Original Research Article

Thermodynamic and kinetic properties for removal of heavy metals from industrial wastewaters using sugarcane bagasse

ABSTRACT:

KEYWORDS: Sugarcane bagasse, Adsorption, heavy metals, wastewater.

- **INTRODUCTION:**

Water is a source of life []. However, the quality of the world's water is increasingly threatened due to freshwater resources becoming heavily polluted by heavy metals, pathogens, turbidity, oil, and its derivatives from industries and agricultural effluents [and]. Among the heavy metals, Cu^{2+}, Cr^{6+}, $Mn^{2+,}$ Ni^{2+}, Fe^{3+}, Cd^{2+}, $Pb^{2+,}$ and Zn^{2+} ions are of primary concern in aquatic and terrestrial environments because of their high toxicity, high mobility, and solubility[]. These metals enter the human body either directly or through the food chain []. They tend to accumulate in the human body [ ] when ingested and cause serious health disorders []. For example, Pb2+ poisoning can lead to low intelligence quotient, concentration issues in children, axon degeneration, edema, infertility, menstrual problems, and stillbirths in adults[, and] while cadmium causes damage to the kidneys, lungs, and liver [].

Currently, numerous conventional physicochemical methods such as electrochemical treatment, ion-exchange, precipitation, reverse osmosis, evaporation, and oxidation/reduction [] have been used for the removal of heavy metal ions from wastewaters. However, these methods have had their limitations, the major ones being: initial high costs, not being eco-friendly as well as incomplete removal of large quantities of toxic sludge produced, a huge amount of energy needed [3]. Adsorption has been used for centuries by Egyptians for the removal of odours and purification of drinking water []. Adsorption is a viable alternative treatment method because it is cost-effective, simple to operate [], requires low energy, offers good selectivity, allows for the recovery of heavy metals [], and provides options for adsorbent regeneration [and].

Bio-adsorbents made from sugarcane bagasse are inexhaustible materials containing carbon-oxygen functional groups such as carboxyl, ketone, ester, aromatic rings, and hydroxyl groups []. These functional groups have capacity for adsorbing metal ions through mechanisms like chelation and electrostatic interactions [], which offer greater selectivity for bio-sorption studies on heavy metal ions, activation increases their efficiency and high adsorption capacity [] due to their large surface area [] and surface reactivity [], an essential property for removing heavy metal ions from contaminated water []. The effectiveness of removing these ions is influenced by experimental conditions such as temperature, concentration, contact time [24], pH, and particle size [, and].

There is need to investigate the kinetic and thermodynamic behaviour of sugarcane bio-sorbent to remove cadmium (Cd2+), chromium (Cr3+), copper (Cu2+), Nickel (Ni2+) and lead (Pb2+) ions from industrial wastewater under varying experimental conditions of pH, contact time [], particle size, initial concentration, adsorbent dosage and temperature [] in order to obtain a detailed understanding of the adsorption mechanism. This is of vital importance because sugarcane bagasse is a low-cost farm waste sorbent that can be regenerated for re-use and exhibits high efficiency in detoxifying extremely dilute effluents. To describe the interactions between liquid and solid phases [], numerous equations have been used to correlate experimental adsorption isotherm data so as to determine the best fit isotherms model []. The Freundlich isotherm has been shown to be suitable for multilayer adsorption caused by various functional groups on the surface of adsorbent. The Langmuir isotherm, on the other hand, is derived on the assumption of monolayer adsorption [].

In this study the adsorption mechanism and maximum adsorption capacity were studied through the application of these adsorption models after which thermodynamic parameters (were determined. The adsorption kinetics were investigated using pseudo-first and pseudo-second order rate equations. The adsorbent was subsequently explored for its efficacy in removing heavy metals from real wastewater samples.

