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Biosorption of Chromium Using Biochar Derived from Fruit Waste: Isotherm and Thermodynamic Analysis

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Abstract:

In recent years, heavy metal contamination has become a major environmental and public health concern. Chromium is considered one of the most toxic heavy metals and is listed as a priority pollutant by the United States Environmental Protection Agency due to its high toxicity. Chromium is widely released from industries such as electroplating, tanning, textile processing, and mining. Hence, it is essential to develop simple, efficient, and sustainable methods for chromium removal from contaminated water. This study investigated the feasibility of using green biochar synthesized from orange peel waste through a simultaneous pyrolysis process for the adsorption of hexavalent chromium from synthetic wastewater. The biochar was characterized using Fourier transform infrared spectroscopy to identify functional groups such as C–O and C–H bonds. Kinetic experiments were performed with contact times ranging from 0 to 330 minutes to determine the equilibrium time, which was found to be approximately 270 minutes. Adsorption behaviour at different chromium concentrations indicated that physisorption dominated at lower concentration (15 mg/L), whereas chemisorption was more prominent at higher concentration (65 mg/L). Batch adsorption studies showed chromium removal efficiencies in the range of approximately 36% to 87%. The maximum adsorption capacity was determined to be about 5.88–3.28 mg/g. The adsorption data were best fit described by the Langmuir isotherm model (R^2 is 0.955). Overall, the results demonstrate that orange peel–derived biochar is a promising, cost-effective, and environmentally friendly adsorbent for hexavalent chromium removal.

Keywords:

Adsorption; Biochar, Chromium; Isotherm; Sustainable; Waste to Wealth

1. Introduction:

According to the United States Geological Survey (USGS), the global reserve of chromite ore is approximately 4.8 × 10^8 metric tons, with nearly 95% of the reserves concentrated in the Southern Africa and Kazakhstan regions. However, chromium consumption is also significant in various industries, particularly in tannery operations in countries such as India [1]. The chromium occurs in varied oxidation states ranging from -2 to +6, but the following two valance forms are more stable, persistent, and highly toxic to human and ecosystem, the first one is trivalent chromium and the next is hexavalent chromium [1, 2, 3]. Chromium is widely used in many of the industrial processes such as textile, tanning, electroplating, paints, alloy production, pigments manufacturing and in welding works. The most common chromium pollution is only from the tannery effluents and they use predominantly hexavalent chromium, and the environment and ecosystem gets highly effected by the release of such untreated effluents [4, 5].

The chromium has been listed as a criteria "A" pollutant by United States Environmental protection agency (USEPA Chromium, even at very low concentrations, can cause allergic reactions and other adverse health effects in humans. [6]. Hexavalent chromium compounds are considerably more hazardous than their trivalent counterpart, mostly because of their increased water solubility, mobility, and ease of transport through biological membranes, which causes damage to intracellular proteins and nucleic acids. The chromium in traces are an important micronutrients for human life, but if it exceeds the desirable levels (0.05 mg per L in liquids and 20 µg per g in soils or sediments) it provokes the environmental and health issues [7].

The chromium (Cr) pollutants in the contaminated areas and waste streams are mandatory to be removed, a variety of mitigating techniques and tactics have been used. Studies are concentrating on encouraging the use of green chemicals through transformations, adsorption, oxidation-precipitation, and oxidation-reduction to remove chromium effectively. The process such as bioremediation and phytoremediation was adopted for the effective removal of Cr contaminated soil [6, 7, 8]. Mitra et al., [9] has adopted nano-fibers based adsorption technique for the removal of chromium from wastewater, chromium removal by iron nanoparticles [5], electrochemical process [10, 11], carbon fibres [12], and by adsorption techniques with soil to plant-based lignin's [13, 14, 15, 16].

The main problems of the aforementioned methods include that the majority of them are uneconomical, unworkable, and ineffectual as well as the fact that they use a lot of chemicals and energy resources while being ineffective at completely removing metal from water, wastewater and contaminated places [17]. Additionally, they produce vast quantities of toxic sludge, which releases additional chemicals into the environment. Thus, it is essential to employ a cutting-edge, cost-effective, and sustainable method to detoxify the harmful heavy metal ions prevalent in industrial effluent. Therefore, using biochar as a green sorbent can be a viable option for the pollutant removal.

According to the review, biochar has a wide range of potential applications for the elimination of typical organic and inorganic contaminants found in industrial effluent. It is a unique kind of highly effective adsorbent [18]. Orange peel derived biochar has shown promising performance in removing toxic metals such as chromium, lead, and cadmium from contaminated water [19]. It provides an eco-friendly alternative adsorbent for treating low-strength wastewater like water, greywater and industrial effluents containing Cr (III) and Fe (III) [20-21]. Orange peel was selected as the precursor material due to its abundant availability, low cost, and high carbon content, which makes it a suitable biomass source for biochar production. The ability of biochar to adsorb inorganic and organic contaminants through a variety of mechanisms, including pore filling, electrostatic interactions, ion exchange, precipitation, and surface sorption, was quite impressive. Additionally, biochar lowers the bioavailability, toxicity, and mobility of both organic and inorganic contaminants. Unlike many previous studies that focused on activated or chemically modified biochar with complex and costly preparation methods, the present work uses non-activated orange peel waste–derived biochar prepared through a simple and sustainable approach. The novelty of this study lies in demonstrating the practical feasibility of low-cost biochar for efficient chromium removal from aqueous solutions**.** Therefore, the present study focused on synthesis of biochar from an orange peel waste, and utilize the produced biochar as an adsorbent for the removal of hexavalent chromium contaminant form the aqueous phase. Hence the objective of the present study was to synthesis of biochar from the waste of orange peels. Then, to perform the batch kinetic and equilibrium study with biochar and modelling the obtained results with various adsorption isotherms and thermodynamics.

2. Materials and Methods

2.1 Preparation of Biochar

The orange peel used for the preparation of biochar was obtained from the near-by fruit market, and was first washed several times with running water and finally with ultra-high pure distilled water. The orange peels were cut into pieces and dried in the natural sunlight for 24 to 48 hours. The obtained peel waste was collected, placed in a crucible and supplied with nitrogen gas at 0.5 L per minute. The temperature in the muffle furnace was gradually increased to a maximum of 550 °C at a heating rate of 10 °C per minute and maintained for 4 hours. After completing the heating process, the furnace was switched off and allowed to cool under natural conditions. Once cooled, the resulting contents was collected and sieved through a 100 µm mesh, the biochar retained on the mesh was collected and then stored in an airtight container for future use. The various stages of processing the orange peel waste that underwent to be converted into a biochar was depicted in Figure 1. The raw orange peel waste collected from the fruit market weighted to be 0.709g with moisture. Thereafter, after the biomass gets dried at sunlight for 48 hours, further processed in muffle, and sieve to obtain a biochar weighing 0.528g. The efficiency or the yield of obtaining the biochar on dry basis was calculated to be nearly 25.52 %.

