

Biosorption of Ni(II), Cr(III), and Co(II) from Solutions using *Acalypha wilkesiana* Leaf: Equilibrium, Kinetics, and Thermodynamics.

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ABSTRACT

Kinetic, equilibrium and thermodynamic studies of the biosorption of Ni(II), Cr(III), and Co(II) by *Acalypha wilkesiana* leaf have been investigated using various physicochemical parameters for each of the metal ions. The FTIR spectral characteristics of *Acalypha wilkesiana* leaf revealed the presence of ionizable groups that could participate in the binding of metal ions in solution. In each case, the biosorption was found to be dependent on the solution pH, contact time, initial metal ion concentration, dosage and temperature of the system.

The kinetic studies showed that the biosorption process was best represented by pseudo-second-order kinetics among four kinetic models tested. Equilibrium data were better represented by Freundlich isotherm among Langmuir and Freundlich adsorption isotherms. The Freundlich model appears to have better regression coefficients than the Langmuir model. The study on the effect of dosage showed that the dosage of the biomass significantly affected the uptake of the metal ions from solution. Thermodynamically, parameters such as standard Gibbs free energy (ΔG°), standard enthalpy (ΔH°), standard entropy (ΔS°) and the activation energy (A) were calculated. The order of spontaneity of the biosorption process was found to be Ni(II)>Cr(III)>Co(II). The activation energy for the biosorption of each of the metal ions was less than 42 kJmol^{-1} at 318 K indicating that each was a diffusion-controlled process.

(Keywords: biosorption, *Acalypha wilkesiana*, Ni(II), Cr(III), Co(II))

INTRODUCTION

The discharge of toxic metals from industrial operations has led to Ni(II), Cr(III), and Co(II) entering the environment. There is the need to regulate their levels in the environment before they enter food chain. The conventional approach to their removal from effluents are rather expensive with associated demerits. Biosorption has been recognised as the alternative technology for efficient and effective removal of these metal ions from solutions. It has been employed using different materials of either animal or plant origin as biosorbents in the removal of toxic metals (Babarinde et al., 2009; Babarinde et al., 2010; Chakravarty et al., 2010; Liu et al., 2010; Uluozlu et al., 2010; Zhang and Wang, 2010; Vijayaraghavan and Balasubramanian, 2010; Fiorentin et al., 2010; Qu et al., 2010; Basu et al., 2010; Babarinde, 2011).

Acalypha wilkesiana Muell Arg (copper leaf) is a plant that is found worldwide especially in the tropics of Africa, America, and Asia (Madziga et al., 2010). The ornamental species are cultivated as foliage plants in gardens and green houses. *Acalypha wilkesiana* has been investigated for its physiological and microbiological applications (Alade and Irobi, 1993; Jekayinfa et al., 1997; Al-Attar, 2010). It has been reported that the leaf of *Acalypha wilkesiana* contains saponins, tannins, anthraquinan, and glycoside (Oladunmoye, 2006). It was on this basis that this readily available weed was investigated for its potential in treating industrial effluents containing Ni(II), Cr(III), and Co(II) in the present study.

METHODOLOGY

Biomass Preparation

Acalypha wilkesiana leaves were harvested from the mini campus of Olabisi Onabanjo University, Ago-Iwoye, Ogun State, Nigeria. The leaves were carefully collected inside a transparent nylon, sun dried immediately and kept dry till time of usage.

Preparation of Solution

All chemicals used in this study were of analytical reagent grade and were used without further purification. Standard solutions of Ni(II), Cr(III), and Co(II) used for the study were prepared from $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$, $\text{Cr}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, and $\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$, respectively. The working solutions with different concentrations of the metal ions were prepared by appropriate dilutions of the stock solution immediately prior to their use with distilled water.

The initial pH of the solution was adjusted accordingly with a pH meter. A thermostated water bath (Haake Wia Model) was used as the medium for the process. The concentration before and after biosorption of each metal ion was determined using a Perkin-Elmer Analyst 700 flame atomic absorption spectrophotometer (AAS) with deuterium background corrector. Fourier transform infrared (FT-IR) spectra of dried unloaded biomass and metal loaded biomass were recorded at $400\text{-}4000\text{ cm}^{-1}$ using a Shimadzu FT-IR model 8400S spectrophotometer.

