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Ginger Shaft as Novel Adsorbent for Chromium (VI) Removal: Kinetics and Adsorption Isotherms

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ABSTRACT

This study investigates the potential of ginger shaft as a bio-sorbent for the adsorption of hexavalent chromium (Cr^{6+}) ions from aqueous solutions. The objectives encompassed the preparation of the ginger shaft as a suitable bio-sorbent and the evaluation of equilibrium isotherms and kinetic models in controlled batch systems. The methods used in this research work included production of adsorbent from ginger shaft to accomplish sustainable material and techniques. The result revealed a profound increase in the rate of chromium adsorption, within contact time intervals of 40 to 60 minutes. The adsorption peaked at pH levels ranging from 1 to 3, with maximum adsorption of 98.77%. There was consistency in increase of chromium ion adsorption as the adsorbent dosage increases indicating that using ginger shaft as adsorbent fully depends on its dosage. The result of adsorption due to temperature was erratic. It was observed that the percentage adsorption increases as the adsorbate concentration increases. The adsorption behavior exhibited by chromium ions on ginger shaft adhered to the Freundlich isotherm model, evident through a linear relationship with a slope value of 1/n exceeding 1, emphasizing $n < 1$, signifying a complex adsorption mechanism that deviates from ideal behaviors. In contrast, the result of Langmuir isotherm model yielded an unfavorably low ($R^2 = 0.06$), indicating that the process is not restricted to monolayer adsorption. In conclusion, the study substantiates that ginger shaft is a promising bio-sorbent for the effective removal of Cr (VI) ions from contaminated water sources, thus presenting a cost-effective alternative to conventional treatment methodologies. The significance of this research reveals that a novel and effective composite material as sorbent was developed to remove Cr (VI) ions from aqueous solution.

Keywords: Time poverty, Women, Ondo State, Nigeria.

Introduction

Hazardous wastes, mainly those in liquid and semi-liquid states pose significant risks to human, animal, and ecological health when inadequately managed. An estimated 90% of such wastes occur as liquids or sludges and often contain high concentrations of heavy metals such as arsenic (As), mercury (Hg), lead (Pb), cadmium (Cd), and chromium (Cr), as well as essential metals like zinc (Zn), copper (Cu), manganese (Mn), cobalt (Co), and iron (Fe), which become toxic when present at excessive levels (Raji *et al*., 2023). These metals can interfere with cellular processes and impede biological growth once exposure exceeds established tolerance thresholds (Raji *et al*., 2023).

In response to the challenges presented by metal-contaminated industrial effluents, various treatment strategies have been widely studied. Methods include adsorption using materials such as activated carbon, chemical coagulation and sedimentation, electrochemical processes, and biological methods

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like activated sludge treatment (Zeng *et al*., 2025; Raji *et al*., 2023). Chromium, particularly in its hexavalent state [Cr (VI)], is of particular concern due to its high toxicity and carcinogenicity, even at trace levels. Conventional remediation techniques for chromium commonly rely on chemical reduction and adsorption, reflecting its chemical stability and the severe health implications allied with exposure (Zeng *et al.*, 2025).

Chromium (atomic number 24) is a transition metal widely applied in corrosion-resistant alloys such as stainless steel and in pigment production. Although its use dates back centuries, present-day environmental issues largely stem from the redox transformations between Cr (III) and the more toxic Cr (VI) species (Zeng *et al.*, 2025). Modern chromium pollution is mostly anthropogenic, with industrial activities including electroplating, mining, smelting, fossil fuel combustion, and sewage discharge accounting for more than 96% of chromium released into the environment each year (Zeng *et al*., 2025).

Adsorption remains the preferred remediation technique because of its low cost, operational simplicity, and high removal efficiency. Recent studies have increasingly focused on biosorbents derived from agricultural and food wastes, which have demonstrated strong potential for Cr (VI) removal under laboratory conditions (Khalfaoui *et al*., 2023; Raji *et a*l., 2023; Ye *et al*., 2025). In line with this research direction, the present study investigates the use of ginger shaft (*Zingiber officinale*) as an affordable and environmentally benign bio-sorbent for chromium remediation. Similar plant-based materials such as rice husk and pomelo peel have shown effective Cr (VI) adsorption at acidic pH, mainly through ion exchange and surface complexation mechanisms (Ye *et al*., 2025; Raji *et al*., 2023).

