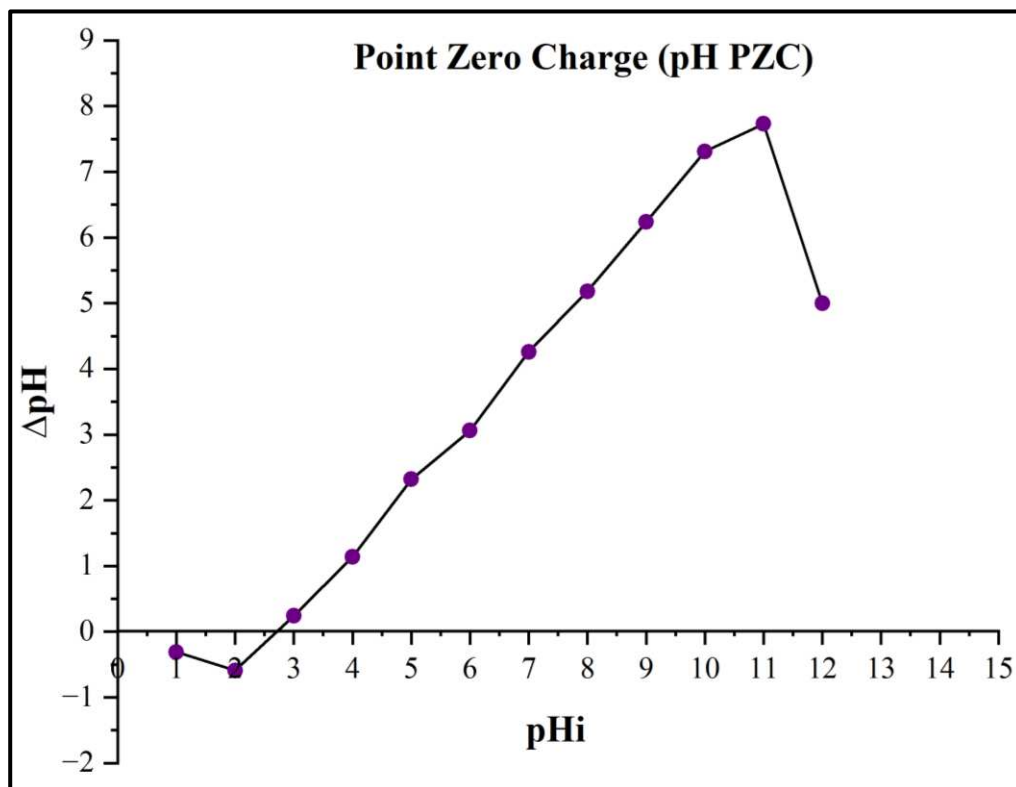


Fig. 3. Determination of pH_{pzc} of BRSP

3.3.Characterization Analysis

3.3.1. BET (Brunauer-Emmett-Teller)

The texture of (BRSP) was studied by BET (Brunauer–Emmett–Teller (BET) surface area analysis, and the results are shown in Table 4. The specific surface area (SBET) of BRSP was 212.2 m²/g, suggesting that a large surface area was available for adsorption. A greater surface area typically results in better adsorption performance because it has more active surface sites for binding. The total pore volume of BRSP was 0.323 cm³/g, indicating the presence of considerable internal pores through which adsorbate molecules can diffuse into the sorbent matrix. Moreover, the average pore diameter was estimated to be 6.403 nm from the graph, indicating the mesoporous characteristics of BRSP because the value falls within the range of mesopores (2–50 nm). Mesoporous structures have special advantages in adsorbing heavy metal ions in aqueous solutions because the surface accessibility and internal surface area can be balanced. Overall, BET analysis indicated that BRSP has a high surface area and mesoporous structure, which can effectively contribute to a high biosorption efficiency for heavy metals, including Cr (III) and Cr (VI), from electroplating wastewater.

Table 4. BET analysis of BRSP

Sample Pore	SBET (m ² /g)	Pore volume(cm ³ /g)	Average pore diameter (nm)
BRSP	212.2	0.323	6.403

3.3.2. Surface morphology

As shown in Fig. 4A (500X, 200 μm), raw BRSP displays elongated fibrous structures, characteristic of wood cellulose, which are loosely arranged with naturally porous and slightly

rough texture. The lower magnification image (100X, 100 μ m) also verifies its natural sponge-like structure (which is favorable for adsorption).

After loading Cr (VI) for adsorption (Fig. 4B), morphological changes were observed. At 500X, a clear striated pattern of the fiber surfaces was observed, indicating the accumulation and interaction of Cr(VI) with the adsorbent matrix. In addition to the larger surface roughness, visible depositions were observed in the 100X image. The pore volume also decreased, which can be attributed to the partial or total blockage of pores by the Cr(VI) particles. Decreased pore volume may enhance the surface activity and increase the proportion of accessible adsorption sites in the adsorbent.