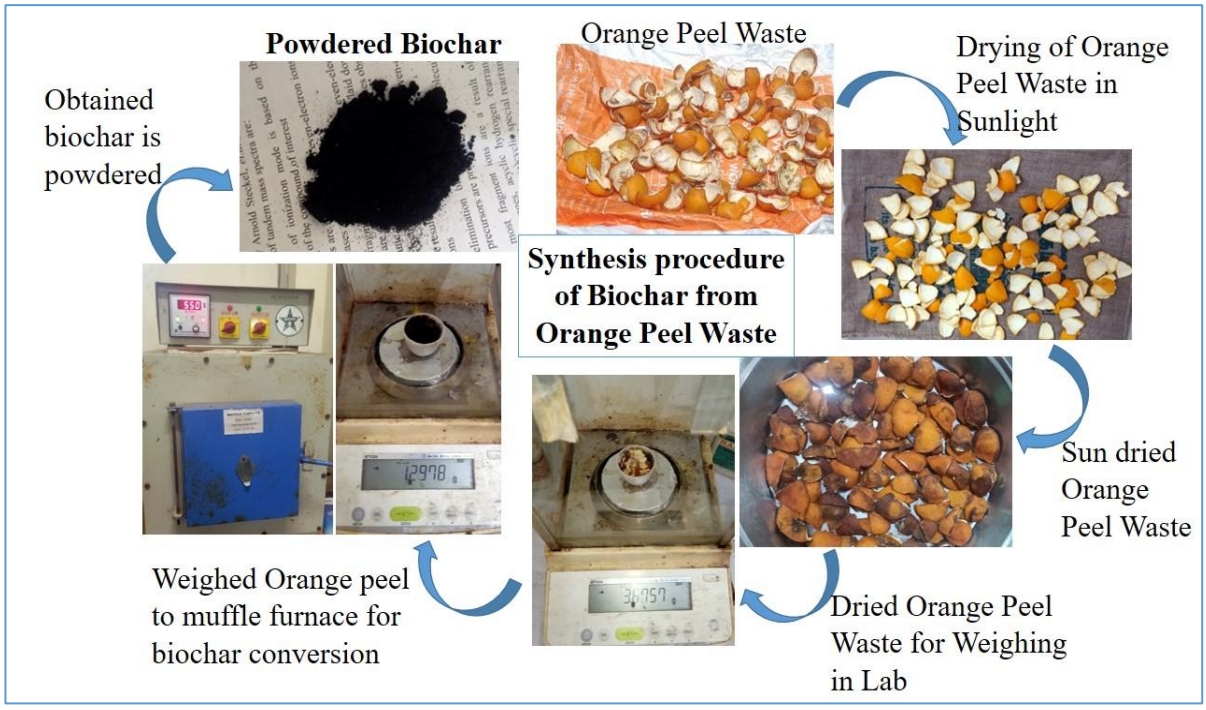


Fig. 1 Schematic representation of synthesis of biochar from Orange Peel Waste

2.2 Characterization of Biochar

The powdered orange peel biochar (OPB) was characterized with Fourier Transform Infrared Spectrophotometer (FTIR), Perkin Elmner, India and x-ray diffraction (XRD), M/s Bruker AXS GmbH, Germany to identify the functional groups and crystalline behaviour respectively. Additionally, the pH of the biochar was determined using the AVI digital pH meter, India. X-ray diffraction (XRD) is a non-destructive analytical technique for determining crystal structure, state, crystal orientation, and other structural properties [22]. FTIR analysis was performed to detect the functional groups on the surface of raw and pollutant augmented biochar at wavenumbers between 3500 and 500 cm^{-1}. The raw biochar and the biochar augmented with pollutant were checked with XRD to understand the bonding nature of carbon, oxygen, nitrogen and hydrogen.

2.3 Adsorption Kinetics and Equilibrium

The adsorption kinetics experiments were conducted in a batch sacrificial mode for the chromium pollutant using orange peel biochar as an adsorbent. The OPB of 5 g was added to a 150 mL Borosil conical flask, and after a pollutant concentration was added, the matrix is subjected to a shaking at 150 rpm. The concentration of pollutant was maintained at a 10 mg per L, and the supernatant were removed at varied time interval such as 0, 5, 10, 15, 20, 30, 60, 90, 120, 180, 240, 300, and 360 minutes. The obtained supernatant were subjected to residual pollutant concentration of chromium (Cr) (65 mg per L and 15 mg per L) and was analysed using UV-Vis spectrometer at 540 nm according to the standard operating procedures. The Cr (VI) concentration in the solution were determined at the beginning and end of the shaking period. Eq (1) and Eq (2) are used to compute the adsorption capacity and removal efficiency respectively of the heavy metal.

$$Q_e = \frac{(C_o - C_e) * V}{m} \quad \text{Eq. 1}$$

$$R = \frac{C_o - C_e}{C_o} * 100 \quad \text{Eq. 2}$$

Where Q_e is the adsorption capacity at equilibrium state in mg per gram, C_o is the initial concentration (mg/L), C_e is the equilibrium concentration (mg/L), V is the volume of the solution (L), m is the mass of the adsorbent (g), and R is the removal efficiency in percentage.

2.4 Adsorption Isotherm

Adsorption isotherm models were used to investigate the adsorption mechanism and the equilibrium distribution of metal ion between the solid and liquid phases. The relationship

between the amount of adsorption and the liquid phase concentration were obtained from kinetics experiments. The following isotherm models Langmuir (Eq. 3) and Freundlich (Eq. 4) models were studied and obtained the best fit model for our experimental study. The linear form of the isotherm equation are as follows,

$$\frac{C_e}{Q_e} = \frac{1}{bQ_{max}} + \frac{C_e}{Q_{max}} \quad \text{Eq. 3}$$

$$\ln Q_e = \frac{1}{n} \ln C_e + \ln K_f \quad \text{Eq. 4}$$

Where Q_{max} is the maximum adsorption capacity corresponding to complete mono layer coverage (mg/g), b is the Langmuir adsorption constant in L per mg, K_F is the Freundlich adsorption constant in L per mg, and 1/n is the heterogeneity factor, C_e is the equilibrium concentration of Cr in mg per L, Q_e is the adsorbed amount of Cr at equilibrium in mg per gram.