Batch Biosorption Study

The biosorption study was determined by batch experiments by contacting 0.5g of the *Acalypha wilkesiana* leaf with 25ml of each metal ion solution under different conditions for a period of time in a glass tube. The biosorption studies were conducted at 27°C using thermostated water bath to determine the effect of pH, contact time and initial metal ion concentration on the biosorption. The residual metal ion of the supernatant was analyzed using AAS. The amount of metal ion biosorbed from solution was determined by difference and the mean value calculated.

Effect of pH on Biosorption

The effect of pH on the biosorption of the metal ion was carried out within pH 1-7 to prevent the precipitation of metal ions. This was done by contacting 0.5g of *Acalypha wilkesiana* leaf with 25ml of 100 mg L^{-1} metal ion solution in a glass tube. The pH of each solution was adjusted to the desired value by drop wise addition of 0.1M HNO_3 and/or 0.1M NaOH. The glass tubes containing the mixture were left in a water bath for 6 hours. The biomass was removed from the solution by decantation. The residual metal ion concentration in the supernatant was analyzed. The optimum pH was determined as the pH with the highest biosorption of each metal ion.

Effect of Contact Time on Biosorption

The biosorption of the metal ions by *Acalypha wilkesiana* leaf was studied at various time intervals (0-360 min) and at the concentration of 100 mg L^{-1} . This was done by contacting 0.5g of *Acalypha wilkesiana* leaf with 25ml of 100 mg L^{-1} of metal ion solution at optimal pH. The leaf was left in solution for different periods of time. At predetermined time, the glass tubes were withdrawn from the bath, and the residual metal ion concentration in solution was determined using AAS. The amount of metal ions biosorbed was calculated for each sample.

Effect of Initial Concentration on Biosorption

Batch biosorption study of metal ion was carried out using a concentration range of $10\text{-}100\text{ mg L}^{-1}$. This was done by contacting 0.5 g of the leaf with 25 ml of each solution at optimal pH. Two glass tubes were used for each concentration. The tubes were left in a thermostated water bath maintained at 27°C for the predetermined optimum time. The leaf was removed from the solution and the concentration of residual metal ion in each solution was determined.

Effect of Temperature on Biosorption

The batch biosorption process was studied at different temperatures within the range $20\text{-}50^\circ\text{C}$ in order to investigate the effect of temperature on the biosorption process. This was done by contacting 0.5 g of *Acalypha wilkesiana* leaf with 25ml of 100 mg L^{-1} of metal ion solution at the optimal pH and time.

Statistical Analyses

The curve fittings of the data obtained were performed using Microcal Origin 6.0 software.

RESULTS AND DISCUSSION

Physical Characterization of *Acalypha wilkesiana*

The biosorption capacity of *Acalypha wilkesiana* leaf biomass depends upon the chemical reactivity of functional groups at the surface. It has been reported that the leaf of *Acalypha wilkesiana* contain saponins, tannins, anthraquinan and glycoside (Oladunmoye, 2006). The presence of sesquiterpenes, monoterpenes, triterpenoids, polyphenols, gallic acid, geranin, and quercetin in *Acalypha wilkesiana* leaf has been reported (Akinde, 1986; Adesina et al., 2000). Therefore, knowledge of the surface functional groups would give insight to the biosorption capacity of the biomass. These groups would form active sites for sorption on the material surface.

The FTIR spectra of dried unloaded and metal-loaded leaf were taken to obtain information on the nature of possible interactions between the functional groups of *Acalypha wilkesiana* leaf biomass and the metal ions as presented in Figure 1. Several peaks were observed from the spectra indicating that *Acalypha wilkesiana* leaf is composed of various functional groups which are responsible for binding of the cations. The IR spectra pattern of the biomass showed distinct and sharp absorptions indicative of the existence of the -OH, -NH, -C-O- and -C-N-groups as shown in Figure 1. These bands are due to the functional groups of *Acalypha wilkesiana* leaf that participate in the biosorption of Ni(II), Cr(III) and Co(II).

