



KINETIC AND EQUILIBRIUM STUDIES ON THE REMOVAL OF CHROMIUM (VI) IONS BY ADSORPTION ON TO LOW COST ACQNC ADSORBENT

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Abstract

The research of the present work was to investigate the removal of Chromium ion from aqueous solution by using Activated Cissus Quadrangularis Stem Nano Carbon. Generally, metal ions are used in chemical, textile, paper, printing, leather, plastics and various food industries. The need for the treatment of metal ion contaminated waste water passed out from the industry. In this study, Activated Cissus Quadrangularis Stem Nano Carbon was studied for its potential use as an adsorbent for removal of Chromium ions. The various factors affecting adsorption, such as initial metal ion concentration, contact time, adsorbent dose and effect of temperature, were evaluated. The experimental data were fitted into the pseudo-second order kinetic model. The equilibrium of adsorption was modeled by using the Langmuir and Freundlich isotherm models. The objective of the present work suggests the Activated Cissus Quadrangularis Stem Nano Carbon may be utilized as a low cost adsorbent for Chromium ions removal from aqueous solution.

Key words: Activated Cissus Quadrangularis Stem Nano Carbon (ACQNC); Chromium; Adsorption isotherm; Kinetics; Equilibrium models

I. Introduction

Wastewater quality can be defined by physical, chemical or biological characteristics. Wastewater generally contains toxic inorganic and organic pollutants. Inorganic pollutants consist of mineral acids, inorganic salts, finely divided

metal compounds, trace elements, cyanides, nutrients and organ metallic compounds. Some of the trace elements play essential roles in biological processes, but at higher concentrations, they may be toxic to the biota; they disturb the biochemical processes and cause hazards. These elements include metals (Cd, Cr, Co, Fe, Cu, Zn, Pd, Hg, Ni, Ag) and metalloids (Se, As, Sb). Most of the trace elements are transition metals with variable oxidation states and coordination numbers. These metals form complexes with organics in the environment thereby increasing their mobility in the biota and manifest toxic effects. Although there are metals that have inherent ability to antagonize the essential functions of other elements, the heavy load of contaminants arising from human activity exceeds the ability of self-purification of aqueous environment.

A number of treatment processes for the removal of heavy metal ions from aqueous solutions have been reported, mainly ion-exchange, electrochemical reduction, evaporation, solvent extraction, reverse osmosis, chemical precipitation, membrane filtration, adsorption, etc. Depending on the nature of the aqueous effluents, flow rates and metal ion concentrations, the industrial application of these processes is restricted by the operating costs or by the inefficiency of the technique [1, 2, 3].

The present study undertaken to evaluate the efficiency of an adsorbent prepared from Cissus Quadrangularis Stem for removal of chromium ion in aqueous solution. In order to design adsorption treatment systems, knowledge of kinetic and



mass transfer processes is essential. In this paper, the applicability of kinetic and mass-transfer models for the adsorption of chromium ion onto Activated Cissus Quadrangularis Stem Nano Carbon was discussed in detailed manner.

II. Experimental section

2.1 Adsorbent Material

The Cissus Quadrangularis Stem was obtained from Agriculture area was carbonized with w/v ratio of con sulphuric acid and activated around 900°C in a muffle furnace for 5 hrs then it was taken out, ground well to fine powder and stored in a vacuum desiccator.

2.2 Batch equilibration method

The adsorption experiments were carried out in a batch process at 30, 40, 50 and 60° C. A known weight of Activated Cissus Quadrangularis Stem Nano Carbon was added to 50 ml of the metal ion solutions with an initial concentration of 50 mg/L to 250 mg/L, which is prepared from 1000 mg/L of metal ion stock solution. The contents were shaken thoroughly using a mechanical shaker with a speed of 120 rpm. The solution was then filtered at present time intervals and the residual metal ion concentration was measured.

2.3.1 Dosage of adsorbents

The various doses consisting of the adsorbents respectively mixed with the metal ions solution and the mixture was agitated in a mechanical shaker. The adsorption capacities for different doses were determined at definite time intervals by keeping all other factors constant.