2.5 Thermodynamic studies

The thermodynamic parameter such as enthalpy (ΔH), adsorption free energy (ΔG), and adsorption entropy(ΔS) are a vital factors that forecasts or elucidates the adsorption mechanism, the removal of pollutant on biochar and the transport behaviour of pollutants. The specific formula are as follows,

$$InK_d = \frac{\Delta S°}{R} - \frac{\Delta H°}{RT} \quad \text{Eq. 5}$$

Where K_d is the distribution coefficient T is the absolute temperature of the solution (K) and R is the universal gas constant (8.314 J/K mol); $\Delta H°$ *and* $\Delta S°$ can be obtained by calculating the slope and the intercept. K_d and $\Delta G°$ can be obtained from the following formula

$$K_d = \frac{q_e}{c_e} \quad \text{Eq. 6}$$

Where q_e and c_e are the same as provided in section 2.4, The $\Delta G°$ value can be calculated according to the van't hoff equation

$$\Delta G° = -RT\ In\ K_d \quad \text{Eq. 7}$$

3. Results and Discussion

3.1 Biochar characterizing

The fresh biochar (raw biochar) and treated (chromium contaminated biochar) was subjected to the, FTIR and XRD analysis. The surface functional groups for the treated and raw OPB in the wavenumber range of 500 to 4000 per cm was recorded on Fourier Transform Infrared

Spectrometer (FTIR). Additionally, the crystalline structure of raw and treated OPB were conducted in X-Ray diffraction (XRD). The FTIR spectra for the OPB is shown in Fig. 2, the broad band at 3150 per cm should be designated to O-H bond deriving from alcohols, phenols and carboxyl groups [23].

The functional groups present on the surface of the orange peel biochar before and after chromium adsorption were analysed using Fourier Transform Infrared Spectroscopy, and the spectra are shown in Fig. 2. A broad absorption band observed around 3200–3400 cm^{-1} corresponds to the stretching vibration of –OH groups, indicating the presence of hydroxyl groups associated with alcohols and phenolic compounds on the biochar surface [24]. The peak around 1700–1750 cm^{-1} can be attributed to the stretching vibration of C=O groups [25], which may arise from carboxylic or carbonyl functional groups present in the biomass-derived carbon structure. Another peak observed near 1400–1600 cm^{-1} corresponds to –COOH functional groups [26], indicating the presence of carboxylic acid groups on the adsorbent surface. The band located around 1000–1200 cm^{-1} is assigned to C–O stretching vibrations, which are typically associated with alcohol, ester, or ether groups in lignocellulosic biochar materials. After chromium adsorption, slight shifts and intensity changes were observed in these functional group peaks, suggesting the involvement of oxygen-containing functional groups in the adsorption process of Hexavalent Chromium. In particular, the appearance or shift of the band around ~850–900 cm^{-1} may be associated with Cr=O vibrations [27], indicating possible interaction between chromium species and the biochar surface. These observations suggest that functional groups [28] such as –OH, –COOH, C=O, and C–O play an important role in the adsorption mechanism through electrostatic interaction and surface complexation [29].

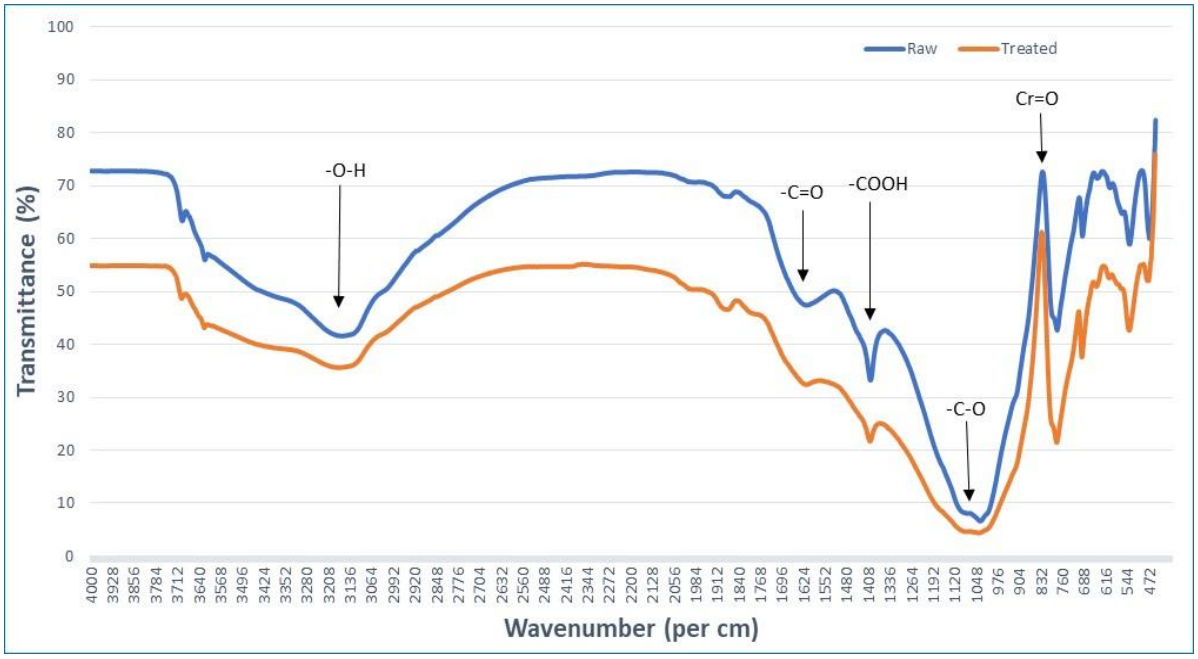


Fig. 2 FTIR spectra for the Orange Peel Biochar (OPB) before and after adsorption of Chromium