On comparison, there are clear band shifts and decrease in intensity between the of bands of the unloaded biomass and the metal-bound biomass as presented in Table 1. The FTIR spectra of the *Acalypha wilkesiana* leaf biomass indicated slight changes in the absorption peak frequencies due to the fact that the binding of the metal ions causes reduction in absorption frequencies. These observed shifts in absorbance implies that there were metal binding processes taking place on the active sites of the biomass. Analysis of the FTIR spectra showed the presence of ionizable functional groups (C=O, O-H, NH₂) which are able to interact with cations (Pradhan et al., 2010; Bueno et al., 2008; Sun et al., 2008;

Ertugay and Bayhan, 2008; Uluozlu et al., 2010). This implies that these functional groups would serve in the removal of positively charged ions from solution.

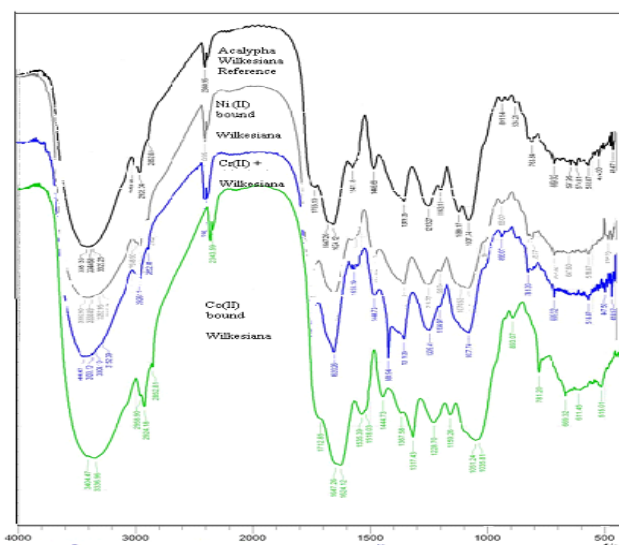


Figure 1: FTIR Spectra of the Free and Metal-Bound *Acalypha wilkesiana* Leaf.

Effect of Solution pH on Metal Ion Biosorption

The pH of the solution usually plays an important role in the biosorption of the metal ions (Vijayaraghavan et al., 2006). It is an important parameter governing the uptake of heavy metals by biosorption process as it not only affects metal species in solution, but also influences the surface properties of biosorbents in terms of dissociation of binding sites and surface charge (Akar et al., 2006).

The net charge of the sorbate and that of the sorbent are dependent on the pH of the solution. At low pH, the metal ion uptake is inhibited by net positive charge on the sorbent and the competition between the metal ions and the hydrogen ions in solution. As the pH increases, the negative charge density on biomass increases as a result of deprotonation of the metal binding sites on the leaf, consequently, the biosorption of the metal ions increases.

Figure 2 shows the variation of the metal ions biosorbed on *Acalypha wilkesiana* leaf at various solution pH values. For the three metal ions, the biosorption increased as the pH increased from pH 1 to pH 4. The increase observed in the biosorption with increase in pH implies that ion-exchange process is involved.

Table 1: The FT-IR Spectral Characteristics of *Acalypha wilkesiana* Leaf before and after Biosorption of Ni(II), Cr(III), and Co(II).

Metal ion	FTIR absorption band peaks (cm ⁻¹)			Assignment
	Before	After	Difference	
Ni(II)	3344.68	3338.89	5.79	Bonded OH,N-H stretching
Cr(III)		3333.10	11.59	Bonded OH,N-H stretching
Co(II)		3336.96	7.52	Bonded OH,N-H stretching
Ni(II)	1624.12	1620.26	3.68	N-H bending
Cr(III)		1620.26	3.86	N-H bending
Co(II)		1624.12	0	N-H bending
Ni(II)	1541.18	1519.95	21.23	N-H bend(1°)
Cr(III)		1535.39	5.79	N-H bend(1°)
Co(II)		1515.03	26.15	N-H bend(1°)
Ni(II)	1319.35	1317.43	1.92	C-O Stretching
Cr(III)		1319.35	0	C-O Stretching
Co(II)		1317.43	1.92	C-O Stretching