2.0 MATERIALS AND METHODS:

2.1 Chemicals, reagents and preparation of metal ion solutions:

All the chemicals used throughout this study were analytical-grade reagents. Double-distilled water was used to prepare all solutions and reagents. Stock solutions of the heavy metal standards were prepared using analytical grade salts (($Cu(NO_3)_2$, $Pb(NO_3)_2$, $Cr(NO_3)_3$, $NiCl_2$, and $CdCl_2$ (purchased from Sigma Aldrich , Kobian Nairobi)) in distilled water to which 3.0 cm^3 concentrated HNO_3 acid had been added, and then diluted to 1.0 Litre. The working standard solutions of metal were obtained by dilution of appropriate amounts of heavy metal solution using distilled water. A few drops of Caesium-lanthanum ($CsCl/LaCl_3$; 5:20 g/L) solution was added to each of the working standards as an interference suppressant. The initial pH of the solutions during the analyses was adjusted using 0.1 M HCl or 0.1 M NaOH.

2.2 Instrumentation:

Flame Atomic Absorption Spectrophotometer (AA model S11 from Thermo Jarell Ash Cooperation of Waltham, MA, USA) with an air acetylene flame was used to analyse heavy metals. pH meter used was Jenway pH meter model 3505, grinding was done using a blender (Heavy duty blender model 24CB10C), muffle furnace (gallenkamp muffle furnace size 2 tactical 308), water bath shaker used (American optical model 406016 NY142). Sieving done using supertek standard sieves. FTIR analyses done using ATR FTIR JASCO 4700 WITH ATR PRO ONE head. Number of scans 40/s. Range 500-4000cm^{-1}. Resolution 4.0cm^{-1}. Detector –TGS

2.3 Sampling sites and wastewater collection:

Waste water Samples were collected from Nakuru City, Nakuru County in Kenya from three different sampling sites that were coded A to C. Figure 1 shows the sites which included Jua Kali (Open air) garage (A), Tannery effluent (B), and Potable water refilling plant (C). Wastewater samples were collected in triplicate using pre-cleaned one litre plastic bottles then acidified with 1.0 ml concentrated HNO_3 and stored in a refrigerator for subsequent analysis.

2.4 Sampling and sample pre-treatment:

Sugarcane bagasse was collected from the Nzoia sugar factory in Western Kenya. Sugarcane bagasse was cut into small pieces (about 2 cm) then washed thoroughly with tap water and rinsed three times with distilled water, dried in air then in an oven at 60 °C for 24 hours then ground into fine powder. Sieving done using 50, 150, 250, 425, 500, 595μm, and 1mm-size standard sieves and labelled normal sugarcane bagasse (NSCB).

2.5 Preparation of Sugarcane bagasse and valorized bagasse:

The sugarcane bagasse sample was heated in a muffle at 300 ^oC for three hours for valorisation to take place then left to cool and sieved to the required particle size. The labelled valorised sugarcane bagasse (VSCB).

2.6 Optimisation experiments:

The experiments were done in 100mL polypropylene bottles at 20 □C using a rotary shaker at 65rpm. Optimized experimental conditions include particle size, contact time, pH, initial metal ion concentration and temperature. This was done by keeping all other parameters constant while varying the one under consideration. 0.1g of adsorbent was placed in polypropylene bottle followed by 100mL of desired metal ion concentration then placed in the shaker for 60 minutes. Effect of particle size (50-595 μm), contact time (1-60mins), pH (2-10), initial metal ion concentration (2-60mg/L) and temperature (25-40^{o}C) were studied where each of the shaken solution was filtered through Whatman filter paper No. 1 then the metal ion concentration of the filtrate determined. All determinations were conducted in triplicate using a flame atomic absorption spectrophotometer (AAS).

2.7 Data analysis:

The removal efficiency (%), amount of HMs adsorbed at a given time (q_t), amount of HMs adsorbed at equilibrium (q_e) given as

(1)

(2)

(3)

Whereby Removal efficiency is the percentage removal of metal ions, C_o is the initial metal ion concentration (mg/L), C_t is the metal ion concentration at time t (mg/L), C_e is the equilibrium concentration (mg/L), V is the volume of solution and m is the mass of adsorbent (g) [].