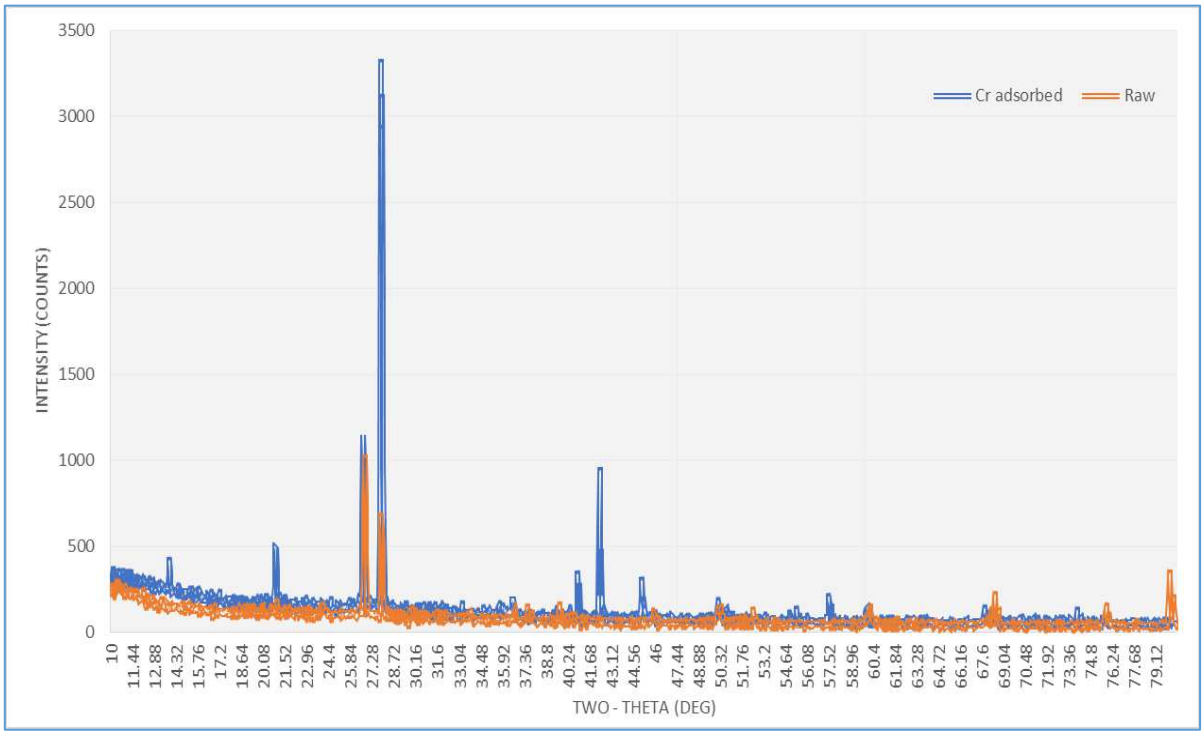


Fig. 3 XRD spectra for the Orange Peel Biochar (OPB) before and after adsorption of Chromium

The raw biochar exhibited a broad diffraction peak around $2\theta \approx 26–29°$, which corresponds to the (002) plane of amorphous carbon, indicating that the prepared biochar possesses a predominantly amorphous carbon structure. Such amorphous characteristics are typical for biochar materials derived from lignocellulosic biomass and are beneficial for adsorption

processes due to the presence of irregular pore structures and surface functional groups [30-32]. After adsorption of Hexavalent Chromium, noticeable changes in peak intensity were observed in the XRD pattern. A sharper and more intense diffraction peak around $2\theta \approx 28°$ and additional peaks around 40–45° suggest the possible deposition or interaction of chromium species on the surface of the biochar [33]. The increase in peak intensity after adsorption indicates that chromium ions were successfully associated with the biochar surface [34]. Furthermore, the absence of many sharp crystalline peaks in both spectra confirms that the biochar mainly retains an amorphous structure, which is typical for pyrolyzed biomass materials. The observed structural changes after adsorption suggest that the biochar surface plays an important role in the immobilization of chromium ions from aqueous solution.

3.2 Adsorption Kinetics

Initially, the standard curves for the chromium salt are generated to get straight-line equations by plotting the obtained absorbance at 540 nm with the known standard solution concentration data as shown in Fig 4. The equation of the line can be used to calculate Cr (VI) levels that are unknown after adsorption. A standard curve is created by preparing a standard solution of $K_2Cr_2O_7$ at 5 ppm, 10 ppm, 20 ppm, 35 ppm, and 50 ppm in a 150 mL volumetric flask. Then, 2 mL of 2M H_2SO_4 solution and 0.5 mL of Diphenyl Carbazide were combined. Standard solutions were tested for absorbance using a UV-Vis spectrophotometer at 540 nm.