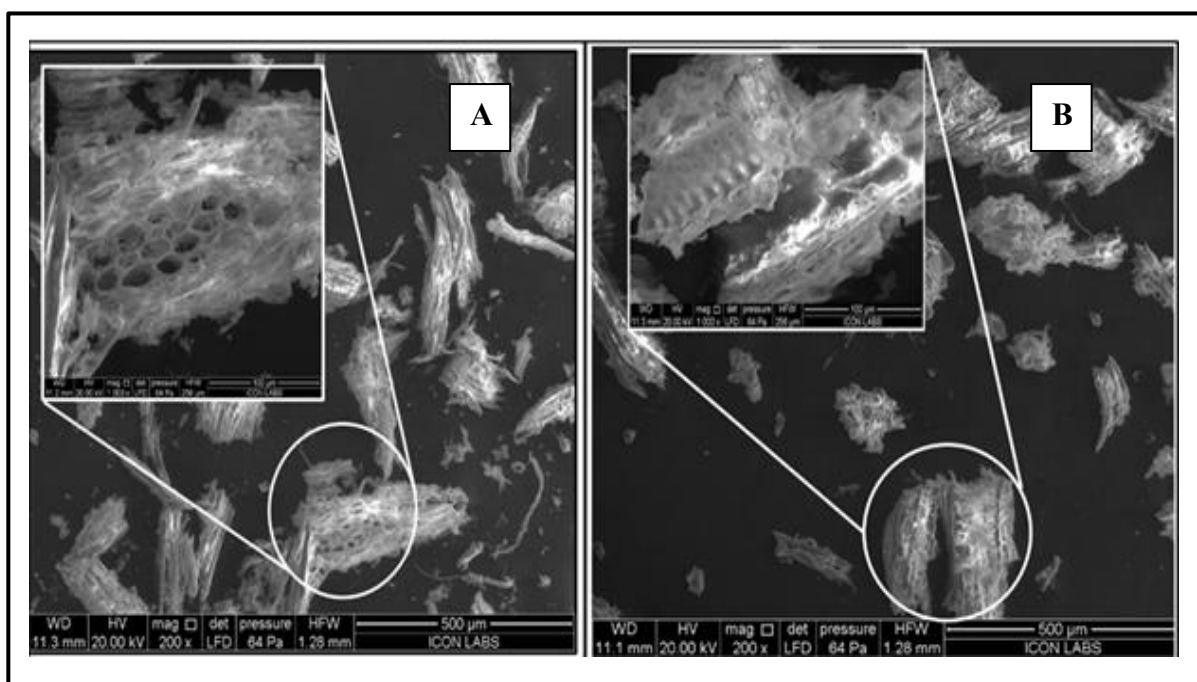


Fig. 4. SEM images of BRSP (A) before and (B) after Cr (VI) adsorption.

3.3.3. EDX (Energy-dispersive X-ray spectroscopy)

The elemental composition of BRSP was examined before and after the adsorption process using energy-dispersive X-ray spectroscopy (EDX). The EDX analysis results of the BRSP biomass before and after the addition of Cr (VI) are shown in Figs. 5 (A) and (B).

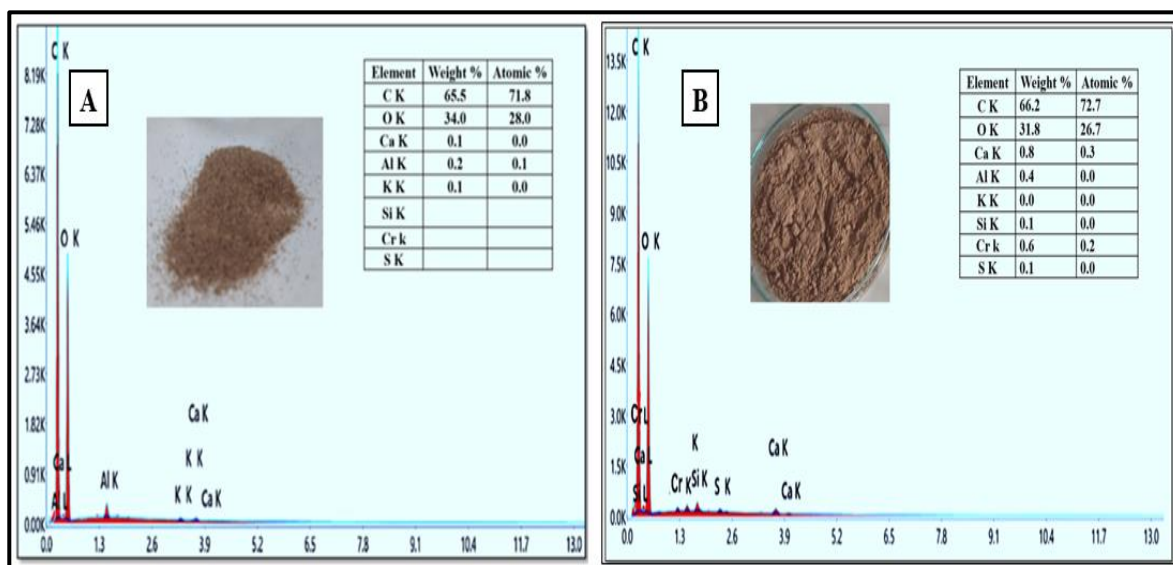


Fig. 5. EDX images (A) before and (B) after Cr (VI) on BRSP

The EDX spectra of chromium-loaded BRSP demonstrated the presence of a chromium peak, confirming the potential of BRSP as a biosorbent. The tables in Figs. 5 (A) and (B) are shown in the quantitative results of the EDX analysis of the BRSP biomass before and after Cr (VI) adsorption. The EDX analysis indicated that chromium was present at a quantity of 0.6%. The EDX images and tabular data demonstrated the adherence of Cr to the biomass surface. O, Si, and Al are the most common elements. EDX revealed the presence of Si, which may be attributed to impurities such as dust particles, and Al, which was present at low levels owing to sample coating at the time of analysis [51].

3.2.4. FTIR (Fourier-transform infrared spectroscopy)

IR spectroscopy is an effective analytical method for identifying the chemical components of biomaterial surfaces. This technique provides essential insights into the bonding relationships between the sorbate (metal) and the sorbent (biomaterial). FTIR spectral analysis of BRSP was performed before and after Cr (VI) adsorption from an aqueous medium. Fig. 6 shows the comparative peaks obtained for the raw BRSP and chromium-laden BRSP.