2.3.2 Initial concentration of metal ion

In order to determine the rate of adsorption, experiments were conducted with different initial concentrations of metal ions ranging from 50 to 250 mg/L. All other factors have kept constant.

2.3.3 Contact time

The effect of period of contact on the removal of the metal ion on adsorbent in a single cycle was determined by keeping particle size, initial concentration, dosage, pH and concentration of other ions constant.

2.3.4 pH

Adsorption experiments were carried out at pH 2,3,4,5,6,7,8,9 and 10. The acidic and alkaline pH of the media was maintained by adding the required amounts of dilute hydrochloric acid and sodium hydroxide solutions. The parameters like particle size of the adsorbents, metal ion concentration, dosage of the adsorbents and concentration of other ions have kept constant while carrying out the experiments. The pH of the samples was determined using a portable pH meter, Systronics make. The pH meter was calibrated with 4.0 and 9.2 buffers.

2.3.5 Chloride

The experiments were done in the presence of varying chloride environments using various chloride solutions. While doing the experiments, the absence of other anions has ensured.

2.3.6 Temperature

The adsorption experiments were performed at four different temperatures viz., 30, 40, 50 and 60°C in a thermostat attached with a shaker, Remi make. The constancy of the temperature was maintained with an accuracy of $\pm 0.5^\circ \text{C}$.

2.3.7 Zero point charge

The pH at the potential of zero charge of the ACQNC was measured using the pH drift method. The pH of the solution was adjusted by using 0.01 M sodium hydroxide or hydrochloric acid. Nitrogen was bubbled through the solution at 25°C to remove the dissolved carbon dioxide. ACQNC 50 mg was added to 50 ml of the solution. After stabilization, the final pH



was recorded. The graphs of final pH versus initial pH used to determine the zero point charge of the ACQNC.

2.3.8 Titration studies

According to Boehm only strong acidic carboxylic acid groups are neutralized by sodium bicarbonate, whereas those neutralized by sodium carbonate are thought to be lactones, lacto and carboxyl group. The weakly acidic phenolic groups only react with strong alkali, sodium hydroxide. Therefore, by selective neutralization using bases of different strength, the surface acidic functional group in ACQNC can be characterized both quantitatively and qualitatively. Neutralization with hydrochloric acid characterizes the amount of surface basic groups that are, for example, pyrones and chromenes. The basic properties have described to surface basic groups and the pi electron system of ACQNC basal planes. The results indicate that the ACQNC used may possess acidic oxygen functional group on their surface and this is supported well by their respective zero point charge values. The results

obtained from the above characterization studies are given in the table 1.

2.3.9 Desorption studies

Desorption studies help to elucidate the nature of adsorption and recycling of the spent adsorbent and the metal ions. The effect of various reagents used for desorption are studied.

III. Results and discussions

3.1 Characterization of the adsorbent

Activated Cissus Quadrangularis Stem Nano Carbon is a widely used adsorbent due to its high adsorption capacity, high surface area, micro porous structure and high degree of surface respectively. The wide usefulness of ACQNC is a result of their specific surface area, high chemical and mechanical stability. The chemical nature and pore structure usually determines the sorption activity. The physico chemical properties are listed in Table 1.

Table 1 Characteristics of the adsorbent

Properties	(ACQNC)
Particle size (mm)	0.048
Density (g/cc)	0.3952
Moisture content (%)	0.65
Loss on ignition (%)	0.82
Water soluble matter (%)	0.06
pH of aqueous solution	6.4
pH _{zpc}	6.25
Surface groups (m equiv/g) :	
i) Carboxylic acid	0.172
ii) Lactone, lactol	0.025
iii) Phenolic	0.022
iv) Basic (pyrones and chromenes)	0.039