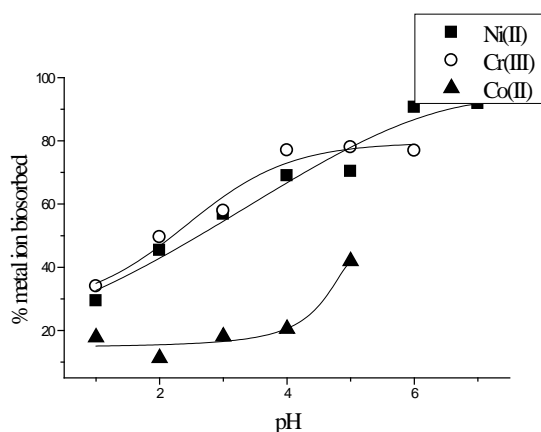


Figure 2: pH-Dependence Profile for the Biosorption of Ni(II), Cr(III), and Co(II) using *Acalypha wilkesiana* Leaf.

The reaction involved the biosorption of metal ion (represented as M^{x+}) from the liquid phase to the solid phase, the biosorbent with lone pair of electron (represented as \ddot{A}), and can be considered as a reversible reaction with an equilibrium being made between the two

phases as schematically shown below for a divalent metal ion in solution:



Biosorption kinetics

Figure 3 illustrates the dynamic biosorption process of the three metal ions on *Acalypha wilkesiana* leaf. It is observed that the biosorptive quantities of the three metal ions on the leaf increase with increasing contact time. In each case, biphasic kinetics is observed: an initial rapid stage (fast phase) where biosorption is fast and contributes to equilibrium uptake and a second stage (slow phase) whose contribution to the metal ion biosorption is relatively smaller.

The fast phase is the instantaneous biosorption stage, it is assumed to be caused by external biosorption of metal ion to the biomass surface. The second phase is a gradual biosorption stage, which is diffusion rate controlled. Finally, the biosorption sites are used up, the uptake of the metal ion reached equilibrium. This phase

mechanism has been suggested to involve two diffusion processes, external and internal, respectively (Wu et al., 2009). The biosorption of each of the three metal ions eventually achieves equilibrium although their rates of uptake and times of reaching equilibrium are different. This might be due to the differences in hydrated ionic sizes of the metal ions (Kielland, 1937).

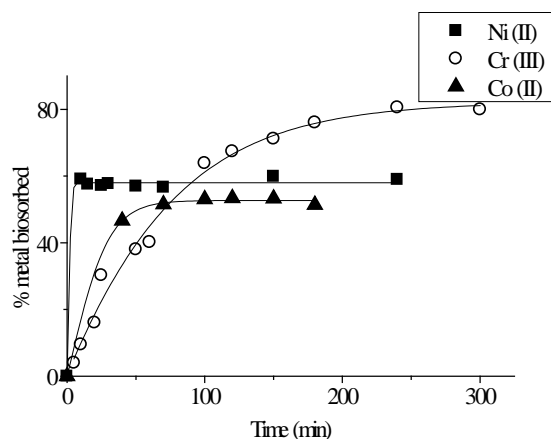


Figure 3: Contact time Dependence Profile for the Biosorption of Ni(II), Cr(III), and Co(II) using *Acalypha wilkesiana* Leaf.

Several kinetic models are needed to establish the mechanism of a biosorption process. In order to investigate the kinetics of the biosorption of these metal ions on *Acalypha wilkesiana* leaf, four kinetic models were employed. These are the pseudo-first-order, the pseudo-second-order, the Elovich kinetic model and the Intra particle diffusion model equations. One of such models is the Lagergren pseudo-first-order model which considers that the rate of occupation of the biosorption sites is proportional to the number of the unoccupied sites (Ertugay and Bayhan, 2008):