The FT-IR spectrum of *Bauhinia racemosa* sawdust powder (BRSP) exhibited several absorption bands, indicative of the chemical complexity of the biomass. The broad hydroxyl (–OH) peak shifted from 3335.97 cm^{-1} before adsorption to 3294.11 cm^{-1} after adsorption, indicating a change in hydrogen bonding due to the interaction with Cr (VI) [62]. The contribution from the aliphatic C–H stretching observed at 2891.92 and 2896.85 cm^{-1} suggests the existence of cellulose and hemicellulose, and their slight shifting is evidence of interaction between Cr (VI) and the carboxyl group [63]. Peaks at approximately 2275.51 and 2290.28 cm^{-1} were presumably assigned to the formation of a complex between chromium ions and the –N=C=O groups [64]. Changes in the C≡O-related bands (at 1984.13 and 1980.84 cm^{-1}) and carboxyl-associated C=O vibrations (from 1602.46 to 1598.35 cm^{-1}) further indicate Cr binding to functional groups such as –COOH [65], [66].

The 1507.25 and 1503.14 cm^{-1} peaks indicate the intermolecular interactions between the carboxyl, hydroxyl, and amine groups for Cr (VI) adsorption [61]. In comparison, shifts from 1425.99 to 1416.96 cm^{-1} and 1330 to 1371 cm^{-1} reveal the role of carbohydrate and C–H

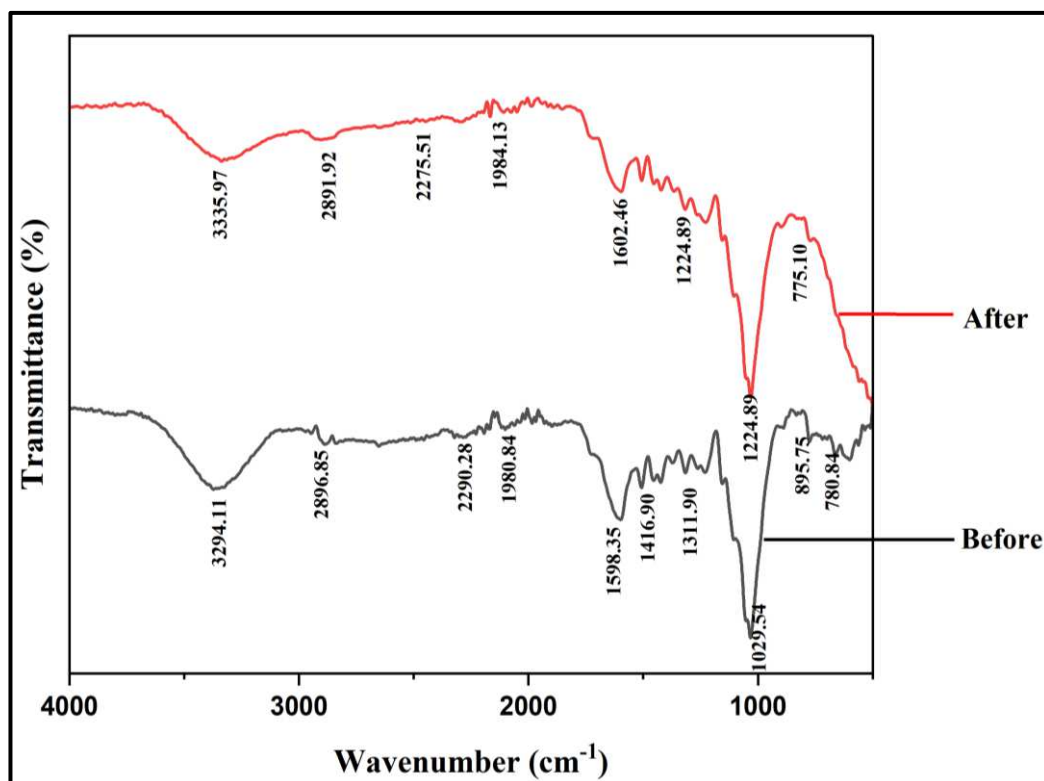


Fig 6. FTIR image of biomass before and after Cr (VI)

rocking vibrations, respectively [67]. The C–O bands observed at 1224.89 and 1225.71 cm^{-1} showed a slight shift, and the C–O peak shifted from 1033.65 to 1029.54 cm^{-1} , indicating that.

Cr (VI) is bound to hydroxyl and carboxyl groups [68]. Displacement of the dichromate-related Cr–O peak from [68] 900 cm^{-1} to 899 cm^{-1} confirmed the binding of Cr (VI) onto BRSP

[36]. Aromatic C–H at 775.10 cm^{-1} were also shifted to 780.84 cm^{-1} for aromatic bonds, which proved interaction of chromium with aromatic groups. These spectral shifts agreed with the Boehm titration findings, which verified the direct involvement of cellulose and hemicellulose functional groups in Cr (VI) adsorption and suggested significant surface chemistry changes in BRSP after Cr (VI) adsorption [69].

3.4. Isotherm Model

The adsorption isotherms indicate an equilibrium relationship between Cr(VI) ions and BRSP. The adsorption behavior was analyzed using four isotherm models (Langmuir, Freundlich, Temkin, and Dubinin–Radushkevich (D–R)), and their parameters are listed in Table 4, and plots are shown in Figs. 7–10.

3.4.1. Langmuir adsorption isotherm model (2-parameter model)

Numerous authors have utilized the Langmuir isotherm model to explain adsorption phenomena. Its purpose is to depict monolayer adsorption on a uniform surface with a limited number of identical sites. The adsorbed molecules did not interact, and the adsorption of one molecule did not affect the adsorption of the other. The adsorption process is reversible, with an equilibrium between the adsorbed and free molecules in the solution.

