Adsorption of Glutaric Acid and Glyoxylic Acid onto Weakly Basic Ion-Exchange Resin: Equilibrium and Kinetics

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Adsorption equilibria of glutaric acid and glyoxylic acid on a weakly basic ion-exchanger which has a tertiary amine functional group were investigated experimentally and theoretically in this study. Amberlite IRA-67 was used as the ion-exchange resin. The time to reach an equilibrium state, effects of amount of adsorbent, temperature, and initial acid concentrations on adsorption efficiency and distribution coefficient of acid adsorption were investigated, experimentally. The Langmuir, Freundlich, and Temkin adsorption isotherms were calculated. The equilibrium isotherms were significantly dependent on initial acid concentration. The Langmuir isotherm was found to best represent the data for both acids. The adsorption of both acids followed pseudosecond-order kinetics. Diffusion is not the only rate-controlling step.

Introduction

Recovery of carboxylic acids is an important process in chemical engineering. Because of the wide range of application of these acids, such as in the pharmaceutical, polymer, food industries, etc., there have been numerous separation techniques developed in recent years. Ion exchange is one of these methods. For carboxylic acid recovery, weakly basic ion exchange resins are commonly used, such as Amberlite IRA-92, IRA-35, and IRA-67. The resins generally contain amine groups; for example, IRA-67 has a tertiary amine group, and so, dissociated carboxylic acid reacts with the resin. This reaction involves protonation of the ionogenic sites of the resin by the acid.[1]

Glutaric acid (pentanedioic acid) is an important dicarboxylic acid and is found in blood and urine. It has a wide range of applications in some industrial fields, especially in the polymer industry. It is used in the production of polyester polyols, polyamides, ester plasticizers, and corrosion inhibitors. It is used in the synthesis of pharmaceuticals, surfactants, and metal finishing compounds.[2]

Glyoxylic acid (oxoacetic acid) is the smallest α-keto acid. It has a ketone group on the carbon atom next to the acid group. Glyoxylic acid has two functional groups, a carboxylic acid and an aldehyde. In industry, it is used as a basic chemical for the synthesis of other chemical products such as acids, esters, and cyclic compounds. Application fields include aroma compounds, agrochemicals, pharmaceuticals, and polymers. Glyoxylates and esters of glyoxylic acid are important in biochemical research.[2] Glyoxylic acid is produced by ozonolysis of maleic acid.

Numerous researchers have investigated the adsorption of carboxylic acids from aqueous solutions by using polymeric sorbents. Tung and King investigated extraction and sorption of succinic and lactic acids using different basic extractants and ion exchange resins.[3,4] Kawabata et al. separated carboxylic acid by using a polymer sorbent of pyridine skeletal structure and a cross-linked structure. The polymer sorbent showed good selectivity and high adsorption capacity for carboxylic acids even in the presence of inorganic salts.[4,5] Gluszcz et al. adsorbated lactic and citric acids onto Amberlite IRA-67 and IRA-92.[6] However, there is not sufficient information about glutaric and glyoxylic acid adsorption in the literature.

The aim of this study is to define the efficiency of Amberlite IRA-67 on the adsorption of glutaric and glyoxylic acid from an aqueous stream. Regeneration was not studied in these experiments.

Material and Methods

Material. Glutaric acid, glyoxylic acid monohydrate, and Amberlite IRA-67 were obtained from Merck. Amberlite IRA-67 is a weakly basic gel-type polyacrylic resin with a tertiary amine functional group. It was used without further treatment. Glutaric acid and glyoxylic acid stock solutions were prepared to be 10.6 %. For determining the effect of the initial acid concentration approximately (2, 4.5, 15.6, and 20.6) % solutions were prepared for glutaric acid and (2, 5.3, 13.6, and 20) % solutions for glyoxylic acid.

Method. Adsorption experiments were carried out in batch type. The aim of these experiments was to determine the effect of important variables on the adsorption, such as amount of adsorbent, time, initial acid concentration, and temperature. The analysis method is a basic acid−base titration. The aqueous phase was titrated with a 0.1 N NaOH solution, using phenolphtalein as the indicator. The optimum amount of adsorbent was determined to be 0.5 g. For determining the optimum adsorbent dose, the adsorption experiment was applied to different amounts of adsorbent. The amount of adsorbed acid by unit adsorbent is expressed by Q_e. For both acids, the highest Q_e values were found for 0.5 g of adsorbent dose.