$$\text{rate} = -\frac{d[A]}{dt} = k [A]^n \quad (2)$$

Which can also be written as

$$\frac{d}{dt} q_t = k_1 (q_e - q_t) \quad (3)$$

Integrating between the limits $q_t = 0$ at $t = 0$ and $q_t = q_t$ at $t = t$, we obtain:

$$\log \left[\frac{q_e}{(q_e - q_t)} \right] = \frac{k_1}{2.303} t \quad (4)$$

This can be rearranged to obtain a linear form:

$$\log(q_e - q_t) = \log q_e - \frac{k_1}{2.303} t \quad (5)$$

where k_1 is the Lagergren rate constant of the biosorption (min^{-1}); q_e and q_t are the amounts of metal ions sorbed (mg g^{-1}) at equilibrium and at time t , respectively. The plot of $\log(q_e - q_t)$ versus t for the biosorption of metal ions on the biomass at initial concentration of 100 mg L^{-1} did not give a straight line implying that the process does not follow first-order kinetic model. The data was equally subjected to the pseudo-second-order kinetic model. The pseudo-second-order kinetic model is represented as:

$$\frac{d}{dt} q_t = k_2 (q_e - q_t)^2 \quad (6)$$

On integrating between boundary conditions, we have:

$$\frac{1}{q_e - q_t} = \frac{1}{q_e} + k_2 t \quad (7)$$

On rearrangement, we have:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t \quad (8)$$

Where k_2 is the equilibrium rate constant of pseudo-second-order biosorption process ($\text{g mg}^{-1} \text{ min}^{-1}$). In the three metal ions under study, the pseudo-first-order kinetics did not fit the data obtained. However, plots of t versus t/q_t showed good fitness of experimental data with the pseudo-second-order kinetic model for different initial concentration of the three metal ions as presented in Figure 4.

The data were also subjected to the Elovich kinetic model given by:

$$q_t = A + B \ln t \quad (9)$$

The Intra particle diffusion model was equally used to analyze the data. The correlation coefficients obtained were found to be highest for the pseudo-second-order kinetics as it was found to be in excess of 0.99 as presented in Table 2.

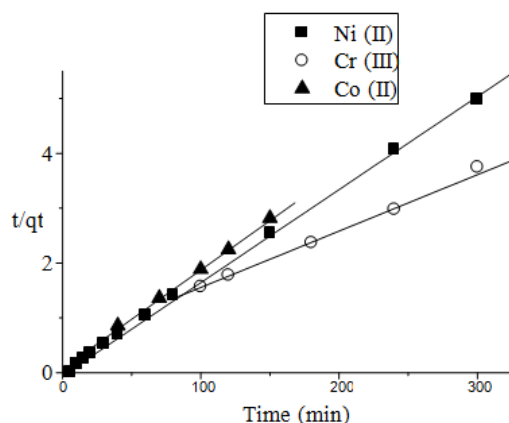


Figure 4: Pseudo-Second-Order Kinetic Plot for the Biosorption of Ni(II), Cr(III), and Co(II) using *Acalypha wilkesiana* Leaf.

On comparison of the values of R^2 for the experimental points, the pseudo-second-order kinetic model is the best kinetic model to predict the dynamic biosorption of Ni(II), Cr(III) and Co(II) on *Acalypha wilkesiana* leaf. The result shows that the rate of biosorption of the metal ions is of the order Ni(II)>Co(II)>Cr(III). The biosorption capacity is in the order Cr(III)>Ni(II)≈Co(II). The differences observed in the rate of biosorption as well as in the biosorption capacity may be accounted for in terms of the differences in ionic charges and hydrated ionic sizes of the ions in solution (Kielland, 1937).

Biosorption Isotherm

Figure 5 reports the biosorption isotherms of Ni(II), Cr(III) and Co(II) on *Acalypha wilkesiana* leaf. The equilibrium biosorption capacity increases with increase in metal ion concentration.