Mathematical expression for Langmuir (linear form)

$$\frac{C_e}{q_e} = \frac{C_e}{q_m} + \frac{1}{k_L q_m} \quad \text{Eq. No.}$$

10

Where

q_e = amount of adsorbate adsorbed per unit of adsorbent at equilibrium (mg/g)

q_m = maximum adsorption capacity of adsorbent (mg/g)

C_e = Equilibrium concentration of adsorbate in solution (mg/L)

K_L = Langmuir adsorbate constant (mg/L) related to the affinity between the adsorbate and adsorbent.

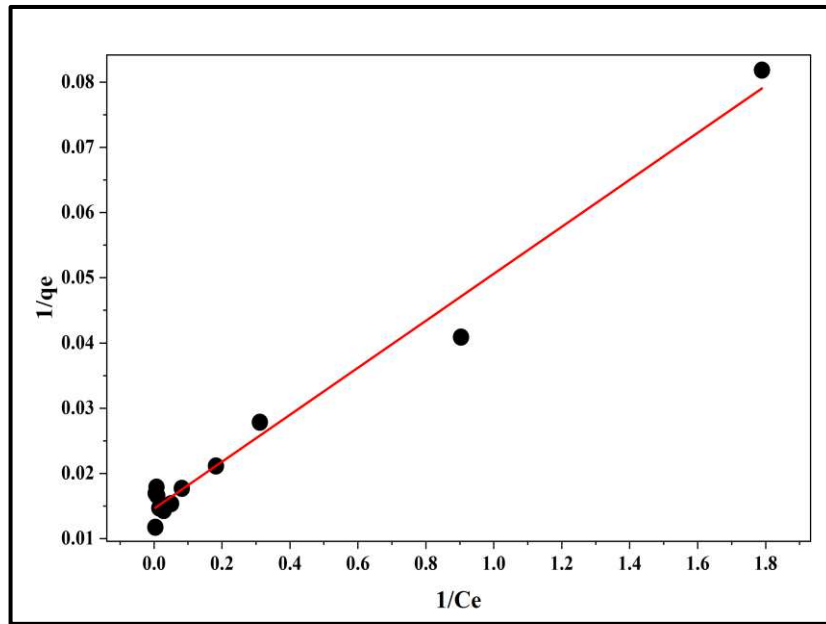


Fig 7. Langmuir adsorption isotherm study for removal of Cr(VI) using BRSP

The Langmuir model, based on monolayer adsorption on a homogenous surface, best fit the data, with an R^2 (0.99). The theoretical maximum monolayer adsorption capacity ($q_{\max}$) was 106.86 mg/g, which is close to the experimental q_e value (105.61 mg/g), indicating that BRSP can effectively adsorb Cr(VI). The dimensionless separation factor (R_L) was calculated to be 0.0653, indicating the favorability of the adsorption process ($0 < R_L < 1$).

3.4.2. Freundlich adsorption isotherm model (2 parameter model)

Freundlich isotherm is an empirical model that describes the adsorption process on heterogeneous surfaces.

The Freundlich equation is expressed as (linear form)

$$\log q_e = \log k_f + (1/n) \log C_e \quad \text{Eq. No. 11}$$

Where,

q_e = The amount of solute adsorbed per unit mass of adsorbent (mg/g)

C_e = The equilibrium concentration of solute in solution (mg/L)

K_f = The Freundlich constant indicative of adsorption capacity

$1/n$ = Freundlich exponent, which indicates the adsorption intensity of the adsorbent.

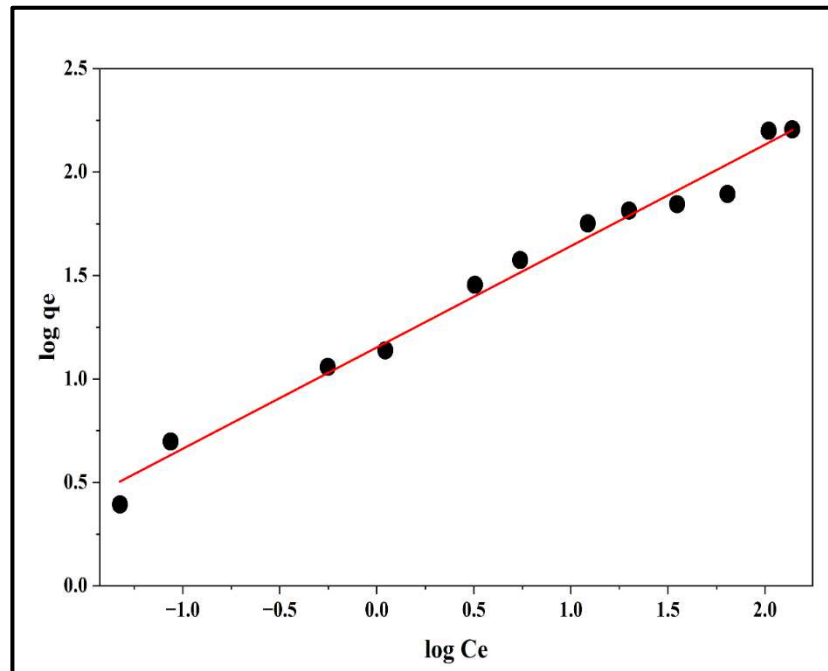


Fig 8. Freundlich adsorption isotherm for the removal of Cr (VI) using BRSP

From Table 5, the value of $1/n$ is greater than that of the Freundlich isotherm, which assumes that the surface of an adsorbent is heterogeneous, with varied affinities and energy levels for