For each experimental run, 5 mL of stock acid solution and a known amount of adsorbent were taken in a 50 mL flask. This mixture was shaken at a constant speed and temperature [(25 ± 2) °C] in a thermostatted shaker. Every 15 min, a sample was taken out, and the aqueous phase was titrated with a 0.1 N NaOH solution, using phenolphtalein as the indicator. Amberlite IRA-67 particles are highly hydrophobic and settled down easily. So, the time to reach

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Table 1. Effect of Contact Time on the Adsorption

acid	initial acid conc. (mol·L^{-1})	initial acid conc. (% w/w)	amount of adsorbent	time (min)	equilibrium conc. C_e (g·L^{-1})	amount of adsorbed acid Q_e (g·mg^{-1})	percentage of removal acid (%)
glutaric acid	0.8	10.6	0.5	15	94.07	0.023	11.00
	0.8	10.6	0.5	30	91.43	0.028	13.50
	0.8	10.6	0.5	60	91.16	0.029	13.75
	0.8	10.6	0.5	75	89.84	0.031	15.00
	0.8	10.6	0.5	90	89.71	0.032	15.13
	0.8	10.6	0.5	120	89.71	0.032	15.13
glyoxylic acid	1.15	10.58	0.5	15	87.45	0.037	17.39
	1.15	10.58	0.5	30	86.53	0.039	18.26
	1.15	10.58	0.5	60	85.97	0.039	18.78
	1.15	10.58	0.5	75	85.24	0.041	19.48
	1.15	10.58	0.5	105	84.96	0.042	19.74
	1.15	10.58	0.5	120	84.23	0.043	20.44
	1.15	10.58	0.5	200	84.13	0.043	20.52

Table 2. Effect of Amount of Adsorbents on the Adsorption

acid	initial acid conc. (mol·L^{-1})	initial acid conc. (% w/w)	amount of adsorbent	equilibrium conc. C_e (g·L^{-1})	amount of adsorbed acid Q_e (g·mg^{-1})	percentage of removal acid (%)	temperature (K)
glutaric acid	0.8	10.6	0.25	89.84	0.063	15.00	298
	0.8	10.6	0.50	72.66	0.066	31.25	298
	0.8	10.6	0.75	60.77	0.059	42.50	298
	0.8	10.6	1.00	48.88	0.057	53.75	298
	0.8	10.6	1.25	38.32	0.054	63.75	298
	0.8	10.6	1.50	31.71	0.049	70.00	298
	0.8	10.6	1.75	22.46	0.048	78.75	298
	0.8	10.6	2.00	18.49	0.044	82.50	298
	0.8	10.6	2.25	11.89	0.042	88.75	298
	0.8	10.6	2.50	7.93	0.039	92.50	298
glyoxylic acid	1.15	10.58	0.25	89.28	0.066	15.65	298
	1.15	10.58	0.50	69.96	0.072	33.91	298
	1.15	10.58	0.75	60.75	0.061	42.61	298
	1.15	10.58	1.00	46.95	0.059	55.65	298
	1.15	10.58	1.25	38.66	0.054	63.48	298
	1.15	10.58	1.50	27.62	0.052	73.91	298
	1.15	10.58	1.75	17.49	0.051	83.48	298
	1.15	10.58	2.00	7.36	0.049	93.04	298
	1.15	10.58	2.25	4.14	0.045	96.08	298
	1.15	10.58	2.50	0.89	0.042	99.16	298

equilibrium was determined as 120 min for glutaric acid and 200 min for glyoxylic acid. For determining the temperature effect on adsorption, an optimum amount of adsorbent and 5 mL of acid stock solution mixture was shaken at (298, 308, and 318) K, then the aqueous phases were analyzed. Langmuir, Freundlich, and Temkin isotherms were calculated, dependent on the initial acid concentration. Pseudofirst-order, pseudosecond-order, and Weber–Morris intraparticular diffusion models were applied to the experimental results.