2.8 Adsorption isotherms:

0.1g of adsorbent was weighed into a glass beaker then 100ml of 10mg/L solution heavy metal (Cu^{2+}, Pb^{2+}, Cr^{3+} , Ni^{2+}, and Cd^{2+})solution was added. A contact time study was done at 1, 2, 3, 4, 5, 30 and 60 mins at pH 5 and at 25 °C. The study on isotherms was done to understand interaction of adsorbent and the heavy metal ions occurs as a monolayer or multilayer. Langmuir isotherm model assumes monolayer coverage [] while Freudlich assumes multilayer coverage []. Langmuir equation is given by equation (4)

(4)

Where q_e is the amount of heavy metal ions adsorbed at equilibrium, q_{max} is is the maximum adsorption capacity (mg/g), K_L is the Langmuir constant and Ce is the heavy metal ion concentration at equilibrium (mg/L).

Freundlich equation is given by equation (5)

log (5)

Where q_e is the amount of heavy metal ions adsorbed at equilibrium, K_F is the Freundlich constant and C_e is the heavy metal ion concentration at equilibrium (mg/L).

2.9 Thermodynamic data modelling:

This was done in order to determine thermodynamic parameters Gibbs energy (ΔG), entropy (ΔS), and enthalpy (ΔH) of the reaction []. Thermodynamic data was obtained by varying the temperature (25-40^{o}C). A plot of ln vs $\frac{1}{T}$ was plotted to estimate the thermodynamic parameters ΔG, ΔS, and ΔH. Van't Hoff's plot gives the relationship between the thermodynamic parameters

+ (6)

2.10 Kinetic data modelling:

Kinetic studies were done by varying the contact time (1-60mins) and obtained data was regressed against two equations the Lagergren pseudo first-order (equation 7) and also against a pseudo-second-order kinetic equations (equation 8).

(7)

(8)

Where q_t is the metal uptake per unit weight of adsorbent (mg g^{-1}) at time t while q_e is the metal uptake per unit weight of adsorbent (mg g−1) at equilibrium. k_1 and k_2 are the rate constants of the first-order kinetics and second order kinetics respectively (min^{-1}). The slopes and intercepts are used to determine the values of k_1 and k_2 as well as the equilibrium capacity (q_e) []. The one with higher R^2 that gives the best fit.

2.11 FTIR analyses:

NSCB and VSCB were dried in an oven at 105°C for 7 hours to remove moisture. The sample was left to cool to room temperature in a dessicator overnight then put in sample vials. NSCB and VSCB were soaked in 500 mg L^{-1} metal ion solution overnight and then filtered. The adsorbent was dried in an oven at 105 ^{o}C in an oven for 7 hours. The sample was left to cool in a dessicator. The samples were then put in sample vials.FTIR spectra were obtained for the adsorbents and for addsorbents treated with metal ions

3.0 RESULTS AND DISCUSSION:

3.1 Concentration of Heavy metals in wastewater:

The results of concentration of the heavy metals in the wastewater samples at sites A, B and C are provided in Table1. It is noted that the lead, cadmium, nickel, and chromium contents of the wastewaters, coming out of the Jua Kali garage, tanning industry and potable water plant, were significantly higher than the permissible limits of the World health organization (WHO, 2011) and Kenya (National Environment Management Authority (NEMA,2011) and Kenya Bureau of Standards (KEBS). Maximum permissible level according to WHO guidelines for drinking water []. The concentrations of copper (Cu) were below the detection limit in all the sampling sites.

Table 1. Concentration (mg/l) of heavy metals in wastewater

Site	**Heavy metal concentration (mg/l)**				
	Pb	**Cu**	**Cd**	**Ni**	**Cr**
A	1.15 ± 0.00	0.81 ± 0.01	0.10 ± 0.01	0.67 ± 0.01	0.66 ± 0.05
B	0.02 ± 0.00	0.02 ± 0.00	0.02 ± 0.00	0.20 ± 0.02	9.94 ± 1.93
C	0.10 ± 0.01	nd	0.02 ± 0.00	0.32 ± 0.00	nd
NEMA (Maximum Allowable effluent discharge Limits)	0.01	1.0	0.003	0.02	0.05

A = Jua Kali garage wastewater, B = Tannery effluent, C = Potable water refilling plant wastewater; nd = not detected, NEMA= National environmental management authority (Kenya)

3.2 Experimental conditions for adsorption:

Table 2: Experimental conditions for adsorption.