Two parameters, K_f and n , were used to interpret the Freundlich constant; a higher K_f value indicates a greater adsorption capacity of the adsorbent[70]. The $1/n$ value indicates the favorability of the adsorption process. The adsorption was more linear for $0 < 1/n < 1$, suggesting a uniform surface energy on the adsorbent. A higher $1/n$ value (greater than 1) indicates greater heterogeneity. The heterogeneity of the surface, exponential distribution of the active sites, and energy of the active sites are all defined by the Freundlich isotherm model [24]. From The Freundlich isotherm describes a characteristic in which the adsorption energy decreases logarithmically as adsorption progresses. The Langmuir isotherm, on the other hand, assumes a uniform adsorption energy[25]. The Freundlich isotherm allows multilayer adsorption, and adsorbed molecules act as additional adsorption sites. Because the Freundlich isotherm is purely empirical, it lacks a theoretical framework associated with isotherms, such as the Langmuir isotherm [26].

3.4.3. Temkin adsorption isotherm model (2 parameter models)

The Temkin adsorption isotherm model is widely used to describe adsorption processes, particularly on heterogeneous surfaces. This model addresses adsorbate interactions, and by incorporating the heat of adsorption, the adsorption energy can be depicted as decreasing linearly with coverage. When the surface of the adsorbent is not homogeneous, this model can provide more accurate expressions for adsorption phenomena [27].

The Temkin equation is expressed as (linear form)

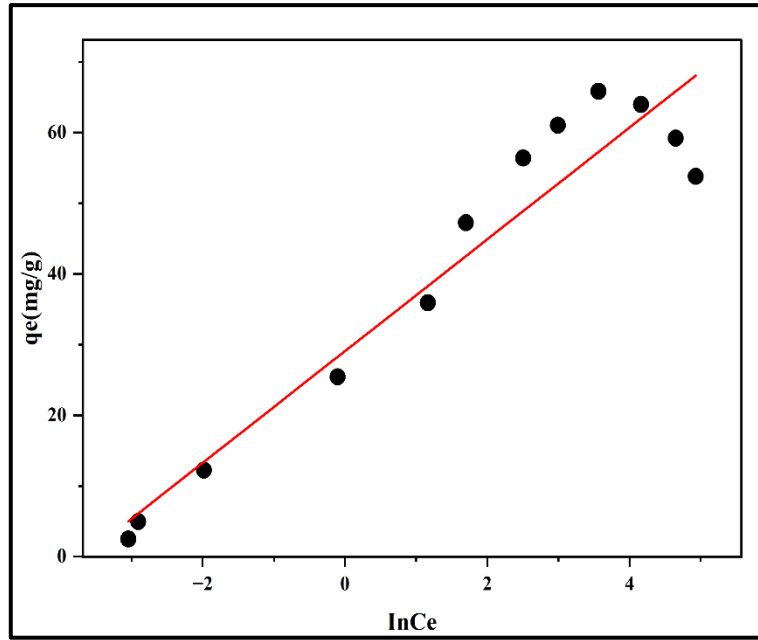


Fig 9. Temkin adsorption isotherm for the removal of Cr (VI) using BRSP

$$q_e = B_T \ln A_T + B_T \ln C_e \quad \text{Eq. No. 12}$$

Where

C_e = Equilibrium concentration of adsorbate (mg/L)

q_e = Amount adsorbed at equilibrium (mg/g)

A_T = Binding equilibrium constant

B_T = Binding equilibrium heat constant (J/mol)

T = Absolute temperature (K)

The Temkin model considers adsorbate–adsorbent interactions and assumes that the heat of adsorption decreases linearly with surface coverage. The linear fit ($R^2 = 0.920$) and Temkin binding energy ($B_T = 316.98$ J/mol) support a moderate adsorption strength. This also suggests chemisorption through surface complexation or ion exchange mechanisms

3.4.4. Dubinin-Radushkevich (D-R) adsorption isotherm model (2-parameter models)

The Cr (VI) using BRSP Dubinin-Radushkevich (D-R) is often utilized in solid-liquid interfaces to describe adsorption equilibria with two parameters. This is highlighted by its ability to consider the adsorption energy and maximum adsorption capacity[31]. The D-R isotherm model is an empirical model that describes adsorption on heterogeneous surfaces. This model helps distinguish between physical and chemical adsorption based on energy[35].

The linear form of the D-R isotherm equation is as follows:

$$\ln q_e = \ln q_m - k\epsilon^2 \quad \text{Eq. No. 13}$$

Where

q_e = Equilibrium adsorbent-phase concentration of adsorbate (mg g^{-1})

q_m = Theoretical saturation capacity (mg g^{-1})

K = Activity coefficient related to mean free energy of adsorption ($\text{mol}^2 \text{kJ}^{-2}$)

ϵ = Polanyi potential (KJ mol^{-1})

The model is summarized by two basic parameters: the maximum adsorption capacity (Q_m) and the characteristic energy of adsorption (ϵ) [33]. Two parameters describe adsorption equilibria, which are often utilized in solid-liquid interfaces.

ϵ is related to the energy required to transfer one mole of the adsorbate from infinity to the adsorbent surface. It is calculated as:

$$\epsilon = \frac{1}{\sqrt{2k}} \quad \text{Eq. No 14}$$

If $E < 8 \text{ KJ/mol}$, the adsorption is physisorption.

If $E > 8 \text{ KJ/mol}$, the adsorption is chemisorption.