Justification

Rapid industrial expansion across the world has contributed to increasing levels of environmental pollution, raising significant concerns due to the toxicity of pollutants and their harmful effects on humans, animals, and ecosystems. Heavy metal contamination, in particular, has been linked to numerous diseases and environmental challenges. In response, the present study aims to propose a sustainable solution to heavy metal pollution through the use of a low-cost adsorbent, offering a practical alternative to conventional and often unwieldy metal-removal technologies.

The Study

Characterize the adsorption isotherms of the selected biosorbent and determine the effect of chromium ion concentration on the adsorption capacity of the adsorbent, as well as evaluate the effects of contact time, adsorbent dosage, pH, and temperature.

Materials and Methods

Ginger shaft was sourced from local vegetation in Akure, Ondo State, Nigeria. The material was washed thoroughly with distilled water three times, followed by a final rinse at neutral pH to remove residual odor and impurities. It was sun-dried and subsequently oven-dried at 105 °C for 24 hours. The dried sample was then pulverized and sieved using a 150 µm mesh.

A stock chromium solution was prepared by dissolving 5.658 g of $K_2Cr_2O_7$ in 1 liter of distilled water for subsequent serial dilutions. The infrared spectra of both the raw and chromium-loaded adsorbent were obtained using a Thermo Nicolet 6700 FTIR spectrometer equipped with KBr pellet technology, operating within the 4000–400 cm^{-1} range. 5 mg of finely powdered sample was pressed into a translucent KBr pellet. The instrument was powered on, initialized, properly aligned, and spectra were recorded.

All chemicals used, $K_2Cr_2O_7$, HCl, NaOH, and HNO_3 were of Sigma analytical grade and prepared according to experimental requirements. Suitable safety procedures were observed throughout the study, with the use of personal protective equipment (PPE) to ensure safe handling of materials.

Adsorption Kinetics

2g portion of the ginger-shaft adsorbent was introduced into 50 mL of a 104 mg/L Cr (VI) solution and agitated for predetermined contact times of 0, 10, 20, 30, 40, 50, 60, and 70 minutes. The solution pH was adjusted to 2.5 before adsorption. Each mixture was placed on a mechanical shaker operating at 150 rpm and kept at room temperature for the specified durations. At the end of each contact time, the samples were filtered using Whatman No. 1 filter paper, and the remaining Cr (VI) concentration in the filtrate was quantified spectrophotometrically using a Shimadzu AA-650 atomic absorption spectrophotometer at a wavelength of 305 nm.

Additional adsorption studies were conducted to examine the effects of pH (2–5), temperature (20–60 °C), initial metal concentration (20–250 ppm), and adsorbent dosage (1.0–3.0 g) on the adsorption capacity. The initial pH of the Cr (VI) solutions was adjusted as necessary using 0.1 mol/dm³ NaOH or 0.1 mol/dm³ HCl. All experiments were performed in triplicate, and data were statistically analyzed using analysis of variance (ANOVA).

Results and Discussion

Effect of Time

The adsorption experiment showed that the maximum chromium removal efficiency of 99.5% was attained at a contact time of 60 minutes. The variation in percentage Cr (VI) removal with time is illustrated in Figure 1. For the ginger-shaft adsorbent, the adsorption rate increased progressively, although not in a linear pattern. In Figure 1, a notable rise in adsorption occurred between 40 and 60 minutes of contact, indicating a rapid uptake of chromium during this interval. This observation aligns with the contact time range of 20–60 minutes commonly reported for the adsorption of divalent metal ions (Oseni *et al*., 2016).

The results further indicate that equilibrium was reached at approximately 60 minutes, corresponding to the point at which the adsorbent surface became saturated. During the initial stages of adsorption, a substantial number of active sites were readily available, enabling rapid metal uptake. However, as time progressed, the remaining vacant sites became increasingly difficult for Cr (VI) ions to access due to repulsive interactions between adsorbed species on the solid surface and ions in the solution phase (Labied *et al.*, 2018).