	Adsorbent dose (g)	pH	Particle size (μm)	Concentration Ppm	Temperature ^{o}C	Time (mins)
Pb	0.1	5	150-250	2 - 60	25	60
Cu	0.1	5	150-250	2 - 60	25	60

Cr	0.1	5	150-250	2 - 60	25	60
	0.1	5	150-250	2 - 60	25	60
Cd	0.1	5	150-250	2 - 60	25	60

3.3 Effect of adsorbent dosage:

Studies have shown that adsorbent dosage is a significant parameter that affects the ability of adsorption and the effectiveness of removal []. It was observed that the higher the adsorbent dose the higher the removal efficiency []. This is because increasing adsorbent dosage increases adsorption capacity [].

3.4 Effect of particle size of adsorbent:

It was observed that smaller particle sized adsorbents (<150μm) exhibited higher adsorption capabilities than larger sizes. Thus, the reduction of size from 595 to 150 microns led to an increase in the adsorption capacity due to the decrease in surface area and is supported by [and].

Fig. 2. Effect of particle size on the adsorption of heavy metal ions on sugarcane bagasse.

3.5 Effect of contact time on adsorption of metal ions:

100 mL of 10 mg/L metal ion solution was used. Initially, metal ion uptake was high, likely due to the significant concentration gradient between the ions in the solution and the abundant vacant sites on the adsorbent surface []. Over time, adsorption onto the remaining sites becomes more challenging, primarily due to the repulsive forces between the adsorbed solute ions on the adsorbent surface and those in the bulk solution [] the maximum adsorption capacity order of the heavy metals in the single system was $Cr^{3+} \geq Cu^{2+} \approx Cd^{2+} \approx Ni^{2+} \geq Pb^{2+}$ for NSCB and $Cr^{3+} \geq Cd^{2+} \geq Ni^{2+} \geq Cu^{2+} \geq Pb^{2+}$ for VSCB and this could probably be because of the different affinities of NSCB and VSCB toward the metal ions. The maximum removal could be achieved within a period of 30 minutes.

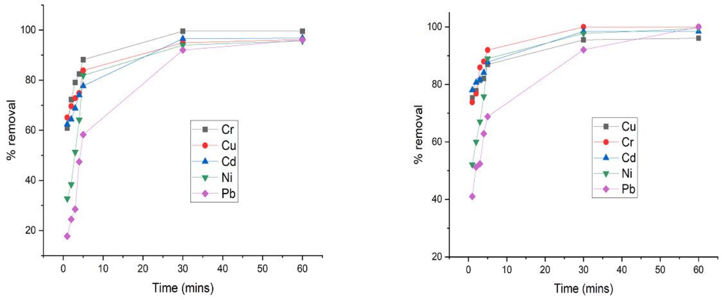

Fig. 3 Effect of increasing contact time (Adsorbent dose 0.1 g, particle size 250 < µm, temperature 20 ^{o}C for (a) NSCB and (b) VSCB

3.6 Effect of pH:

At low pH ≤ 2.0, both the NSCB and VSCB showed very low tendency for uptake of all the investigated metal ions as result of protonation of their varied functional groups and competition of H^{+} ions with metal ions for binding sites []. The binding capacities reached their maximum values around pH 4.0 then remaining nearly constant up to pH 6.0. After pH 6 there is a slight decrease in the amount of metal ions removed from the solution, whereas at high pH > 7.0, there is precipitation which leads to a decrease in the removal of metal ions [25]. Consequently, subsequent adsorption experiments were done under acidic conditions at the optimum pH 5.0.

Fig. 4. Removal efficiency of metal ions (Pb^{2+}, Cr^{3+} and Cd^{2+}) as function of pH using 0.1 g NSCB and at T = 25 °C.

3.7 Effect of initial concentration of metal ions:

An inverse relationship was observed between metal ion concentrations and the removal capabilities. At low concentration there are enough active sites for adsorption. The overall reduction in metal ion removal with increasing ion concentration is attributed to the saturation of available active adsorption sites adsorbate ions on the adsorbent surface [].