3.2 Effect of contact time and initial metal ion concentration

The experimental results of adsorptions of at various concentrations (50 to 250 mg/L) with contact time are shown in Figure 1. The equilibrium data were collected in Table 2 reveals that, percent adsorption decreased with increase in initial chromium ion concentration, but the actual amount of chromium ion adsorbed per unit mass of adsorbate increased with increase in chromium ion concentration. It means that the adsorption is highly dependent on initial concentration of chromium ion. It is because of that at lower concentration, the ratio of the initial number of chromium ion to the

available surface area is low subsequently the fractional adsorption becomes independent of initial concentration. However, at high concentration the available sites of adsorption becomes fewer and hence the percentage removal of chromium ion is dependent upon initial concentration [5, 6]. Equilibrium have established at 45 minutes for all concentrations. Figure 1 reveals that the curves are single, smooth, and continuous, leading to saturation, suggesting the possible monolayer coverage of the chromium ion on the ACQNC surface.

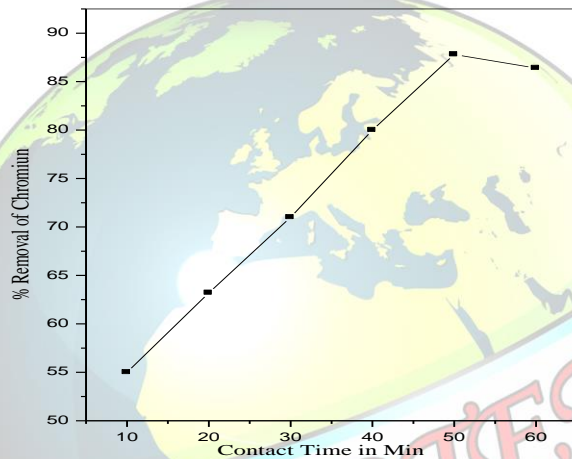


Fig:1-Effect of Contact Time on the Removal of Cr Ion
[Cr]=50 mg/L; Temperature 30°C; adsorbent dose=25mg/50ml

Table - 2 EQUILIBRIUM PARAMETERS FOR THE ADSORPTION OF CHROMIUM ION ONTO ACQNC

Cr ₀	Ce (Mg / L)				Qe (Mg / g)				Removed (%)			
	30° C	40° C	50° C	60° C	30° C	40° C	50° C	60° C	30° C	40° C	50° C	60° C
25	2.06	1.08	1.68	1.37	45.87	47.82	46.62	47.24	91.75	95.64	93.25	94.49
50	7.34	6.54	5.61	4.55	85.30	86.90	88.77	90.88	85.30	86.90	88.77	90.88
75	15.26	13.63	12.09	10.68	119.4	122.7	125.8	128.6	79.64	81.81	83.87	85.75
100	29.56	27.02	12.09	22.57	140.8	145.9	175.8	154.8	70.43	72.97	87.90	77.42
125	45.62	42.73	24.68	37.88	158.7	164.5	200.6	174.2	63.50	65.81	80.24	69.68

3.3 Effect of concentration:

The adsorption of the chromium ion on ACQNC was studied by varying the concentration (10-250 mg/50ml) for 50 mg/L of chromium ion concentration. The percent adsorption increased with increase

in the ACQNC concentration (Figure 2). This was attributed to increased ACQNC surface area and availability of more adsorption sites [5, 6]. Hence remaining part of experiments is carried out with the adsorbent dose of 25 mg/50 ml.

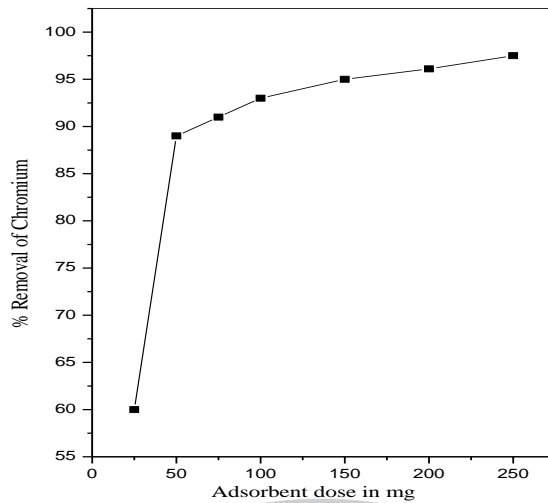


Fig:2- Effect of Adsorbent dose on the removal of Chromium
[Cr]=50mg/L; Contact Time 60min; Temperature 30°C

3.4 Adsorption isotherm

The experimental data analyzed according to the linear form of the Langmuir and Freundlich isotherms [7, 8].