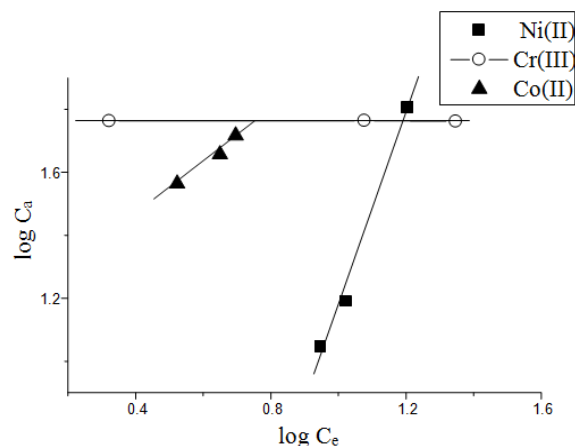


Figure 5: Freundlich Isotherm for the Biosorption of Ni(II), Cr(III), and Co(II) using *Acalypha wilkesiana* Leaf.

The Freundlich and Langmuir isotherms were employed to calculate the biosorption capacity. The Freundlich isotherm is an empirical equation describing adsorption onto a heterogeneous surface. The Freundlich isotherm is expressed as:

$$\log \Gamma = \frac{1}{n} \log C_e + \log K_f \quad (10)$$

Where K and $\frac{1}{n}$ are the Freundlich constants related to the biosorption capacity and biosorption intensity of the biosorbent, respectively.

The linear form of the Langmuir equation is expressed as:

$$\frac{1}{\Gamma} = \frac{1}{b_m} \frac{1}{C_e} + \frac{1}{\Gamma_m} \quad (11)$$

Where Γ , Γ_m and b_m are the Langmuir parameter. The Freundlich isothermal parameters for the biosorption are presented in Table 3.

Table 2: Parameters of the Pseudo-Second-Order Kinetic Model for the Biosorption of Ni(II), Cr(III), and Co(II) using *Acalypha wilkesiana* Leaf.

Metal ion	k_2 (g.mg ⁻¹ .min ⁻¹)	q_e (mg. g ⁻¹)	R^2	S.D.
Ni(II)	1.86×10^{-2}	59.70	0.9994	0.04
Cr(III)	2.42×10^{-4}	93.28	0.9968	0.06
Co(II)	2.5248×10^{-3}	56.21	0.9993	0.02

Table 3: Freundlich Isothermal Parameters the Biosorption of Ni(II), Cr(III), and Co(II) using *Acalypha wilkesiana* Leaf.

Metal ion	1/n	K _f	R ²	S.D
Ni(II)	3.0554	67.482	0.9531	0.0223
Cr(III)	0.0126	1.0409	0.9675	0.0071
Co(II)	0.5519	19.3584	0.9416	0.0516

The results show that the regression coefficients obtained for Freundlich isotherm are higher than for Langmuir isotherm. This implies that the biosorption is assumed to be a monolayer sorption with a heterogeneous energetic distribution of active sites, accompanied by interactions between biosorbed molecules (Bueno et al., 2008).

Biosorption Efficiency

The result of the study on the effect of initial metal ion concentration on biosorption efficiency is shown in Figure 6. The plots show that the biosorption efficiency of the biomass reduces with increase in the initial metal ion concentration of Cr(III) which might be due to the fixed number of binding sites in the biosorbent having more ions than at lower concentration. On the other hand, the biosorption efficiency increased with increase in initial metal ion concentration for Ni(II) and Co(II). The biosorption efficiency (E) for each metal ion was calculated as:

$$E = 100 \left(\frac{C_i - C_e}{C_i} \right) \quad (12)$$

Where C_i and C_e are the initial and the equilibrium metal ion concentrations (mg L⁻¹), respectively.

Effect of Biomass Dosage on Biosorption

The effect of biomass dosage on biosorption capacity is reported in Figure 7. The general trend of increase in metal ion biosorbed with increase in biomass dosage indicates an increase in uptake due to more binding sites on the biomass available for biosorption. It was found that biosorption capacity increases with increase in dosage of the biosorbent. This is due to the fact that increase in biomass dosage leads to increase in the number of active sites available for biosorption. Hence, biosorbate available for biosorption per gram of biosorbent will be less when the amount of biosorbent is increased. The difference in biosorption

capacity *q* (mg g⁻¹) at the same initial metal ion concentration and contact time may also be attributed to the difference in their chemical affinities and ion exchange capacity, with respect to the chemical functional group on the surface of the biosorbent. This trend has been reported for other biosorbents (Miranda et al., 2010).