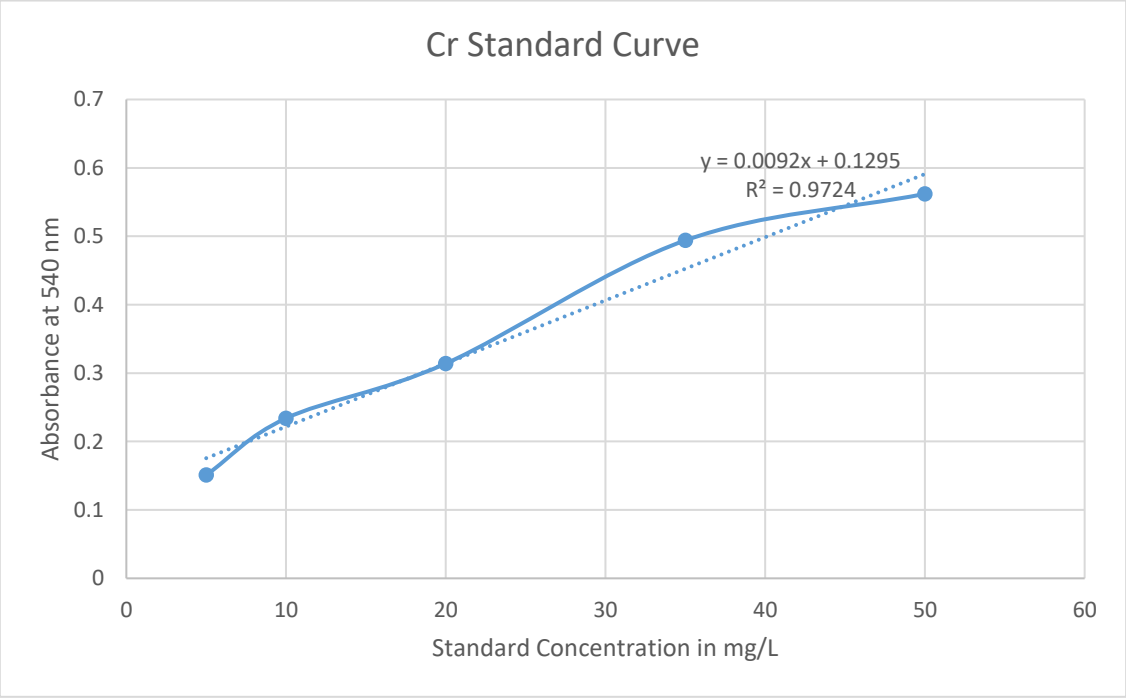


Fig. 4 Standard curve for the Chromium solution at 540 nm wavelength

The equilibrium time was determined based on batch adsorption experiments conducted in sacrificial mode using the synthesized OPB. Two different initial Cr concentrations, 65 mg/L and 15 mg/L, were studied while maintaining the solution pH at 4.5 and keeping the adsorbent dosage at 5 g. The variations in adsorption capacity and Cr removal efficiency using OPB are shown in Figures 5 and 6. During the initial stage of the batch experiment, samples were collected at frequent intervals within the first 30 minutes, and the experiment was continued up to a total contact time of 330 minutes. As illustrated in Figures 5 and 6, the adsorption rate was faster at the beginning of the experiment due to the abundance of available active sites on the biochar surface [35, 36]. As adsorption progressed, the rate gradually decreased as the active sites became occupied, leading the system towards saturation. The saturation phase indicates that most of the adsorption sites were occupied, and further extension of contact time could result in desorption rather than additional adsorption [36]. The kinetic study revealed that the equilibrium time for both Cr -65 and Cr -15 systems was approximately 270 minutes. Previous studies have also reported similar behaviour, where rapid pollutant removal occurs during the initial stage of adsorption, followed by attainment of a near-steady state after several hours of contact time [37]. For instance, adsorption of dyes on waste-derived biochar has been shown to exhibit rapid removal within the first few minutes and reach equilibrium after extended contact periods. The adsorption capacity and removal efficiency increased with increasing contact time [38]. At 270 minutes of equilibrium time, the adsorption capacity was recorded as 5.88 mg/g for Cr-65 and 3.28 mg/g for Cr–15 (Table 1 and 2). The removal efficiency was comparatively lower at higher initial pollutant concentration; the removal efficiencies were 36% for Cr-65 and 87% for Cr-15. This behaviour may be attributed to the limited number of active adsorption sites available on the biochar surface relative to the higher pollutant loading [39, 40]. The observed adsorption trend indicates that the initial concentration of the pollutant significantly influences biosorption performance. Similar findings have been reported in adsorption studies where increasing pollutant concentration enhances adsorption capacity but reduces overall removal efficiency due to saturation of available binding sites [39, 40]. The biosorption process at the liquid–solid interface is governed by several sequential mass transfer steps, including transport of pollutants from the bulk solution to the boundary layer surrounding the adsorbent particles, diffusion through the boundary layer to the external

surface of the adsorbent, intra-particle pore diffusion, and finally adsorption onto the internal active sites through physical or chemical interactions [40].

Table 1 Adsorption kinetics parameters for Cr adsorption onto OPB – 65 mg/L

Time (min)	Concentration (mg/L)	% Removal	Adsorption capacity (mg/g)
0	65	0	0
5	63.14	2.85	0.46
10	58.34	10.23	1.66
15	57.04	12.23	1.98
30	56.93	12.40	2.016
60	55.95	13.91	2.26
90	47.47	26.95	4.38
120	46.50	28.46	4.62
150	46.39	28.62	4.65
180	45.74	29.63	4.81
210	45.74	29.63	4.81
240	44.87	30.96	5.03
270	43.45	36.21	5.88
300	42.91	33.97	5.52
330	32.26	34.98	5.68

Table 2 Adsorption kinetics parameters for Cr adsorption onto OPB – 15 mg/L

Time (min)	Concentration (mg/L)	% Removal	Adsorption capacity (mg/g)
0	15	0	0
5	14.37	4.17	0.15
10	14.37	4.177	0.15
15	13.93	7.10	0.26
30	13.93	7.10	0.26
60	13.49	10.02	0.375
90	12.18	18.79	0.70
120	10.86	27.56	1.033
150	9.98	33.41	1.25
180	8.67	42.18	1.58
210	8.67	42.18	1.582
240	5.16	65.58	2.45
270	1.86	87.53	3.28
300	2.09	86.04	3.22
330	2.71	81.89	3.071