The Langmuir isotherm represented by the following equation

$$\frac{C_e}{Q_e} = \frac{1}{Q_m b} + \frac{C_e}{Q_m}$$

Where C_e is the equilibrium concentration (mg/L), Q_e is the amount adsorbed at

equilibrium (mg /g) and Q_m and b is Langmuir constants related to adsorption efficiency and energy of adsorption, respectively. The linear plots of C_e/Q_e versus C_e suggest the applicability of the Langmuir isotherms. Values of Q_m and b were determined from slope and intercepts of the plots and are presented in

Table 3.

TABLE: 3. LANGMUIR AND FREUNDLICH ISOTHERM PARAMETER FOR THE ADSORPTION OF CHROMIUM ION ON TO ACQNC

TEMP. (C°)	LANGUMUIR PARAMETER		FRUENDLICH PARAMETER	
	Q_m	b	K_f	n
30°	181.73	0.13	4.7	2.47
40°	181.32	0.18	5.31	2.90
50°	278.41	0.09	4.68	1.77
60°	194.94	0.19	5.26	2.54

From the results, it is clear that the value of adsorption efficiency Q_m and adsorption energy b of the ACQNC adsorbent increases on increasing the temperature. The observed Q_m values conclude that the maximum adsorption corresponds to a saturated monolayer of adsorbate molecules on adsorbent surface with constant energy and no transmission of adsorbate in the plane of

the adsorbent surface. The observed b values shows that the adsorbent prefers to bind acidic ions and that speciation predominates on sorbent characteristics, when ion exchange is the predominant mechanism takes place in the adsorption of chromium ion. Further, it confirms the endothermic nature of the process involved in the system [9, 10, and 11]. To confirm the favorability of the adsorption process, the separation



factor (R_L) has calculated and presented in Table 4. The values were found to be between 0 and 1 and confirm that the

ongoing adsorption process is favorable [12].

TABLE: 4. DIMENSIONLESS SEPERATION FACTOR (R_L) FOR THE ADSORPTION OF CHROMIUM ION ON TO ACQNC

(C _i)	TEMPERATURE °C			
	30°C	40°C	50°C	60°C
25	0.23	0.18	0.29	0.16
50	0.13	0.09	0.17	0.09
75	0.09	0.06	0.12	0.06
100	0.06	0.05	0.09	0.04
125	0.05	0.04	0.07	0.03

The Freundlich equation was also employed for the adsorption of chromium ion on the adsorbent. The Freundlich isotherm have represented as

$$\log Q_e = \log K_f + \frac{1}{n} \log C_e$$

Where Q_e is the amount of chromium ion adsorbed (mg/g), C_e is the equilibrium concentration of chromium ion in solution (mg/L) and K_f and n are constants incorporating all factors affecting the adsorption capacity and intensity of adsorption, respectively. Linear plots of $\log Q_e$ versus $\log C_e$ shows that the adsorption of chromium ion follows the Freundlich isotherm. The found values of K_f and n have given in the Table 3 shows that the increase in negative charges on the adsorbent surface, that makes electrostatic force like

Vanderwaal's between the ACQNC surface and chromium ion. This increases the adsorption of chromium ion. The higher atomic weight, large size and radii of the chromium ion have limits the possibility of the adsorption of chromium ion onto adsorbent in higher concentration. However, the values clearly show the dominance in adsorption capacity. The intensity of adsorption is an indicative of the bond energies between chromium ion and adsorbent and the possibility of slight chemisorptions rather than physisorption of chromium ion. However, the multilayer adsorption of chromium ion through the percolation process may be possible. The values of n are greater than one indicating the adsorption is much more favorable [11, 12].