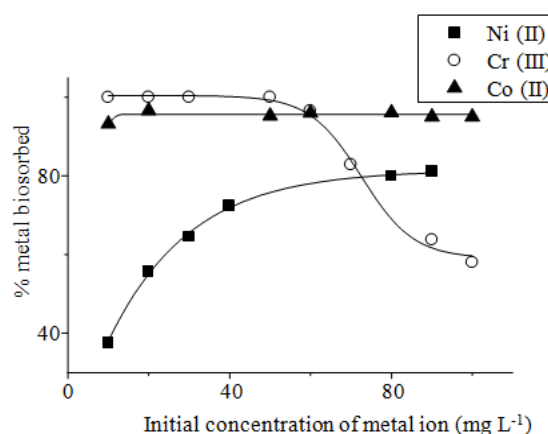


Figure 6: Efficiency Plot for the Biosorption of Ni(II), Cr(III), and Co(II) Ions using *Acalypha wilkesiana* Leaf.

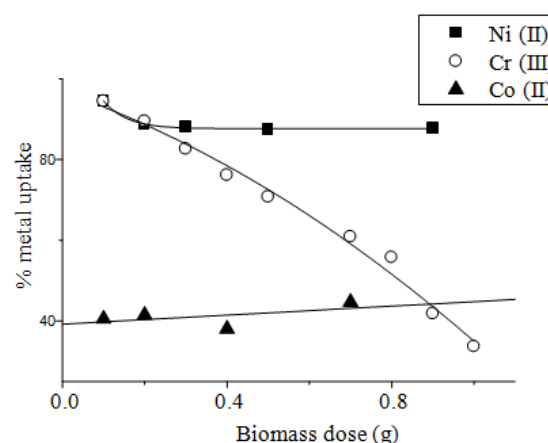


Figure 7: Effect of Biomass Dosage on the Biosorption of Ni(II), Cr(III), and Co(II) using *Acalypha wilkesiana* Leaf.

Biosorption Thermodynamics

The biosorption of metal ions may involve chemical bond formation and ion exchange since the temperature is a main parameter affecting them. The variation of temperature affects the biosorption of metal ions onto solid surfaces of biomass since the biosorption process is a reversible one. The nature of each side of the equilibrium determines the effect temperature has on the position of equilibrium. The side that is endothermic is favored by increase in temperature while the contrary holds for the exothermic side. The corresponding free energy change was calculated from the relation (de la Rosa et al., 2008; Sun et al., 2008):

$$\Delta G^\circ = -RT \ln K_c \quad (13)$$

Where T (K) is the absolute temperature. The equilibrium constant (K_c) was calculated from the following relationship:

$$K_c = \frac{C_{ad}}{C_e} \quad (14)$$

Where C_e and C_{ad} are the equilibrium concentrations of metal ions (mg L^{-1}) in solution and on biosorbent, respectively. Consequently, the thermodynamic behavior of the biosorption of Ni(II), Cr(III) and Co(II) onto *Acalypha wilkesiana* leaf was evaluated through the change in free energy (ΔG°), enthalpy (ΔH°) and entropy (ΔS°). The thermodynamic parameters like enthalpy and entropy were calculated using van't Hoff equation (Qu et al., 2010; Uluzlu et al., 2010). The change in free energy is related to other thermodynamic properties as:

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ \quad (15)$$

$$\ln K_c = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT} \quad (16)$$

Where T is the absolute temperature (K); R is the gas constant ($8.314 \text{ J mol}^{-1} \cdot \text{K}^{-1}$). ΔH° ($\text{J} \cdot \text{mol}^{-1}$) and ΔS° ($\text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$) were calculated from the slope and intercept of the linear plot of $\ln K_c$ vs $1/T$, respectively. The thermodynamic parameters obtained for this study are presented in Table 4.