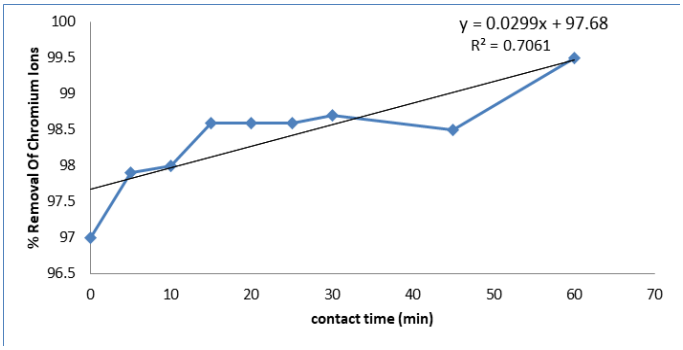

Figure 1. Removal of Cr^{6+} ions from aqueous solution (50ml, pH 2.5) with time, ginger shaft (2g) as an adsorbent.

This finding is particularly relevant because establishing an optimal equilibrium time is crucial for designing cost-effective and efficient wastewater treatment systems.

Effect of Adsorbent Dosage

The influence of adsorbent dosage on chromium removal from aqueous solution was examined by varying the mass of ginger-shaft adsorbent from 1.0 to 3.0 g. As anticipated, increasing the adsorbent dosage resulted in enhanced adsorption of Cr (VI), owing to the greater availability of active binding sites on the adsorbent surface. This observation is consistent with previous findings reported for Cr (VI) sorption (Sarrj *et al*., 2015). Consequently, competition among Cr (VI) ions for adsorption sites diminishes as the quantity of adsorbent increases.

Results presented in Figure 2 confirm this trend, indicating a direct relationship between adsorbent dosage and removal efficiency. These findings suggest that the adsorption performance of ginger

shaft is highly dependent on the quantity of adsorbent introduced into the solution.

Effect of Temperature

As shown in Figure 3, the adsorption behavior of Cr (VI) with respect to temperature did not follow a consistent pattern. An increase in adsorption was observed between 30 °C and 40 °C, which aligns with findings reported by Bayuo *et al*. (2019). However, a notable decline in adsorption efficiency occurred between 40 °C and 50 °C, followed by a subsequent increase in adsorption as the temperature rose from 50 °C to 60 °C.

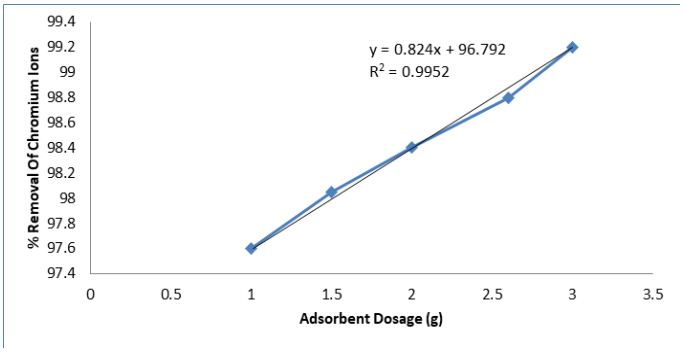

Figure 2. Removal of Cr^{6+} ions from aqueous solution with varied adsorbent dosage (50 ml, pH 2.5).

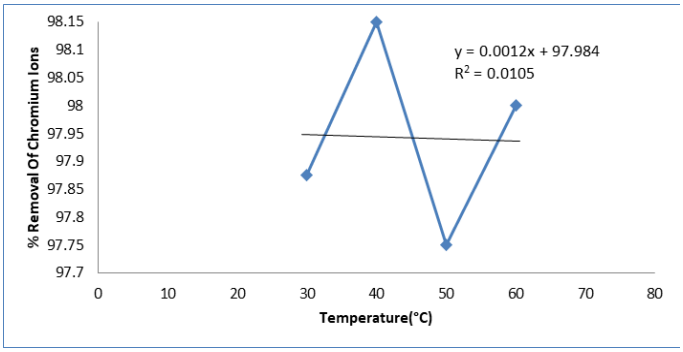

Figure 3. Removal of Cr^{6+} ions from aqueous solution (50ml, pH 2.5) at various temperatures.