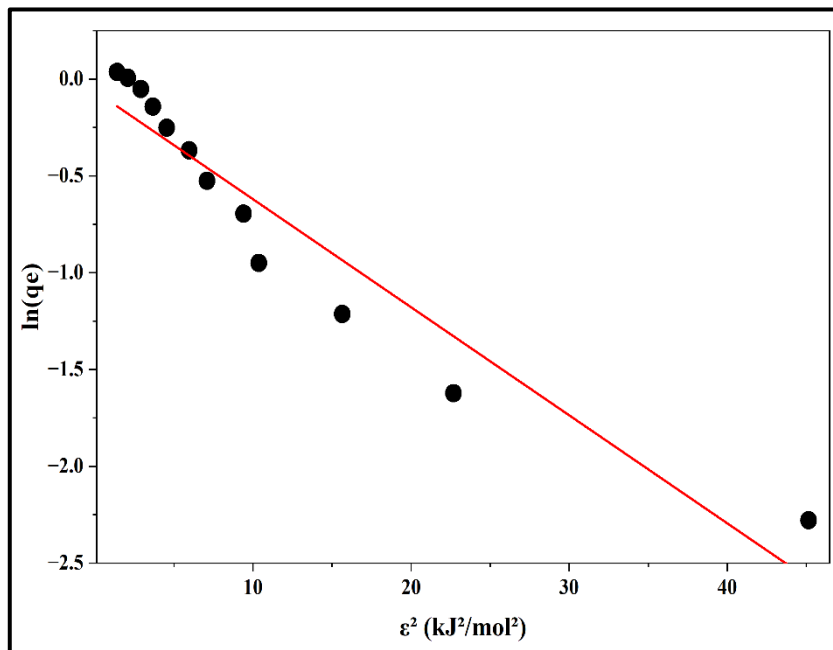


Fig 10. D-R adsorption isotherm for the removal of Cr (VI) using BRSP

The D–R model, which is typically used to distinguish between physical and chemical adsorption, yielded a relatively low correlation coefficient ($R^2 = 0.91664$). The mean adsorption energy ($E = 2.99 \text{ kJ/mol}$), derived from the D–R constant ($\beta = 0.0558 \text{ mol}^2/\text{kJ}^2$), suggests a predominantly physisorption mechanism; however, this contradicts the kinetic and thermodynamic data, which indicate chemisorption. This discrepancy may stem from the limited applicability of the D–R model to systems with complex biosorbent surfaces.

Table 5. Isotherm and parameters

Isotherm Model	Parameter	Values
Langmuir Adsorption Isotherm (2 Parameters)	$q_{\max} \text{ (mg g}^{-1}\text{)}$	106.86
	$K_L \text{ (L mg}^{-1}\text{)}$	0.286

	R_L	0.0653
	R^2	0.99119
Freundlich Adsorption Isotherm (2 Parameters)	K_f	68.983
	$1/n$	2.07615
	R^2	0.9827
Temkin Adsorption Isotherm (2 Parameters)	B_T (J/mol)	316.98
	K_T (J/mol)	0.315
	R^2	0.92006
Dubinin-Radushkevich (D-R) adsorption isotherm (3 parameters)	β (mol ² /kJ ²)	0.0558
	E (kJ/mol)	2.99
	q_m (mmol/g)	0.9984
	R^2	0.9164

3.5. Kinetics Model

3.5.1. Pseudo-First Order

The direct correlation between the adsorption rate and the difference between the equilibrium adsorption capacity (q_e) and the adsorption capacity at a particular time (q_t) is the foundation of the pseudo-first-order model, which is defined by the Lagergren equation. This is the usual way to represent the model.

$$\log(q_e - q_t) = \log q_e - \frac{k_1}{2.303} t \quad \text{Eq. No. 15}$$

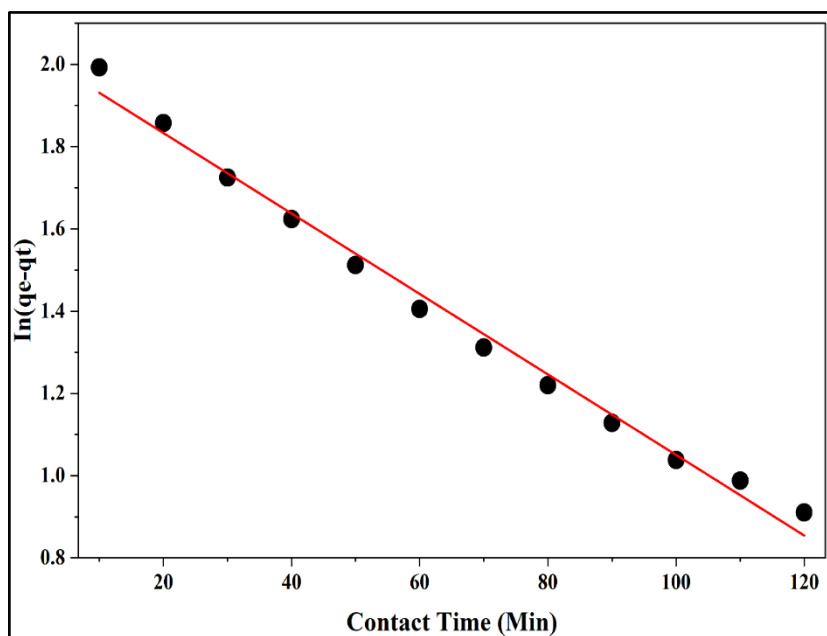


Fig. 11. Pseudo-first-order kinetics for Cr (VI) removal using BRSP

Where q_e and q_t = the amount of chromium adsorbed on the adsorbent at equilibrium, and at any time t , respectively, and K_f = the Rate constant

The slopes and intercepts of the $\log (q_e - q_t)$ vs. $t(\text{min})$ plot are shown in Fig. 11. The first-order rate constant K_f was calculated to be 0.034453/min, and the equilibrium adsorption capacity was 106.23 mg/g.