Results and Discussion

This study reports data on the time to reach equilibrium and effects of adsorbent loading, initial acid concentration, and temperature on equilibrium adsorption. Results of this experimental procedure were used for determining the reaction kinetics and equilibrium parameters.

Process Variables. Effect of Contact Time. The effects of contact time for the adsorption of glutaric acid and glyoxylic acid by Amberlite IRA-67 were studied for a period of 200 min. In this study, the initial glutaric acid concentration is 0.80 mol·L^{-1}, and the initial glyoxylic acid concentration is 1.15 mol·L^{-1} at 298 K. The optimum Amberlite IRA-67 dosage was 0.5 g. The results of the effect of contact time on removal of glutaric acid and glyoxylic acid are presented in Table 1. For both adsorbents, uptake of adsorbate species is fast in the initial stages of the contact period and, thereafter, becomes slower near the equilibrium. In between these two stages of the uptake, the rate of adsorption is found to be nearly constant. This is obvious from the fact that a large number of vacant surface sites are available for adsorption during the initial stage, and after a lapse of time, the remaining vacant surface sites are difficult to be occupied due to repulsive forces between the solute molecules on the solid and bulk phases.[7]

Effect of Amount of Adsorbent. The effect of adsorbent dose on the extent of solute adsorption was investigated by varying the dose from (0.25 to 2.50) g for IRA-67. In this experiment, the same initial acid concentrations were used. It is observed from Table 2 that, when the amount of adsorbent increases, the percentage removal of the acid increases. When the maximum dose of IRA-67 was used, the maximum adsorption capacity was obtained. These values are 92.50 % for glutaric acid and 99.16 % for glyoxylic acid.

Effect of Initial Acid Concentration. Different initial acid concentrations were studied; for glutaric acid (0.16 mol·L^{-1}, 0.34 mol·L^{-1}, 0.80 mol·L^{-1}, 1.18 mol·L^{-1}, and 1.56 mol·L^{-1}) and for glyoxylic acid (0.23 mol·L^{-1}, 0.58 mol·L^{-1}, 1.15 mol·L^{-1}, 1.48 mol·L^{-1}, and 2.19 mol·L^{-1}). It is observed that by increasing the initial acid concentration the adsorbed acid concentration decreased in efficiency (Table 3). The percentage of removed acid decreased from 86.35 % to 14.10 % for glutaric acid and from 98.77 % to 13.24 % for glyoxylic acid with the increased initial acid concentration. This may be explained by saturation of the accessible exchangeable sites of this adsorbent.

Effect of Temperature. Three different temperatures were studied for 10.6 % of acid solution and optimum (0.5 g) adsorbent dose. The temperatures chosen for this study were (298, 308, and 318) K. As shown in Table 4 and Figure 1,

Table 3. Effect of Initial Acid Concentration on the Adsorption

acid	initial acid conc. ($\text{mol}\cdot\text{L}^{-1}$)	initial acid conc. (% w/w)	amount of adsorbent	equilibrium conc. C_e ($\text{g}\cdot\text{L}^{-1}$)	amount of adsorbed acid Q_e ($\text{g}\cdot\text{mg}^{-1}$)	percentage of removal acid (%)	temperature (K)
glutaric acid	0.16	2.11	0.5	2.91	0.036	86.35	298
	0.34	4.53	0.5	23.78	0.042	47.06	298
	0.80	10.60	0.5	72.66	0.066	31.25	298
	1.18	15.62	0.5	120.23	0.071	22.88	298
	1.56	20.63	0.5	177.04	0.058	14.10	298
glyoxylic acid	0.23	2.10	0.5	0.26	0.042	98.77	298
	0.58	5.35	0.5	24.85	0.057	53.45	298
	1.15	10.58	0.5	69.96	0.072	33.91	298
	1.48	13.64	0.5	104.02	0.064	23.65	298
	2.19	20.16	0.5	174.90	0.053	13.24	298

Table 4. Effect of Temperature on the Adsorption

acid	initial acid conc. ($\text{mol}\cdot\text{L}^{-1}$)	initial acid conc. (% w/w)	amount of adsorbent	equilibrium conc. C_e ($\text{g}\cdot\text{L}^{-1}$)	amount of adsorbed acid Q_e ($\text{g}\cdot\text{mg}^{-1}$)	percentage of removal acid (%)	temperature (K)
glutaric acid	0.8	10.6	0.5	72.66	0.066	31.25	298
	0.8	10.6	0.5	75.10	0.061	30.00	308
	0.8	10.6	0.5	75.31	0.061	28.75	318
glyoxylic acid	1.15	10.58	0.5	69.96	0.072	33.91	298
	1.15	10.58	0.5	75.48	0.061	28.70	308
	1.15	10.58	0.5	77.32	0.057	26.96	318

the adsorption efficiency of the adsorbent decreased with increasing temperature. It is understood that the adsorbent shows an exothermic nature of adsorption, like most adsorption reactions.