Effect of pH

As illustrated in Figure 4, pH plays a critical role in the adsorption of metal ions from aqueous solutions because it influences metal solubility, the ionization state of the adsorbate, and the availability of counter ions on the functional groups of the adsorbent. Chromium species vary with pH: at low pH, Cr (VI) is predominantly present as $HCrO_4^-$ and $Cr_2O_7^{2-}$, while at pH values above 7, the dominant and more stable species is CrO_4^{2-} (Bayuo *et al*., 2018). Consequently, electrostatic interactions between the adsorbate and adsorbent are strongly affected by changes in solution pH.

From Figure 4, the adsorption of Cr (VI) increased sharply between pH 1 and 3, reaching a maximum at pH 2.5. This trend is consistent with the findings of Bishnu *et al*. (2022), who also reported optimal Cr (VI) adsorption at pH 2. Beyond this point, increasing the pH resulted in a pronounced decline in adsorption efficiency. This reduction may be attributed to weakened electrostatic attraction between the oppositely charged adsorbent and adsorbate, ultimately lowering the sorption capacity (Sarroj *et al.,* 2015).

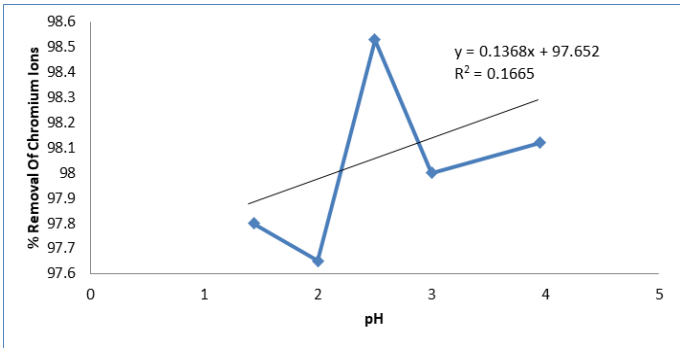

Figure 4. Removal of Cr^{6+} ions from aqueous solution (50 ml) at different pH using ginger shaft as adsorbent

Effect of Initial Concentration

As shown in Figure 5, an increase in adsorbate concentration from 20 to 100 mL resulted in a corresponding rise in the percentage of Chromium adsorption. However, a sharp decline in adsorption efficiency was observed when the concentration increased further from 100 to 160 mL. The initial increasing trend suggests that higher adsorbate concentrations provide more metal ions per available binding site on the adsorbent surface, thereby enhancing the likelihood of interaction between the adsorbent and adsorbate. This observation is

consistent with the findings of Adelaja *et al*. (2011), who reported similar behavior in related adsorption studies.

Adsorption Isotherms

It is generally expected that chromium adsorption onto ginger shaft would conform to the Freundlich or Langmuir isotherm models, given the potential for multilayer metal ion accumulation on the adsorbent surface (Bishnu *et al*., 2022). However, the experimental results obtained in this study did not support this assumption, indicating that the adsorption mechanism may not align with the classical isotherm

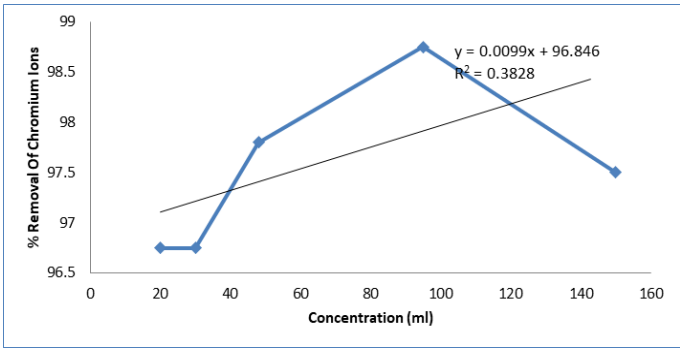

Figure 5. Removal of Cr^{6+} ions from aqueous solution of various initial concentrations at pH of 2.5.

models.