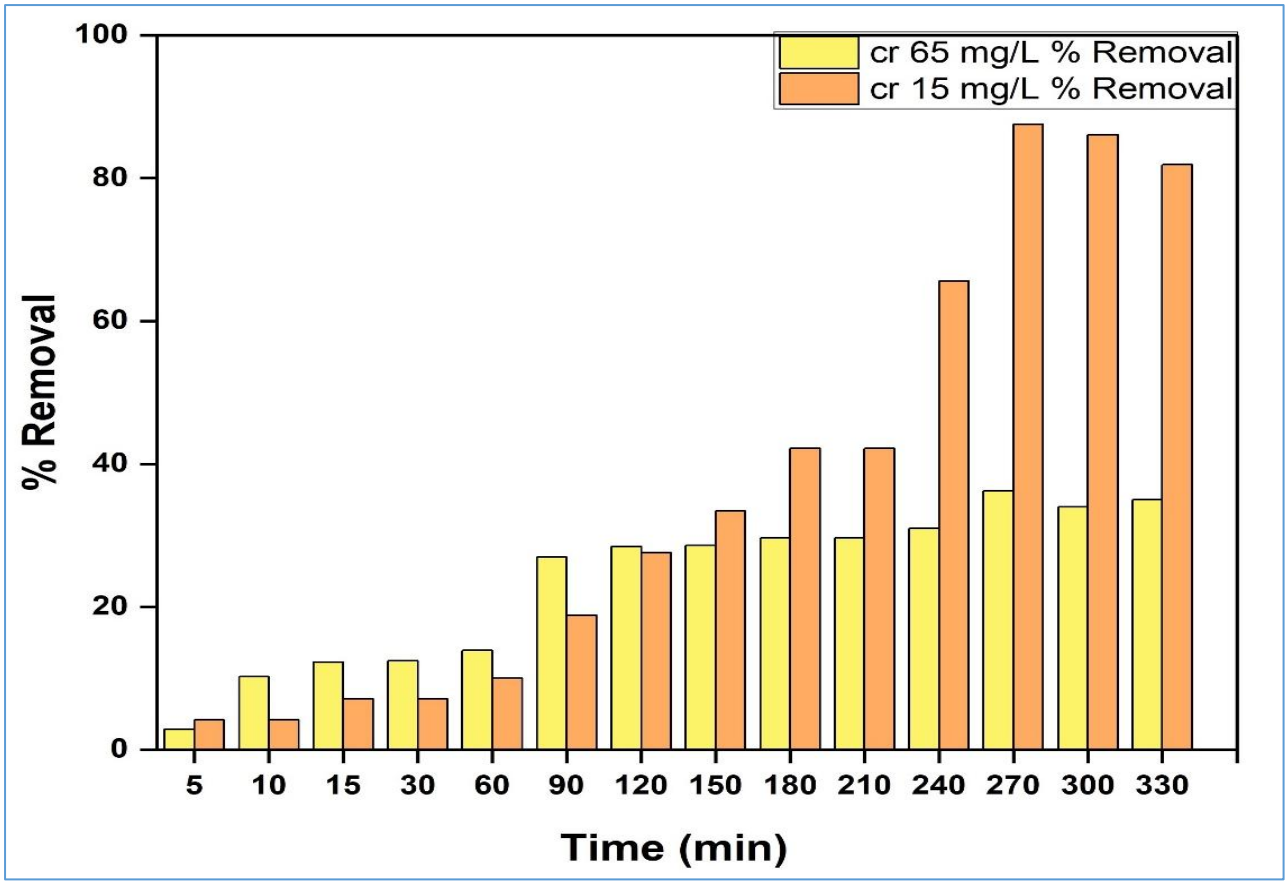


Fig. 5 Effect of contact time (0–330 min) on the percentage removal of Chromium VI using orange peel biochar (OPB) at an initial dye concentration of 65 & 15 mg/ L, adsorbent dosage of 5 g per 125 mL

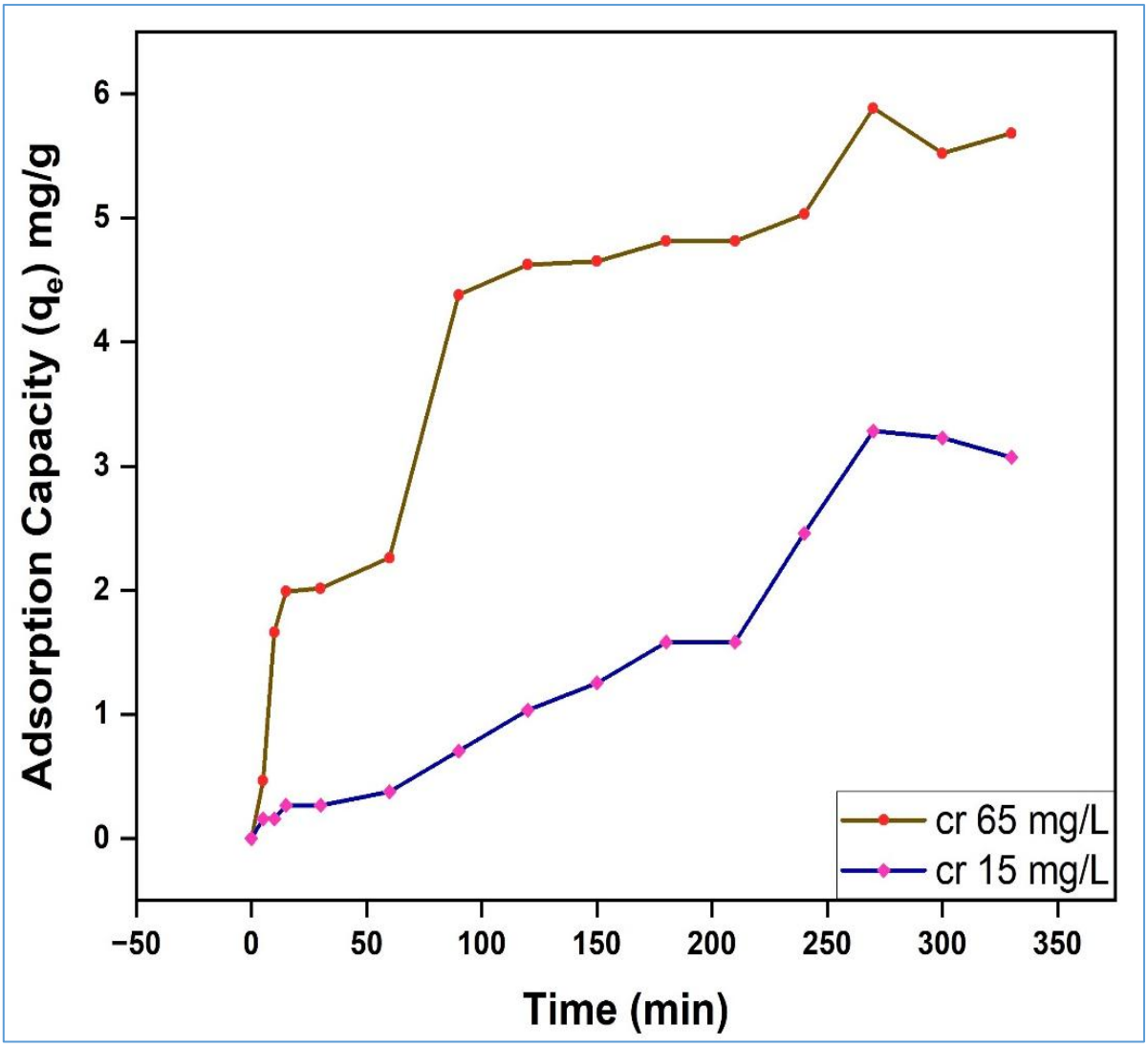


Fig. 6 Adsorption Capacity of orange peel biochar with effect of contact time

3.3 Adsorption Isotherm

The experimental data collected at a fixed amount of biochar (5g), at room temperature (28C) and at neutral pH of 4.5 .0 with an initial concentration of 65 mg per L of Chromium was fitted with tow standard models viz., a viz., Freundlich and Langmuir isotherm model. The equilibrium connection between the concentration of the adsorbate and adsorbent is predicted by the Langmuir and Freundlich isotherms model [41, 42]. The curve fitting of the experimental adsorption results with the linear equations (equation 3 and 4) of Langmuir and Freundlich isotherm models were depicted as a graphical form in Fig. 7(a) and (b). The adsorption experimental data best fit to the Langmuir model according to the R^2 value (0.95) as seen in Table 3. The equilibrium adsorption data were best described by the Langmuir adsorption isotherm model, indicating monolayer adsorption on a homogeneous surface. The

calculated maximum adsorption capacity (qmax) was 31.85 mg g^{-1}.While, with the Freundlich model the experimental adsorption values are not fitting properly, and has a regression coefficient (R^2) as 0.87.