Equilibrium. A dynamic phase equilibrium is established in adsorption for the distribution of the adsorbate between the fluid and the adsorbent surface. This equilibrium is generally expressed in terms of the concentration of the adsorbate in the fluid and the adsorbate loading on the adsorbent. The adsorption isotherms obtained from the experimental studies will provide an upper limit on the adsorption of adsorbate from a given fluid mixture on a specific adsorbent for a designated set of conditions.[8] Langmuir, Freundlich, and Temkin isotherms were applied to the experimental data in this study.

Langmuir Isotherm. The Langmuir equation[6,9,10]

$$q_A = \frac{K_A \cdot Q_0 \cdot C_e}{1 + K_A \cdot C_e} \tag{1}$$

Q_0 denotes the maximum adsorbent uptake; q_A denotes the experimental adsorbent uptake; and K_A is a coefficient that is related to the affinity between the adsorbent and adsorbate. The values of K_A and Q_0 are determined from the following equation from which eq 1 was transformed.

$$C_e = -\frac{1}{K_A} + C_e \cdot \frac{Q_0}{q_A} \tag{2}$$

$$K_L = \frac{1}{K_A} \tag{3}$$

The values of K_L and Q_0 are determined from the intercept and slope of the straight line in Figure 2. The Langmuir isotherm constants calculated from the experimental data are given in Table 5.

Freundlich Isotherm. The second isotherm used in this study was the Freundlich isotherm.[9,11]

$$Q_e = K_f \cdot C_e^{1/n} \tag{4}$$

A logarithmic plot linearizes the equation enabling the exponent n and the constant K_f to be determined

$$\log Q_e = \log K_f + (1/n) \log C_e \tag{5}$$

The values of K_f and $1/n$ at different concentrations were determined from the slope and intercept of the linear plots of log Q_e and log C_e. Figure 3 shows the plots of Freundlich equilibrium isotherms for glutaric acid and glyoxylic acid adsorption. The Freundlich isotherm constants are listed in Table 5.

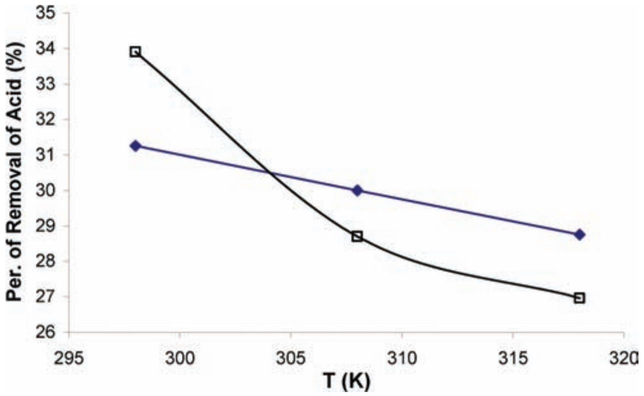

Figure 1. Plot of effect of temperature on the adsorption. □, glyoxylic acid; ♦, glutaric acid.

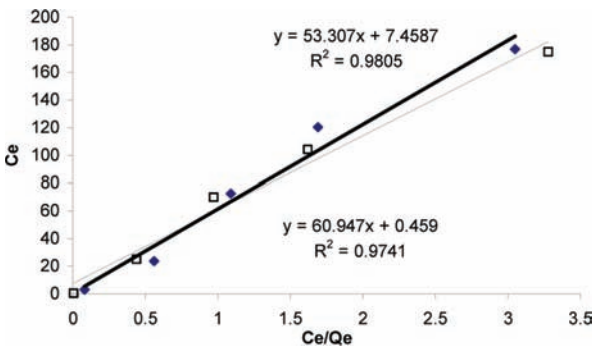

Figure 2. Plot of the Langmuir isotherm equation for the acid adsorption onto IRA-67. □, glyoxylic acid; ♦, glutaric acid.