3.5 Effect of temperature

The adsorption capacity of the ACQNC increased with increase in the temperature of the system from 30°-60°C. Thermodynamic parameters such as change in free energy (ΔG°) (kJ/mol), enthalpy (ΔH°) (kJ/mol) and entropy (ΔS°) (J/K/mol) were determined using the following equations

$$K_0 = \frac{C_{\text{solid}}}{C_{\text{liquid}}}$$

$$\ln K_0 = -\frac{\Delta G^\circ}{RT}$$

$$\log K_0 = \frac{\Delta S^\circ}{(2.303RT)} - \frac{\Delta H^\circ}{(2.303RT)}$$

Where K_0 is the equilibrium constant, C_{solid} is the solid phase concentration at equilibrium (mg/ L), C_{liquid} is the liquid phase concentration at equilibrium (mg/L), T is the temperature in Kelvin and R is the gas constant. The ΔH° and ΔS° values obtained from the slope and intercept of Van't Hoff plots have presented in Table 5. The values of ΔH° are within the range of 1 to 93 KJ/mol indicates the physisorption. From the results we could

make out that physisorption is much more favorable for the adsorption of chromium ion. The positive values of ΔH° show the endothermic nature of adsorption and it governs the possibility of physical adsorption. Because in the case of physical adsorption, while increasing the temperature of the system, the extent of chromium ion adsorption increases, this rules out the possibility of chemisorption [12, 13, and 14]. The low ΔH° value depicts chromium ion are physisorbed onto adsorbent ACQNC.

The negative values of ΔG° (Table 5) shows the adsorption is highly favorable and spontaneous. The positive values of

ΔS° (Table 5) show the increased disorder and randomness at the solid solution interface of chromium ion with ACQNC, while the adsorption there are some structural changes in the chromium ion and the adsorbent occur. The adsorbed water molecules, which have displaced by the adsorbate species, gain more translational entropy than is lost by the adsorbate molecules, thus allowing the prevalence of randomness in the system. The enhancement of adsorption capacity of the ACQNC at higher temperatures was attributed to the enlargement of pore size and activation of the adsorbent surface [12,13].

TABLE: 5. THERMODYNAMIC PARAMETER FOR THE ADSORPTION FOR THE ADSORPTION OF CHROMIUM ION ON TO ACQNC

C ₀	ΔG°				ΔH°	ΔS°
	30° C	40° C	50° C	60° C		
25	-6069.9	-8039.3	-7053.5	-7869.4	7.26	45.66
50	-4430.8	-4925.1	-5553.6	-6367.5	15.02	63.98
75	-3437.4	-3913.2	-4428.4	-4970.2	12.04	51.05
100	-2187.3	-2584.9	-5327.0	-3411.7	17.90	66.93
125	-1395.2	-1704.5	-3764.9	-2304.8	13.61	50.02

3.6 Kinetics of adsorption

The kinetics of sorption describes the solute uptake rate, which in turn governs residence time or sorption reaction. It is one of the important characteristics in defining the efficiency or sorption. In the present study, the kinetics of the chromium ion removal was carried out to understand the behaviour of these low cost ACQNC adsorbent. The adsorption of chromium ion from an aqueous follows reversible second order kinetic, when a single species are considered on a heterogeneous surface. The heterogeneous equilibrium between the chromium ion solutions and the ACQNC are expressed as



Where k_1 is the forward rate constant and k_2 is the backward rate constant. A represents chromium ion remaining in the aqueous solution and B represent chromium ion adsorbed on the surface of ACQNC. The equilibrium constant (K_0) is the ratio of the concentration adsorbate in adsorbent and in aqueous solution ($K_0 = k_1/k_2$).