According to the Langmuir model, there are only a limited number of sites on a solid surface that indicate uniform adsorption energies regardless of the level of coverage, suggesting monolayer adsorption. It indicates that each vacant site on the OPB adsorbent was filled with a molecule of chromium. In Langmuir model, adsorption occurs on a homogeneous surface containing a fixed number of identical and energetically equivalent active sites. According to this model, once a molecule occupies an adsorption site, no further adsorption can occur at that site, leading to the formation of a monolayer coverage. The model assumes that there is no interaction between adsorbed molecules and that the adsorption energy remains constant regardless of surface coverage. This means that all adsorption sites have equal affinity for the adsorbate, and the probability of adsorption is the same across the surface [39, 43]. On the other hand, the heterogeneity of the process and the extensive dispersion of Chromium molecules on the OPB adsorbent surface is explained by the Freundlich model, which also explains the multilayer creation. The OPB is mostly homogeneous in texture, hence the above results are in good agreement with many literatures [43, 44, 39, and 16]. Kosale et al., [43] has shown that the activated Black plum seed biochar for removal of various industrial cationic and anionic dyes. They showed that both the dyes followed the Langmuir isotherm.

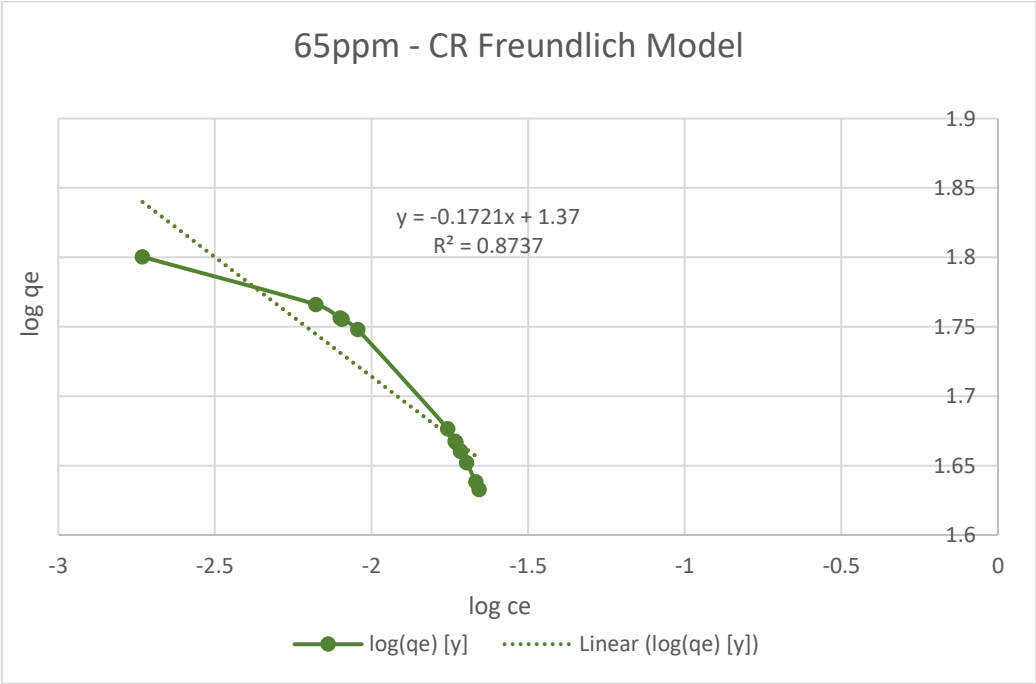


Fig. 7(a) The Freundlich Isotherm model graph for Cr65

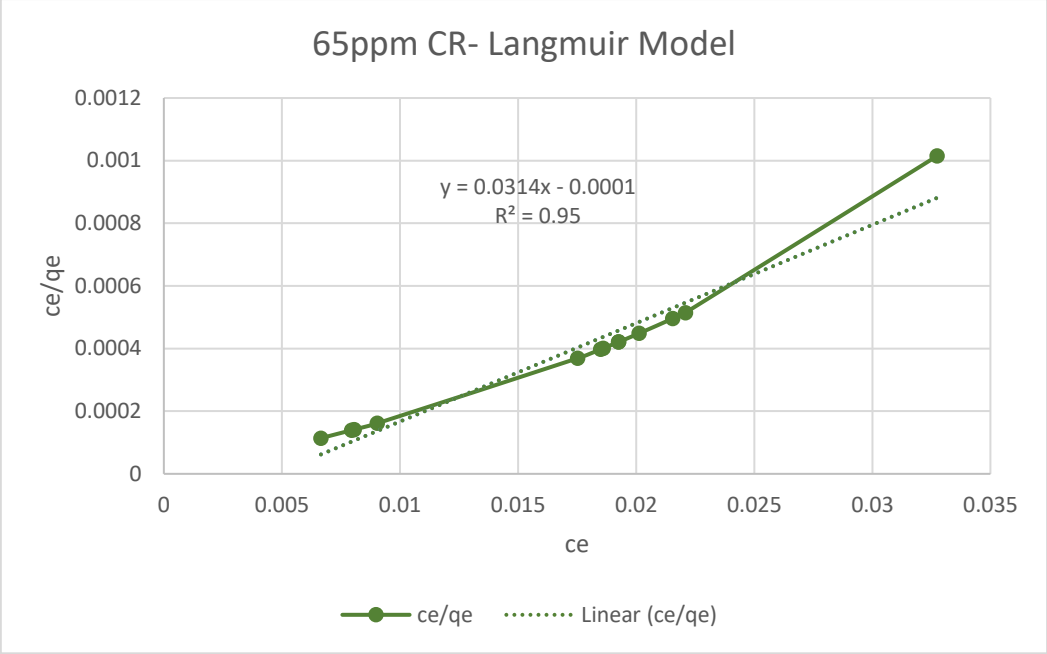


Fig. 7(b) The Langmuir Isotherm model graph for Cr65

Table 3 Isotherms parameters for Cr adsorption onto OPB with Langmuir, and Freundlich models

Pollutant	Langmuir			Freundlich		
	Q_m	K	R^2	K_f	1/n	R^2
CR-65	31.85	314	0.950	19.81	0.21	0.87

3.4 Thermodynamic Study

The thermodynamic study is conducted to study the nature of the adsorption process and the feasibility of the study for piloting. The temperature for the thermodynamic study were varied out from 299 to 303 K by keeping the other parameters constant for the Cr pollutant. The thermodynamic study graph was plotted between inverse of temperature in 1/T k^{-1} in x axis versus the ln of dispersion coefficient (Kd) (Fig. 8).