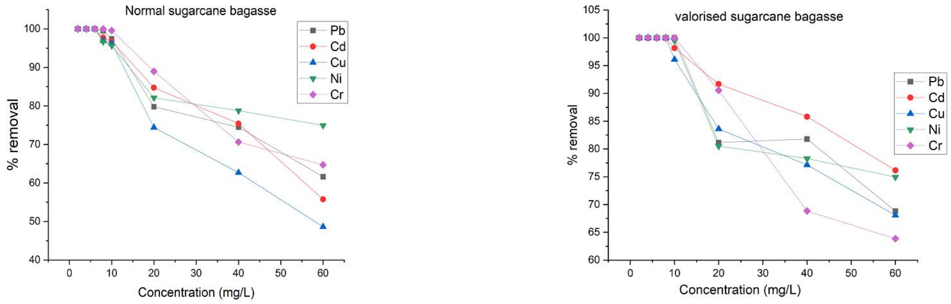

Fig .5 Effect of initial concentration of metal ions

3.8 Effect of temperature:

It was found that at higher temperatures the percentage removal was also higher. This can be attributed to increased kinetic energy for the molecules. However extreme temperatures can also change adsorbent structure lead to decrease in removal of metals.

Table 3: Percentage removal of metal ions at different temperatures (0.1 g/ (150-250 µm adsorbent, pH 5

Temp (°C)	20	25	30	35	40	60
% removal Cr	86	89	93	95	96	98
%removal Cd	87	89	90	92	93	99
% removal Pb	79	82	87	91	93	99
% removal Ni	79	81	89	91	93	97
% removal Cu	74	81	87	89	93	95

3.9 Characterization: FTIR analysis:

The absorption band at 3860–338 cm^{-1} can be attributed to –OH which is stretching vibration. The band at 1702 cm^{-1} was assigned to carbonyl (C=O) groups, and at 1600-1536 cm^{-1} represents C=C for alkene groups. The absorption bands at 1029 and 1034 cm^{-1} was attributed to C–O stretching vibration of cellulose, lignin and hemicelluloses. After interaction with metal ions, the absorption band of –OH [] in the NSCB and VSCB shifted 3334 cm^{-1} to 3346 cm^{-1}; and from 3796 to 3800 cm^{-1} in VSCB only. Absorption band at 1702 represents representing the carbonyl group. Band at 1590, 1509 is attributed to alkene group. This indicates that on adsorption the metal ion are attached to NSCB and VSCB through O-H or carboxylate, carbonyl and C=C aromatic groups.

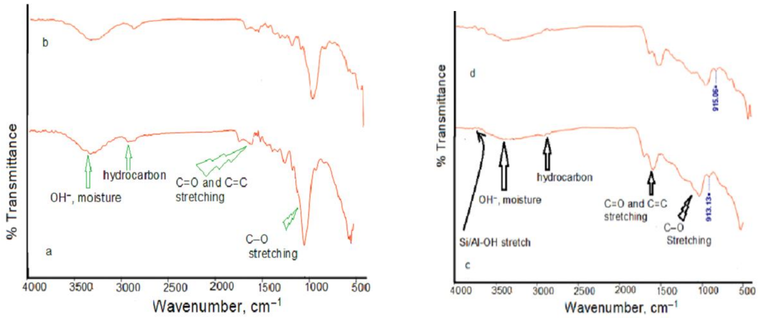

Fig. 6. FTIR spectra of NSCB (a) prior to adsorption and (b) following adsorption; VSCB (c) before adsorption and (d) after adsorption.

3.10 Adsorption isotherms and adsorption capacity:

From this study the data fitted well the Langmuir (R^2 = 96.9–99.4%) and Freundlich (R^2 = 95.6–99.9%) adsorption isotherms models for Cr $^{3+}$, Cd $^{2+}$, Cu $^{2+}$, Ni $^{2+}$ and Pb $^{2+}$ ions onto NSCB and VSCB adsorbent surfaces. From Langmuir adsorption isotherm the parameter R_L (separation factor) was in the range of 0.144–0.260, which justify the adsorption processes for Cr $^{3+}$, Cd $^{2+}$, Cu $^{2+}$, Ni $^{2+}$ and Pb $^{2+}$ ions SCB and VSCB. The slope of the Freundlich isotherm (1/n), on the other hand, were found to lie in the range (0.206-0.513); showing that normal adsorption process took place []. The Freundlich constant (1/n) suggests that the isotherm process is more favorable in cooperative adsorption, including both physisorption and chemisorption [], and that chemisorption takes place on the initial layer of active sites for all functional groups on the SCB surface [].