Table 5. Isotherm Parameters for Adsorption of Glutaric and Glyoxylic Acid onto Amberlite IRA-67

Langmuir Isotherm

Glutaric Acid			Glyoxylic Acid		
Q_0	K_L	R^2	Q_0	K_L	R^2
60.947	0.459	0.9741	53.307	7.4587	0.9805

Freundlich Isotherm

Glutaric Acid					Glyoxylic Acid				
log K_f	1/n	K_f	n	R^2	log K_f	1/n	K_f	n	R^2
4.4783	0.153	30081.54	6.54	0.90	4.417	0.0822	26121.61	12.17	0.88

Temkin Isotherm

Glutaric Acid				Glyoxylic Acid			
B_1	ln K_T	K_T	R^2	B_1	ln K_T	K_T	R^2
9642.2	2.246	9.45	0.85	4277.6	11.05	62614	0.86

Temkin Isotherm. The Temkin isotherm contains a factor that explicitly takes into account the adsorptive–adsorbent interactions. This isotherm assumes that (1) the heat of adsorption of all the molecules in the layer decreases linearly with coverage due to adsorbent–adsorbate interactions and that (2) the adsorption is characterized by a uniform distribution of binding energies, up to some maximum binding energy.[7]

$$q_e = \frac{RT}{b} \ln(K_T C_e) \tag{6}$$

Equation 6 can be linearized as

$$q_e = B_1 \ln K_T + B_1 \ln C_e \tag{7}$$

In eq 7

$$B_1 = \frac{RT}{b} \tag{8}$$

A plot of q_e versus ln C_e enables the determination of the isotherm constants B_1 and K_T from the slope and the intercept.[7] Figure 4 shows the Temkin isotherm plots for both acids, and the isotherm parameters are shown in Table 5.

The experimental data of the two acids fit the Langmuir isotherm, satisfactorily, with R^2 values of 0.98 for glyoxylic acid and 0.97 for glutaric acid. For this reason, the Langmuir isotherm was found to best represent the data for glutaric and glyoxylic acid adsorption onto Amberlite IRA-67.

Distribution Coefficient. The adsorption distribution coefficient (K) ratio of the equilibrium concentration in adsorbent and aqueous phase has a unit of (Q_e (mg·g^{-1})/Ca_o (mg·mL^{-1})) or mL·g^{-1} adsorbent and is shown in Figure 5. If the distribution coefficient has a high value, the adsorption characteristics of the adsorbent are good.[12] Amberlite IRA-67 exhibited a K value of 1703 mL·g^{-1} for glutaric acid and 1984 mL·g^{-1} for glyoxylic acid. For both acids, K values decrease with increasing C_e values. If the K values of Amberlite IRA-67 are compared to many adsorbents which are used for industrial separation processes, many with distribution coefficient smaller than 10 mL·g^{-1}, then it can be seen that IRA-67 is an efficient adsorbent for carboxylic acid separation.

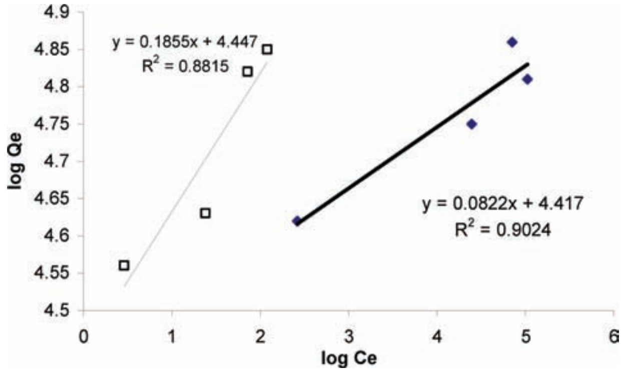

Figure 3. Plot of the Freundlich isotherm equation for the acid adsorption onto IRA-67. □, glyoxylic acid; ♦, glutaric acid.