As illustrated in Figure 6, the Langmuir isotherm model describes monolayer adsorption occurring on a homogeneous surface containing a finite number of identical and energetically uniform binding sites. The model assumes that the adsorption energy is independent of surface coverage and that no interactions or steric hindrance occur between adsorbed species and incoming molecules. The adsorption data were analyzed using the linearized form of the Langmuir equation:

$$\frac{C_e}{Q_e} = \frac{1}{Qb} + \frac{C_e}{Q} \qquad (i)$$

where Q represents the maximum sorption capacity (mmol g^{-1}) corresponding to monolayer saturation, b reflects the sorption enthalpy (dm^3 mol^{-1}), Q_e is the amount of adsorbate adsorbed at equilibrium

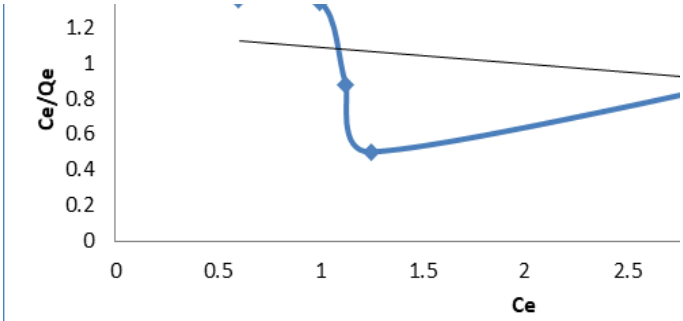

Figure 6. Langmuir adsorption isotherm of Cr^{6+} ions onto 2g ginger shaft in 50ml of adsorbate, with 7.5 minutes agitation time at pH 2.5 and at 30°C.

(mol g^{-1}), and C_e is the equilibrium concentration of adsorbate in solution (mol dm^{-3}).

The results of the present study show that Cr (VI) adsorption onto ginger shaft does not conform to the Langmuir isotherm model, as the generated plot failed to produce a linear relationship characteristic of Langmuir-type adsorption.

Freundlich Adsorption Isotherm

The Freundlich adsorption isotherm is a widely applied empirical model that describes adsorption on heterogeneous surfaces, accounting for the exponential distribution of active sites and their energies toward the adsorbate. The linearized form of the Freundlich equation is expressed as:

$$\frac{C_e}{Q_e} = \frac{1}{Qb} + \frac{C_e}{Q} \qquad (ii)$$

where is the amount of adsorbate adsorbed at equilibrium (mol g^{-1}), is the equilibrium concentration of adsorbate in solution (mol dm^{-3}), is the sorption capacity of the adsorbent (mmol g^{-1}), and is a characteristic constant representing the intensity of adsorption.

As shown in Figure 7, the adsorption of Chromium ion onto ginger shaft conforms to the Freundlich isotherm, evidenced by the linear relationship of the plot. The slope of the graph, corresponding to, was

found to be greater than 1, indicating that is less than 1, which reflects favorable adsorption conditions (Bayuo *et al.*, 2019).

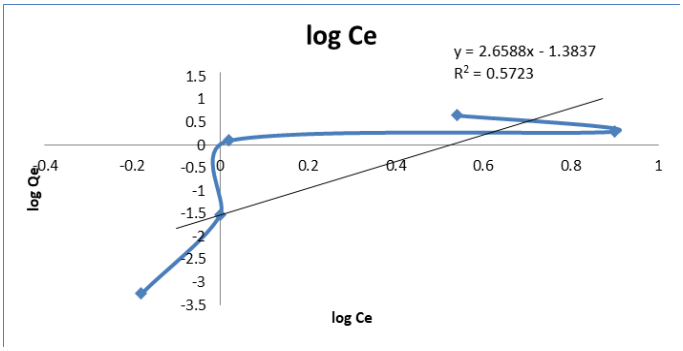

Figure 7. Freundlich adsorption isotherm of Cr^{6+} ions onto 2g ginger shaft in 50ml of sorbate, with 10 minutes agitation time at pH 2.5 and at 30°C.

Conclusion

The study demonstrates that ginger shaft can serve as an effective biosorbent for the removal of Cr (VI) from aqueous solutions. Maximum chromium removal of 98.77% was achieved at pH 2.5, comparable to the adsorption efficiencies reported for other plant-based biosorbents. The results indicate that Cr (VI) adsorption is influenced by several experimental parameters, including contact time, initial metal concentration, temperature, pH, and adsorbent dosage. Furthermore, the adsorption process aligns with the Freundlich isotherm model, with suggesting favorable adsorption and strong interaction between Cr (VI) and the adsorbent surface.

These findings highlight the potential application of ginger shaft as a cost-effective and environmentally friendly adsorbent for treating Cr (VI) contaminated wastewater.

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