The thermodynamic parameters (free energy (ΔG°), enthalpy (ΔH°) and entropy (ΔS°)) for the biosorption of the metal ions were determined by the application of Equations 15 and 16 as presented in Table 4.

In general, the change of standard free energy for physisorption is in the range of -20 to 0 kJ mol^{-1} and for chemisorption varies between -80 and -400 kJ mol^{-1} (Vimonses et al. 2009; Sen et al., 2011). In the present study, the overall ΔG° (as shown in Figure 8) has values ranging from -5.6 to $-0.06 \text{ kJ mol}^{-1}$. These results correspond to a spontaneous physical adsorption of the metal ions, indicating that this system does not gain energy from external resource (Vimonses et al. 2009; Arias and Sen 2009).

The decrease in ΔG° with increase in temperature indicates more efficient biosorption at higher temperature. The order of spontaneity of the biosorption process was found to be Ni(II)>Cr(III)>Co(II) similar to the order reported for the biosorption of these metal ions with banana leaf (Babarinde et al., 2012). The positive value of enthalpy change (ΔH°) indicates the endothermic nature of the biosorption process while negative value implies exothermic process. The positive values of ΔH° for the biosorption of Ni(II) and Co(II) suggest an endothermic nature of each biosorption process. This is also supported by the increase in the value of biosorption capacity of the biosorbent with rise in temperature. The positive value of ΔH° indicates the presence of an energy barrier in the biosorption process.

Table 4: Thermodynamic Parameters for the Biosorption of Ni(II), Cr(III), and Co(II) onto *Acalypha wilkesiana* Leaf.

Metal ion	ΔH° (kJ mol ⁻¹)	ΔS° (J mol ⁻¹ K ⁻¹)	A (kJ mol ⁻¹) (303K)	A (kJ mol ⁻¹) (318K)
Ni(II)	4.31	30.61	6.83	6.95
Cr(III)	-4.90	-4.53	-2.38	-2.26
Co(II)	13.56	46.57	16.08	16.20

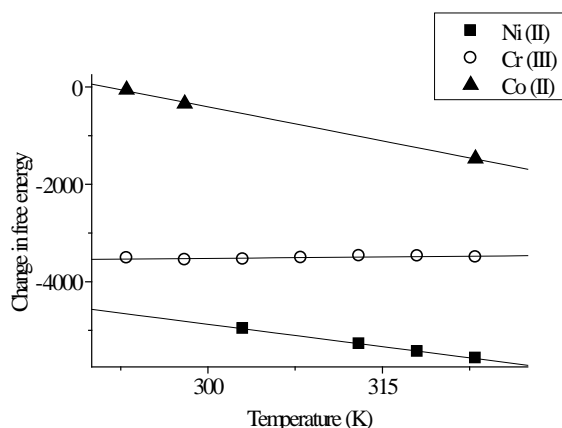


Figure 8: Thermodynamic Plots for the Biosorption of Ni(II), Cr(III), and Co(II) onto *Acalypha wilkesiana* Leaf.

Energies of activation, A, below 42 kJ/mol indicate diffusion-controlled processes, and higher values give chemical reaction-based processes. Therefore, energy of activation, A, has been calculated as per the following relation:

$$A = \Delta H^\circ + RT \quad (17)$$

The values of A at two different temperatures have been tabulated in Table 4. In this study, the activation energy (A) values were less than 42 kJmol⁻¹ indicating diffusion-controlled adsorption processes.

CONCLUSIONS

In this work we have studied the biosorption of Ni(II), Cr(III), and Co(II) by *Acalypha wilkesiana* leaf under various conditions. The biosorption of each was influenced by each of the parameters investigated. The pH has much effect on the biosorption of these metal ions from aqueous solutions. The rate of the biosorption of these metal ions followed pseudo-second-order kinetic model. The sorption isotherms of these metal ions onto the biosorbent are better represented by the Freundlich isotherm model. The thermodynamic study shows that the biosorption of each of Ni(II), Cr(III) and Co(II) was spontaneous in the order Ni(II) > Cr(III) > Co(II). The order of disorderliness being Co(II) > Ni(II) > Cr(III).

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