Kinetics. To determine the kinetics of adsorption of glutaric and glyoxylic acid on IRA-67, pseudofirst-order, pseudosecond-order, and intraparticle diffusion models were applied.

Pseudofirst-Order Model.[7] The pseudofirst-order equation is

$$\frac{dq_t}{dt} = k_f(q_e - q_t) \tag{9}$$

Q_t is the amount of adsorbate, adsorbed at time t (mg·g^{-1}); q_e is the adsorption capacity at equilibrium; k_f is the pseudofirst-order rate coefficient (min^{-1}); and t is the contact time (min). The integration of eq 9 when $q_t = 0$ at $t = 0$

$$\log(q_e - q_t) = \log q_e - \frac{k_f}{2.303}t \tag{10}$$

The values of k_f and q_e can be found from a plot of log(q_e − q_t) versus t. The pseudofirst-order parameters are shown in Table 6, and the model plots for both acids are shown in Figure 6.

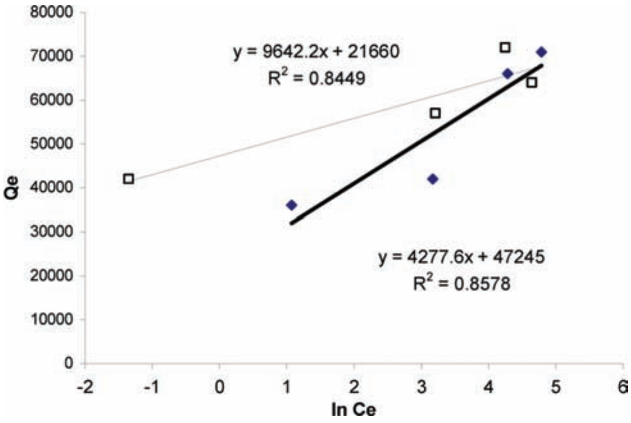

Figure 4. Plot of the Temkin isotherm equation for the acid adsorption onto IRA-67. □, glyoxylic acid; ♦, glutaric acid.

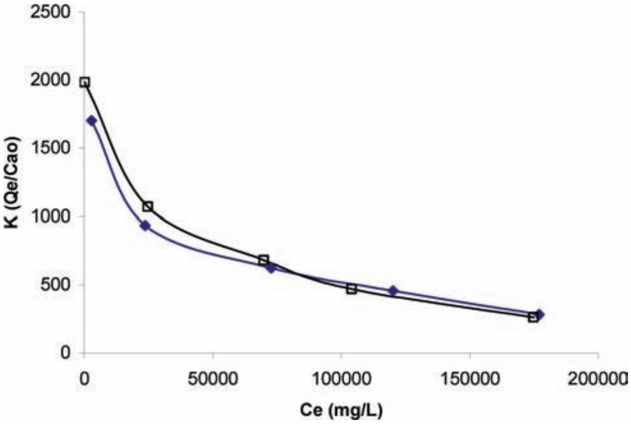

Figure 5. Distribution coefficient of acid adsorption onto IRA-67. □, glyoxylic acid; ♦, glutaric acid.

Table 6. Kinetic Parameters for the Removal of Carboxylic Acids by IRA-67

Pseudofirst-Order Model							
Glutaric Acid				Glyoxylic Acid			
$Q_{e,exp}$ ($g \cdot mg^{-1}$)	$Q_{e,calc}$ ($g \cdot mg^{-1}$)	$k_{f(min^{-1})}$	R^2	$Q_{e,exp}$ ($g \cdot mg^{-1}$)	$Q_{e,calc}$ ($g \cdot mg^{-1}$)	$k_{f(min^{-1})}$	R^2
0.032	0.013	0.031	0.89	0.043	$8.32 \cdot 10^{-3}$	0.018	0.89

Pseudosecond-Order Model							
Glutaric Acid				Glyoxylic Acid			
$Q_{e,calc}$ ($g \cdot mg^{-1}$)	Γ ($g \cdot mg^{-1} \cdot min^{-1}$)	k_s ($mg \cdot g^{-1} \cdot min^{-1}$)	R^2	$Q_{e,calc}$ ($g \cdot mg^{-1}$)	Γ ($g \cdot mg^{-1} \cdot min^{-1}$)	k_s ($mg \cdot g^{-1} \cdot min^{-1}$)	R^2
0.034	$4.55.10^{-3}$	3.94	0.9983	0.044	$9.75.10^{-3}$	5.04	0.9993