3.5.2. Pseudo-second order

The pseudo-second-order model assumes that the adsorption rate is proportional to the square of the difference between q_t and q_e . The model is expressed as

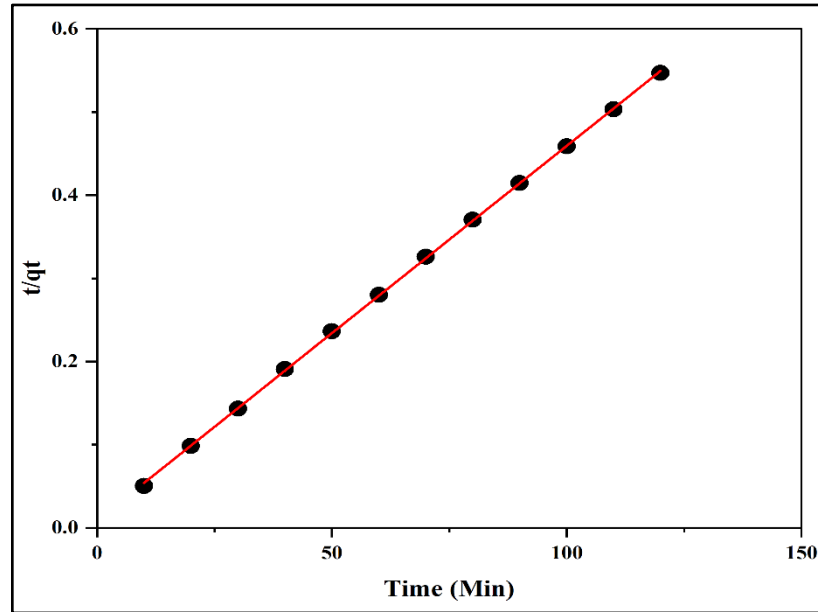


Fig 12. Pseudo-second-order kinetics for Cr (VI) removal using BRSP

$$\frac{1}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \quad \text{Eq. No. 16}$$

Where K_f = Equilibrium rate constant, and q_e and q_t are the amounts of chromium adsorbed on the adsorbent at equilibrium and time t , respectively.

The slopes and intercepts of the t/q_t versus t (min) plot are presented in Fig. 12. The pseudo-second-order rate constant K_2 was calculated as 5.35×10^4 g/mg/min and q_e as 105.6073 mg/g, respectively.

Table No. 6. Kinetic Parameters for Cr (VI) adsorption onto Sawdust

Kinetics	Parameter	Value
Pseudo-first order	q_e	106.23 mg/g
	K_1	0.0344/min
	R^2	0.99757
Pseudo-second order	q_e	105.60729 mg/g
	K_2	5.35×10^{-4} g/mg/min
	R^2	0.99998

Kinetic studies on Cr (VI) adsorption revealed that the adsorption process was well-fitted by pseudo-first-order and pseudo-second-order kinetics, as shown in Fig. 13. The pseudo-first-order model produced an equilibrium adsorption capacity of 106.83 mg/g, with a rate constant of $0.034453 \text{ min}^{-1}$. The pseudo-second-order model yielded a capacity of 50.6073 mg/g and a rate constant of $5.35 \times 10^{-4} \text{ g/mg/min}$, as shown in Table 6. The fact that the data were best fitted to the pseudo-second-order model indicates that the adsorption mechanism was chemical adsorption involving valence forces or electron sharing[29]. This is an essential revelation of adsorption kinetics and adsorbent selection processes to achieve improved efficiency of Cr (VI)removal by adsorbents.

3.6.Thermodynamics Study

Thermodynamic parameters are crucial for understanding the' feasibility, nature, and mechanisms of adsorption processes. The main thermodynamic parameters were used to evaluate the Gibbs free energy change (ΔG^0), enthalpy change (ΔH^0), and the entropy change. (ΔS^0),[36] which provides insight into whether the adsorption process is spontaneous,

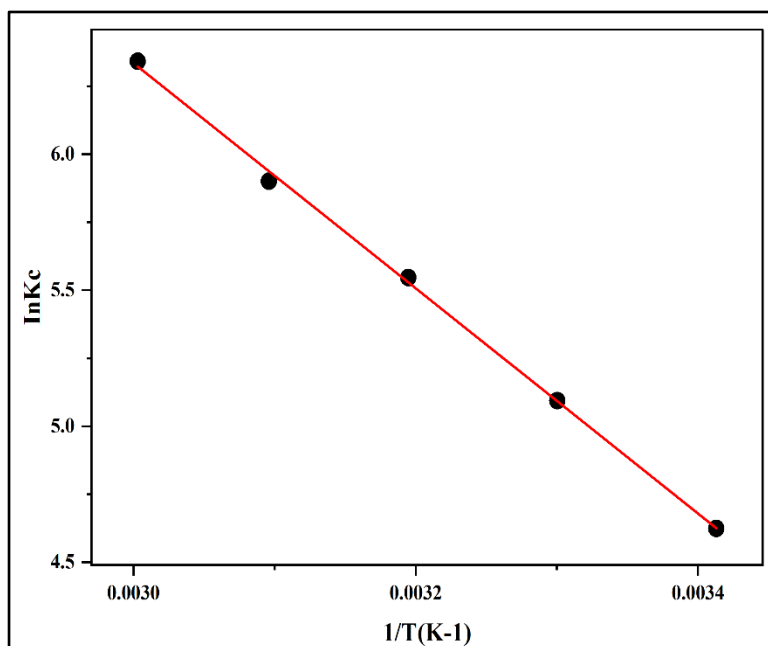


Fig. 13. Vant Hoff plot for the removal of Cr (VI) by adsorption using BRSP

exothermic or endothermic, and the degree of randomness at the solid-liquid interface [37].