Table 4 Fitting of the parameters of the experimental results to the Langmuir and Freundlich equation parameters (pH 5, C_0 = 10 mg/L, V = 100 mL, 25 °C)

Adsorbent	Adsorbate	Langmiur isotherm				Freundlich isotherm			
		q_{max} (mg/g)	K_L (L/mg)	R_L	R^2	K_F	n	1/n	R^2
NSCB	Pb^{2+}	44.053	0.234	0.230	0.9392	11.939	2.804	0.357	0.9529
	Cu^{2+}	31.645	0.307	0.197	0.9771	11.665	3.899	0.257	0.9461
	Cd^{2+}	35.845	0.496	0.144	0.9922	13.359	3.362	0.297	0.9693
	Ni^{2+}	56.818	0.184	0.260	0.8228	12.331	2.339	0.428	0.9322
	Cr^{3+}	78.740	0.485	0.146	0.9512	17.624	4.852	0.206	0.9435

Langmiur isotherm **Freundlich isotherm**

Adsorbent	**Adsorbate**	**q_{max} (mg/g)**	**K_L (L/mg)**	**R_L**	**R^2**	**K_F**	**n**	**1/n**	**R^2**
VSCB	Pb^{2+}	45.871	0.459	0.152	0.9496	10.515	1.948	0.513	0.9810
	Cu^{2+}	47.393	0.257	0.219	0.9459	12.758	2.663	0.376	0.9669
	Cd^{2+}	51.020	0.490	0.145	0.9748	17.230	2.766	0.362	0.9850
	Ni^{2+}	51.282	0.243	0.226	0.7549	17.976	4.272	0.234	0.7982
	Cr^{3+}	38.022	0.595	0.126	0.9505	11.579	2.640	0.379	0.9279

3.11 Kinetics for NSCB and VSCB:

The effect of contact time on metal adsorption is shown in figure 3. The experimental results show that NSCB and VSCB have very fast adsorption rate toward heavy metal ions. The parameters for pseudo-first-order and pseudo-second-order models that were used to evaluate the kinetic mechanism which controls the adsorption process [] are shown in table 5 below. The correlation coefficient for pseudo second order kinetics (in the range R^2= 0.9961 - 0.999) is higher than that for pseudo first order kinetics (in the range R^2=0.8801 – 0.9993). Suggesting that pseudo second kinetic have a better fit for the experimental results.

Table 5 Kinetic parameters for the adsorption of heavy metals by NSCB and VSCB.

NSCB	Pseudo-First-order model			Pseudo-Second-order model		
	k_1 (min^{-1})	q_1 (mg/g)	R^2	k_2 (mg g^{-1} min^{-1})	q_2 (mg/g)	R^2
Pb^{2+}	0.101	8.019	0.9833	0.016	10.638	0.9961
Cd^{2+}	0.176	4.509	0.9993	0.094	9.881	0.9998
Ni^{2+}	0.119	5.394	0.9179	0.045	9.960	0.9999
Cu^{2+}	0.107	3.047	0.9762	0.118	9.765	0.9999
Cr^{3}	0.298	5.131	0.9858	0.133	10.101	0.9999
VSCB	Pseudo-First-order model			Pseudo-Second-order model		
	k_1 (min^{-1})	q_1 (mg/g)	R^2	k_2 (mg g^{-1} min^{-1})	q_2 (mg/g)	R^2
Pb^{2+}	0.295	8.260	0.8990	0.061	10.320	0.9994
Cd^{2+}	0.153	2.426	0.9302	0.194	9.911	0.9999
Ni^{2+}	0.187	5.976	0.9464	0.083	10.152	0.9998
Cu^{2+}	0.208	5.821	0.8801	0.120	16.807	0.9999
Cr^{3}	0.267	10.342	0.8164	0.032	10.582	0.9984