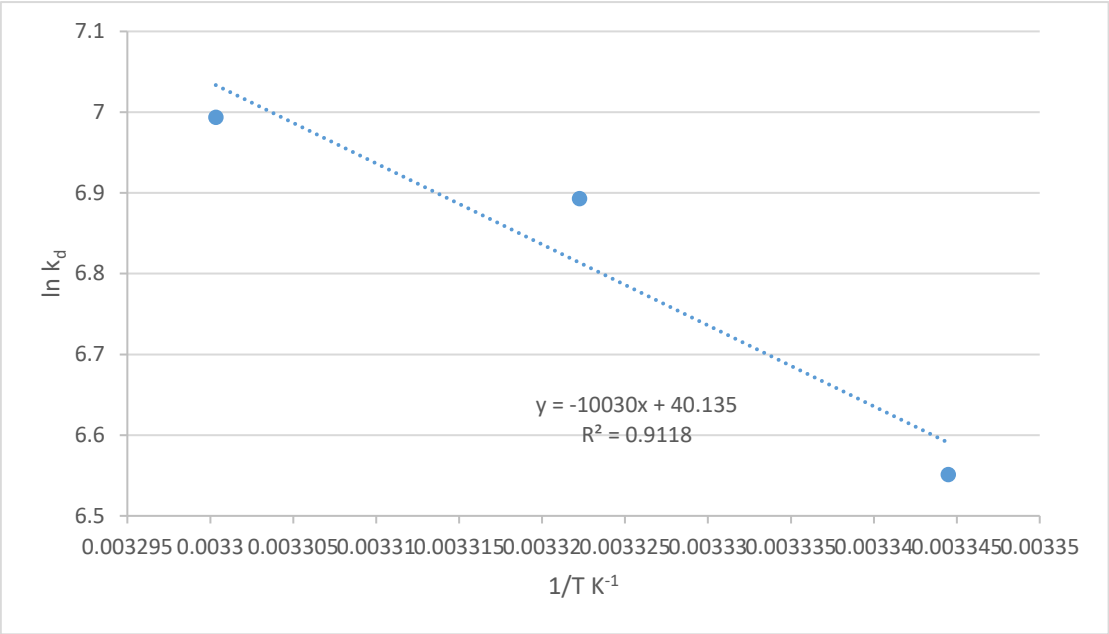


Fig. 8. Thermodynamic plots for Cr adsorption (with a dosage 5 g, pH 4.5 , concentration 65 mg/L, and contact time 330 min, temp. 299–303 K)

The thermodynamic parameters for the adsorption of Hexavalent Chromium onto OPB were evaluated at temperatures ranging from 299 to 303 K, and the results are presented in Table 4 and Fig.8. The negative values of the Gibbs free energy change (ΔG°) indicate that the adsorption process is spontaneous and thermodynamically feasible within the studied temperature range. Moreover, the magnitude of ΔG° slightly increased with increasing temperature, suggesting that higher temperature conditions may enhance the adsorption process. The calculated enthalpy change (ΔH°) and entropy change (ΔS°) were 83.39 kJ mol^{-1} and 333.68 J mol^{-1} K^{-1}, respectively. The positive value of ΔH° indicates that the adsorption process is endothermic in nature, implying that an increase in temperature favors the adsorption of chromium ions onto the OPB surface [45]. Similarly, the positive ΔS° value suggests an increase in randomness at the solid–liquid interface during the adsorption process, which may be associated with structural changes in the adsorbent surface, the randomness and kinetic energy of the system and the displacement of water molecules during chromium uptake [46]. As temperature rises, the movement of molecules becomes more vigorous, which may enhance the interaction between the adsorbate and the adsorbent surface. However, excessive temperature can also disrupt adsorption stability by increasing desorption tendency, which may reduce adsorption yield in some cases. However, it should be noted that the thermodynamic analysis was conducted over a relatively narrow temperature range, which may limit the precision of the calculated thermodynamic parameters [47-48]. Therefore, while the positive

ΔH° value indicates the possibility of stronger interactions between chromium ions and the biochar surface, further studies over a wider temperature range would provide a more reliable understanding of the adsorption mechanism.

Table. 4 Thermodynamics parameter for Chromium pollutant (with a dosage 5 g, pH 4.5, concentration 65 mg/L, contact time 330 mins, temp. 299–303 K)

Heavy metal	Temperature (K)	-ΔG° (kJ per mol)	ΔH° (kJ per mol)	ΔS° (J per K per mol)
Cr	303	17.62	83.39	333.68
	301	17.25		
	299	16.29		

Conclusion

The novelty of this study lies in assessing the feasibility of biochar derived from locally available orange peel waste for chromium (VI) removal from aqueous solutions. The biochar was prepared using a simple and sustainable synthesis method without activation, making it suitable for low-cost and decentralized wastewater treatment applications. Orange peel waste is an abundant and inexpensive biomass resource, and its conversion into biochar provides an effective adsorbent for chromium remediation. Batch kinetic experiments were conducted with sampling intervals ranging from 30 to 330 minutes, and the adsorption system reached equilibrium at approximately 270 minutes of contact time. The equilibrium adsorption data were evaluated using Langmuir and Freundlich isotherm models. The results indicated that the Langmuir model provided the best fit, suggesting predominantly monolayer adsorption behaviour, with a maximum adsorption capacity of 31.85 mg/g and a regression coefficient of 0.95. In summary, the study confirms that orange peel biochar is a practical, efficient, and economical adsorbent for chromium removal from wastewater. The findings also highlight the potential application of biochar for treating low-concentration wastewater, such as greywater.

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to the CENTAB facility, SASTRA Deemed University for characterization the samples with sophisticated instruments.

Data Availability statement

All the data are available in the article.

Ethical Approval

Not Applicable

Competing Interests

The authors declare there is no conflict of interest.

Consent to Participate

Not applicable, as the study does not involve human participants

Consent to Publish

Not Applicable

Authors Contributions

Sowndarya Sekar – Synthesis, preparation of fruit waste derived biochar, thermodynamics study and draft report

Vyshak, C and Gopikrishna, M – Batch adsorption kinetics, and equilibrium study, draft report compilation, VC – additionally contributed to characterization of biochar.

Ramprasad Chandrasekaran – Study conceptualization and formulation, methodology preparation, arranging funding and lab facilities, supervised the work, reviewed and final correction of the manuscript.

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