Calculation of thermodynamic parameters

The standard Gibbs free energy change (ΔG) for adsorption was calculated using the following equation:

$$\Delta G^0 = -RT \ln K_c \quad \text{Eq. No. 17}$$

Where

R = Universal gas constant (8.314 J/mol^{-1})

T = Temperature (K)

K_c = Equilibrium constant of the adsorption process

The equilibrium constant K_c is calculated from

$$k_c = \frac{C_{ads}}{C_e} \quad \text{Eq. No 18}$$

Where

C_{ads} = concentration of adsorbate on the adsorbent at equilibrium (mg/L)

C_e = Equilibrium concentration of the adsorbate in solution (mg/L)

The energy change (ΔG⁰), enthalpy change (ΔH⁰), and entropy change (ΔS⁰) were evaluated for each sample.

The Van't Hoff equation was used.

$$\ln k_c = \frac{-\Delta H^0}{R} \cdot \frac{1}{T} + \frac{\Delta S^0}{R} \quad \text{Eq. No. 19}$$

By plotting van 't Hoff ln K_c vs. 1/T, the slope (- ΔH⁰ / R) and intercept (ΔS⁰ /R) can be determined, as shown in Fig.13. The results are presented in Table 7.

Table 7. Thermodynamics interpretation				
Temperature (°C)	ΔG (kJ/mol)	ΔH ⁰ (KJ/mol)	ΔS ⁰ (kJ·mol ⁻¹)	R ²
20	-1.0764	34.4198	1.774811	0.99884
30	-1.18112		1.186698	
40	-1.29107		0.892773	
50	-1.40607		0.716518	
60	-1.45289		0.597879	

Table 7 shows the thermodynamic properties of the adsorption process, which indicate the feasibility and nature of adsorption. The negative ΔG values at all temperatures suggest that adsorption was spontaneous. The endothermic nature of adsorption (positive ΔH⁰ = 34.4198 kJ·mol⁻¹) indicates preferential adsorption at higher temperatures. A positive ΔS⁰ indicates a higher disorder at the solid-liquid interface upon absorption. The high R² value (R² = 0.99884) of the van't Hoff plot demonstrates a strong linear correlation between the curve endpoints, supporting the accuracy of this thermodynamic study.

Future Scope:

The following are some possible future research directions derived from this study on the use of Bauhinia racemosa (BRSP) for Cr removal:

- The removal of heavy metals and pollutants other than chromium by BRSP was studied.
- Investigate options for increasing the adsorption capacity of BRSP, eg, through chemical modification or activation procedures.
- Pilot testing was conducted to determine the BRSP efficiency in industrial wastewater treatment.

- Establish regenerative and reuse procedures to enhance the sustainability and cost-effectiveness of BRSP as an adsorbent.
- Investigate the feasibility of BRSP in multi-component adsorption systems containing several heavy metals or pollutants.
- Explore the BRSP application in flow adsorption studies or fixed-bed columns.
- Develop BRSP-based composites or hybrid adsorbents to improve performance.
- Explore the potential uses of chromium-loaded BRSP post-adsorption, for example, in construction materials or as a soil conditioner.

Conclusions:

This work studied the efficiency of *Bauhinia racemosa* sawdust powder (BRSP) as an adsorbent of Cr (VI) from aqueous solutions. The characterization of BRSP showed good adsorption properties, such as the heterogeneous surface with different functional groups and a large specific surface area. The adsorption was pH sensitive, and maximum adsorption at pH 4.0. Batch experiments have indicated that the particle size, initial concentrations of Cr (VI), and the dosage of adsorbent significantly enhance the removal of Cr (VI), with minimum particle sizes, lower initial Cr (VI) concentrations, and a greater dosage of adsorbent showing the best results. Chemisorption was found to be the dominant mechanism according to the pseudo-second-order model of the adsorption kinetics. Based on the isotherm examination, the model of Langmuir, which implies monolayer adsorption onto a homogeneous surface, describes the adsorption most appropriately. The maximum adsorption capacity was calculated to be 106.83 mg g⁻¹, implying the CrVI removal was due to the high potential of BRSP.

Thermodynamic studies showed that the adsorption process was spontaneous and endothermic. FTIR and SEM-EDX studies indicated that chromium has been successfully adsorbed onto the surface of BRSP, and the surface morphology and elemental content changed significantly after adsorption. In conclusion, this study shows that it can be a potentially useful, eco-friendly, and low-cost candidate for Cr (VI) removal from aqueous solution. These observations enhance the concept of green water treatment and provide a potential cost-effective strategy for the remediation of industrial effluents contaminated with Cr (VI).

Ethical Approval: Not Applicable

Informed Consent: Not Applicable

Statement Concerning Research with Human Participants and/or Animals: This study does not involve any clinical trial and therefore does not require clinical trial registration

Consent Form for Publication: Not Applicable

Consent to Participate: Not Applicable

Disclosure Statement: The authors declare no pertinent financial or nonfinancial interests.

Data Availability Statement (DAS): Data available on request from the authors

Author's Contribution:

Sr. No.	The sequence of authors in the submitted paper	Contribution of the Author in the paper*
1.	1 st author	Experimentation and analysis for a research study, Collected data, worked on data and analysis, tools, and wrote all manuscript sections.
2.	2 nd author	Supervision conceived and planned the study, reviewed and corrected the manuscript.

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Competing Interests: The authors declare no competing interests relevant to the content of this study.

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