3.12 Thermodynamic parameters of Adsorption:

The results show that ΔH° and ΔS° are positive across all experiments, while ΔG° is negative in every case indicating the adsorption process was feasible. The positive ΔH° values demonstrate that the adsorption process is endothermic. The positive value of ΔS° suggests increased randomness and an increase in the degrees of freedom at the bio-adsorbent-solution interface as heavy metal ions are immobilized on the adsorbent's active sites.

Table 6: Thermodynamic parameters

	NSCB			**VSCB**		
	$\Delta G^{\#}$	$\Delta H^{\#}$	$\Delta S^{\#}$	$\Delta G^{\#}$	$\Delta H^{\#}$	$\Delta S^{\#}$
	kJmol^{-1}K^{-1}	kJmol^{-1}	Jmol^{-1}K^{-1}	kJmol^{-1}K^{-1}	kJmol^{-1}	Jmol^{-1}K^{-1}
Cr^{2+}	-5.652	49.451	184.912	-6.300	74.840	272.284
Pb^{2+}	-3.802	76.562	269.681	-5.515	46.947	176.049
Ni^{2+}	-4.019	61.007	218.209	-5.210	48.117	178.950

Cd^{2+}	-4.758	57.867	210.153	-6.322	96.359	344.233
Cu^{2+}	-3.776	40.706	149.269	-4.946	28.340	111.698

3.13 Heavy metal removal studies on industrial effluents:

Analysis was done to determine the amounts of heavy metal ions adsorbed or removed. The results obtained are given in Table 7. All the effluents were adjusted to the pH of 5, adsorbent dosage level was set at 0.1 g for 60 minutes at room temperature (25 1 °C).

Table 7: Effectiveness of optimal conditions for removing heavy metals from wastewater samples

		Removal Efficiency (%)		
Adsorbent	**Adsorbate**	A	B	C
SCB	Pb	94.8 (1.09)	95.0 (0.02)*	60.0 (0.06)
	Cd	50.0 (0.01)	50.0 (0.01)	50.0 (0.01)
	Ni	79.1 (0.53)	nd	30.0 (0.06)
	Cu	92.6 (0.75)	nd	nd
	Cr	88.0 (0.58)	47.2 (4.69)	nd
VSCB	Pb	94.8 (1.09)	95.0 (0.02)	40.0 (0.04)
	Cd	90.0 (0.09)	50.0 (0.01)	50.0 (0.01)
	Ni	85.1(0.57)	35.0 (0.07)	68.8 (nd)
	Cu	97.5 (0.79)	nd	nd
	Cr	94.0 (0.62)	27.8 (2.76)	nd

A = Jua Kali garage wastewater, B = Tannery effluent, C = Potable water refilling plant wastewater;
nd = not detected. *Amount of heavy metal adsorbed (mg/g) are in parenthesis.

4.0 CONCLUSION

VSCB possess pollutant binding properties which can be extremely useful in water treatment. Sugarcane based activated carbon can be extremely useful for removal of heavy metals from aqueous solutions. Valorising sugarcane bagasse significantly increased capacity of the groups on the surface of sugarcane bagasse. Adsorption of metals was dependent on the pH, initial concentration, particle size and temperature. Adsorption of heavy metals reached equilibrium at 1 hour. Adsorption followed pseudo second order kinetics. In NSCB Pb^{2+} and Ni^{2+} showed better fitting for Freundlich isotherm while Cd^{2+}, Cu^{2+} and Cr^{3+} showed better fit for Langmuir isotherm. For VSCB Freundlich isotherm had a better fitting for experimental results for all metals except Cr^{3+} showed better fit for Langmuir isotherm. Thermodynamic properties indicated that Gibbs free energy have negative values indicating a spontaneous process. The results from this study suggest carbonyl, hydroxyl and alkene functional groups are the main adsorption sites in sugarcane bagasse as well as in the valorised bagasse.

REFERENCES