In order to study the kinetics of the adsorption process under consideration the following kinetic equation proposed by Natarajan and Khalaf as cited in literature has been employed [1].

$$\log C_0/C_t = (K_{ad}/2.303)t$$



Where C_0 and C_t are the concentration of the chromium ion (in mg/L) at time zero and at time t , respectively. The rate constants (K_{ad}) for the adsorption processes have been calculated from the slope of the linear plots of $\log C_0/C_t$ versus t for different concentrations and temperatures. The determination of rate constants as described in literature given by

$$K_{ad} = k_1 + k_2 = k_1 + (k_1/K_0) = k_1 [1 + 1/K_0]$$

The overall rate constant k_{ad} for the adsorption of chromium ion at different temperatures are calculated from the slopes of the linear Natarajan-Khalaf plots. The rate constant values are collected in Table 6 shows that the rate constant (k_{ad}) increases with increase in temperature suggesting that the adsorption process is endothermic in nature. Further, k_{ad} values decrease with

increase in initial concentration of the chromium ion. In cases of strict surface adsorption a variation of rate should be proportional to the first power of concentration. However, when pore diffusion limits the adsorption process, the relationship between initial chromium ion concentration and rate of reaction will not be linear. Thus, in the present study pore diffusion limits the overall rate of chromium ion adsorption. The overall rate of adsorption is separated into the rate of forward and reverse reactions using the above equation. The rate constants for the forward and reverse processes are also collected in Table 6 indicate that, at all initial concentrations and temperatures, the forward rate constant is much higher than the reverse rate constant suggesting that the rate of adsorption is clearly dominant [1,11,13].

TABLE: 6. THE KINETIC PARAMETERS FOR ADSORPTION FOR THE ADSORPTION OF CHROMIUM ION ON TO ACQNC

M	Temp p °C	PSEUDO SECOND ORDER				ELOVICH MODEL			INTRAPARTICLE DIFFUSION		
		q_e	k_2	γ	H	α	β	γ	K_{id}	γ	C
25	30	50.76	22×10^{-3}	0.992	6.66	80.32	0.14	0.990	1.65	0.9921	0.16
	40	52.93	16×10^{-3}	0.991	6.25	51.79	0.12	0.991	1.63	0.9920	0.18
	50	51.47	20×10^{-3}	0.993	7.78	71.62	0.13	0.994	1.65	0.996	0.17
	60	51.17	17×10^{-3}	0.996	7.46	149.76	0.15	0.995	1.69	0.999	0.14
50	30	93.65	25×10^{-3}	0.997	13.54	146.38	0.07	0.996	1.62	0.992	0.17
	40	95.44	25×10^{-3}	0.998	13.60	169.57	0.07	0.997	1.63	0.993	0.16
	50	96.95	23×10^{-3}	0.995	14.42	223.18	0.08	0.998	1.65	0.991	0.15
	60	99.49	22×10^{-3}	0.993	14.60	217.31	0.07	0.999	1.66	0.990	0.15
75	30	130.80	26×10^{-3}	0.992	19.06	309.65	0.05	0.995	1.61	0.993	0.15
	40	136.00	27×10^{-3}	0.992	18.38	188.81	0.05	0.994	1.59	0.996	0.17
	50	139.00	27×10^{-3}	0.990	19.43	199.91	0.05	0.995	1.61	0.997	0.17
	60	140.38	24×10^{-3}	0.992	17.34	351.96	0.05	0.991	1.64	0.991	0.15
100	30	158.97	30×10^{-3}	0.993	17.38	106.05	0.04	0.995	1.47	0.993	0.20
	40	164.66	31×10^{-3}	0.991	17.72	108.16	0.03	0.994	1.48	0.994	0.20
	50	168.15	14×10^{-3}	0.991	20.37	160.43	0.04	0.996	1.53	0.993	0.18
	60	171.58	28×10^{-3}	0.992	23.03	215.38	0.04	0.997	1.56	0.994	0.17
125	30	183.21	32×10^{-3}	0.993	17.04	73.353	0.03	0.998	1.37	0.995	0.23
	40	189.04	32×10^{-3}	0.994	17.82	78.16	0.03	0.992	1.39	0.991	0.23
	50	198.72	21×10^{-3}	0.995	17.67	73.18	0.02	0.993	1.40	0.992	0.23
	60	197.20	31×10^{-3}	0.996	21.02	119.52	0.03	0.992	1.46	0.997	0.20