W−M Intraparticle Diffusion Model					
Glutaric Acid			Glyoxylic Acid		
k_{id} ($g \cdot mg^{-1} \cdot min^{-1/2}$)	I ($g \cdot mg^{-1}$)	R^2	k_{id} ($g \cdot mg^{-1} \cdot min^{-1/2}$)	Γ ($g \cdot mg^{-1}$)	R^2
0.0012	0.0197	0.88	0.0006	0.0351	0.88

Pseudosecond-Order Model.[7] The equation for the pseudosecond-order model is shown below.

$$\frac{dq_t}{dt} = k_s(q_e - q_t)^2 \tag{11}$$

In this equation, k_s is the pseudosecond-order rate coefficient ($mg \cdot g^{-1} \cdot min^{-1}$). If eq 11 is integrated, a linear equation is obtained. This equation is shown as follows

$$\frac{t}{qt} = \frac{1}{k_s q_e^2} + \frac{1}{q_e} t \tag{12}$$

The initial sorption rate, Γ ($g \cdot mg^{-1} \cdot min^{-1}$), at $t \rightarrow 0$ is defined as

$$\Gamma = k_s q_e^2 \tag{13}$$

The values of k_s and calculated q_e are obtained from the slope of the plot t/q_t versus t. Γ and k_s are obtained from the intercept. The pseudosecond-order model parameters are shown in Table 6, and plots of both acids can be seen in Figure 7.

Pseudofirst-order and pseudosecond-order models were compared with the correlation coefficients of both of the acids, calculated from linear regression. The correlation coefficients of the pseudosecond-order model are closer to unity than the pseudofirst-order model. The correlation coefficient for glutaric acid is 0.9983 and for glyoxylic acid is 0.9993. Therefore, the adsorption of glutaric acid and glyoxylic acid on Amberlite IRA-67 is fitted to a pseudosecond-order kinetic model.

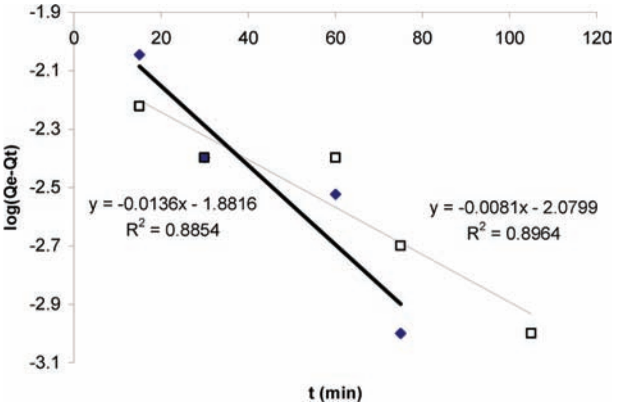

Figure 6. Pseudofirst-order plot for the removal of carboxylic acids by IRA-67. □, glyoxylic acid; ♦, glutaric acid.

Weber and Morris Intraparticle Diffusion Model.[7] Intraparticle diffusion can be estimated by using the Weber−Morris intraparticle diffusion model.

$$q_t = k_{id} t^{1/2} + \mathrm{I} \tag{14}$$

In eq 14, k_{id} is the intraparticle diffusion rate coefficient and I gives an idea about the thickness of the boundary layer. These values can be found by a plot of q_t versus $t^{1/2}$. The slope is k_{id}, and the intercept is I. As seen in Figure 8, the straight lines deviate from the origin. The difference between final mass transfer rate and initial mass transfer rate may cause the deviations of the straight lines. Also, this deviation can show

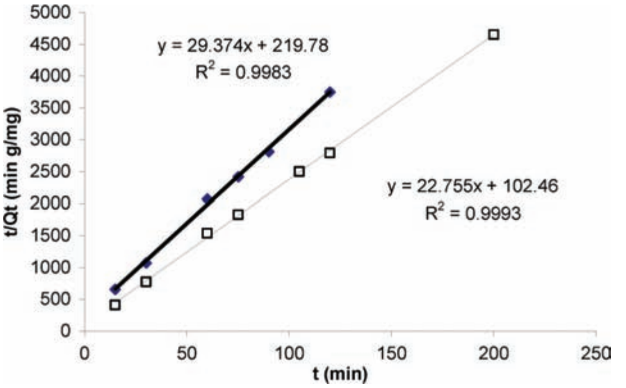

Figure 7. Pseudosecond-order plot for the removal of carboxylic acids by IRA-67. □, glyoxylic acid; ♦, ghlutaric acid.