3.8 Effect of pH

The experiments carried out at different initial pH show that the adsorption percentage increases with increase in initial pH of the medium in the range studied i.e. 3 to 10 as depicted in the Figure 3. This behaviour can be explained using pH_{ZPC} of the adsorbent. In the present study the pH_{ZPC} of ACQNC is 6.4. At any pH below pH_{ZPC} , the surface of adsorbent is positively charged and at pH above pH_{ZPC} , the surface is negative. When the solution pH exceeded pH_{ZPC} , the chromium ions are more easily

attracted by the negatively charged surface of adsorbent, favoring accumulation of chromium ion on the surface and thus promoting adsorption. In addition the increase is partially attributed to the formation of different hydroxo species with rise in solution [1, 12]. The decrease in adsorption of metal ions at low pH can be attributed to the competition between H^+ and metal ions. It is thus clear from Figure 3 that at lower pH, the adsorption of chromium ion studied is drastically reduced. This observation was made use of to desorb the chromium ion from the adsorbed material.

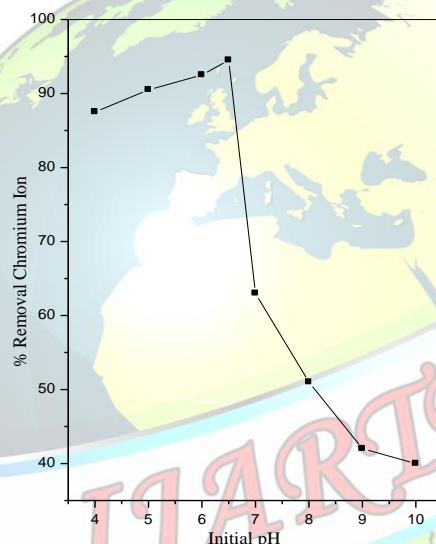


Fig.3-Effect of Initial pH on the removal of Cr Ion
[Cr]=50mg/L; Contact time=60 min; adsorbent dose=25mg/50ml

3.9 Effect of the ionic strength on the adsorption of chromium ion on ACQNC

The effect of sodium chloride on the adsorption of chromium ion on ACQNC is shown in Figure 4. In a low solution concentration NaCl had little influence on the adsorption capacity. At higher ionic strength the adsorption chromium of ion on ACQNC will be increased due to the partial neutralization of the positive charge on the ACQNC surface and a consequent compression of the electrical double layer by the Cl^- anion. The chloride ion can also enhance adsorption of chromium ion on ACQNC by pairing of their charges and hence reducing the repulsion between the

chromium ions adsorbed on the surface [1, 17]. This initiates carbon to adsorb more of positive chromium ions.

3.10 Desorption studies

Desorption studies help to elucidate the nature of adsorption and recycling of the spent adsorbent and the chromium ions. If the adsorbed chromium ions can be desorbed using neutral pH water, then the attachment of the chromium ions of the adsorbent is by weak bonds. If sulphuric acid or alkaline water desorb the chromium ion then the adsorption is by ion exchange. If organic acids, like acetic acid can desorb the chromium ions, then the chromium ions



has held by the adsorbent through chemisorption [12,18]. The effect of various reagents used for desorption studies indicate that hydrochloric acid is a better reagent for desorption, because we could get more than 75% removal of adsorbed chromium ions. The reversibility of adsorbed chromium ions in mineral acid or base is in agreement with the pH dependent results obtained. The desorption of chromium ions by mineral acids and alkaline medium indicates that the chromium ions were adsorbed onto the ACQNC through by physisorption mechanisms.

4. Conclusions

The experimental data correlated reasonably well by the Langmuir and Freundlich adsorption isotherms and the isotherm parameters were calculated. The low as well high pH values pay the way to the optimum amount of adsorption of chromium ion. The amount of chromium ion adsorbed increased with increasing ionic strength and increased with increase in temperature. The dimensionless separation factor (R_L) showed that the ACQNC could be used for the removal of chromium ion from aqueous solution. The values of ΔH° , ΔS° and ΔG° results shows that the ACQNC employed has a considerable potential as an adsorbent for the removal of chromium ion.

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