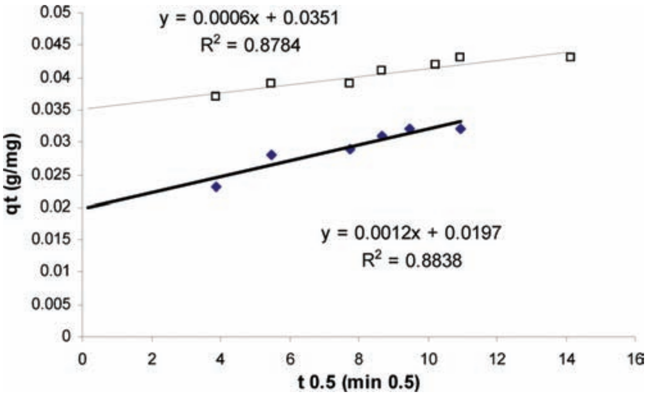

Figure 8. Weber and Morris intraparticle diffusion plot for the removal of carboxylic acids by IRA-67. □, glyoxylic acid; ♦, glutaric acid.

that the pore diffusion is not the sole rate-controlling step.[7] I and k_{id} values are shown in Table 6.

Conclusions

The following conclusions can be presented related to this work:

1. This study shows that Amberlite IRA-67 is a very effective ion-exchange resin for glutaric acid and glyoxylic acid. The parameters which affect the adsorption reaction were determined. An increase of amount of adsorbent affects adsorption positively, an increase of initial acid concentration affects adsorption negatively, and an increase of temperature affects adsorption negatively. It is understood that the adsorption reaction is an exothermic reaction.

2. Langmuir, Freundlich, and Temkin isotherms were applied to the experimental data, and equilibrium data for the adsorption of both acids were best represented by the Langmuir isotherm.

3. Adsorption kinetics were found to follow a second-order rate expression for glutaric acid and glyoxylic acid. Diffusion is not the only rate-controlling step.

Nomenclature

q_{e}	equilibrium solid phase concentration, $\mathrm{g}\cdot\mathrm{mg}^{-1}$
K_{A}	coefficient related to the affinity between the sorbent and sorbate
Q_0	maximum sorbate uptake under the given conditions
C_{e}	equilibrium liquid phase acid concentration, $\mathrm{g}\cdot\mathrm{L}^{-1}$
K_{L}	constant of Langmuir isotherm, $\mathrm{L}\cdot\mathrm{mg}^{-1}$
K_{F}	constant of Freundlich isotherm, $\mathrm{L}\cdot\mathrm{mg}^{-1}$
n	exponent in Freundlich isotherm model
K_{T}	constant of Temkin isotherm, $\mathrm{L}\cdot\mathrm{mg}^{-1}$
q_t	amount of adsorbate adsorbed by adsorbent at time t, $\mathrm{g}\cdot\mathrm{mg}^{-1}$
T	temperature, K
t	time, min.
k_{f}	rate coefficient of pseudofirst-order adsorption model, min^{-1}
k_{s}	rate coefficient of pseudosecond-order adsorption model, $\mathrm{mg}\cdot\mathrm{g}^{-1}\cdot\mathrm{min}^{-1}$
Γ	initial sorption rate, $\mathrm{g}\cdot\mathrm{mg}^{-1}\cdot\mathrm{min}^{-1}$
k_{id}	intraparticle diffusion rate coefficient, $\mathrm{g}\cdot\mathrm{mg}^{-1}\cdot\mathrm{min}^{-1/2}$
I	constant that gives idea about the thickness of boundary layer, $\mathrm{g}\cdot\mathrm{mg}^{-1}$
C_{Ao}	initial acid concentration, $\mathrm{g}\cdot\mathrm{L}^{-1}$

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