Removal of Reactive Blue 221 by Kaolinite from Aqueous Solutions

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The adsorption behavior of reactive blue 221 (RB221) on kaolinite was investigated by batch tests. The experiments were performed by employing a spectrophotometer to measure the concentration of RB221 before and after adsorption. The effects of various parameters such as initial solution pH, ionic strength, temperature, and acid activation were determined. The adsorption process reached equilibrium within 3 h. The adsorbed amount of RB221 increased with increasing ionic strength, temperature, and acid activation, but it decreased with increasing pH. Langmuir and Freundlich isotherms were applied to fit the equilibrium data to identify the best isotherm to describe the RB221 adsorption. The data were best described by the Langmuir isotherm. The isosteric heat of adsorption indicated the endothermic nature of RB221 adsorption on kaolinite. It was concluded that reactive blue 221 physically adsorbs on kaolinite. The value of the dimensionless separation factor (R_L) suggests that kaolinite can be used for the removal of reactive blue 221 from aqueous solutions. The experimental results were applied to a batch design. As a result, kaolinite could be used for the removal of dyes from aqueous solutions.

1. Introduction

Frequent changes of the dyestuff used in dyeing processes cause considerable variations in the wastewater characteristics, particularly color, pH, and chemical oxygen demand (COD).[1] Moreover, the presence of coloring material in water system also reduces the penetration of light, thereby affecting photosynthesis in aquatic planktons.[2] Untreated disposal of this colored water into a receiving water body causes damage not only to aquatic life, but also to human beings through mutagenic and/or carcinogenic effect. The contaminants in such water can cause severe damage to the reproductive system, liver, and brain and dysfunction of kidneys.[3,4] Removal of dyes from wastewater before it is discharged into the environment and from raw water before it is offered for public use is essential for the protection of health and the environment. Textile effluents are usually treated by physical, biological, and chemical processes such as flocculation, oxidation, coagulation, precipitation, adsorption, membrane filtration, electrochemical techniques, ozonation, and fungal decolorization.[5,6] Because of low biodegradability of dyes, a conventional biological treatment process is not very effective. Dye-laden wastewaters are usually treated by physical or chemical processes.[7] Color removal by activated carbon, H_2O_2, sodium hyperchlorite, and other chemical agents has been widely practiced in the textile industries.[4] All of these methods have different color removal capabilities, capital costs, and operating rates.

Among these treatments, adsorption has been shown to be an effective technique, with its efficiency, capacity, and applicability on a large scale to remove dyes, as well as its potential for regeneration, recovery, and recycling of adsorbents.[5,6] Adsorption has a specific advantage of removing the complete dye molecule, unlike certain removal techniques that destroy only the dye chromophore, leaving the harmful residual moieties (such as metals) in the effluent.[7] Activated carbon is the most widely used adsorbent with great success because of its high adsorption capacity and high surface area.[8] The potential efficiency of activated carbon cloth or fiber for the removal of many pollutants from wastewater by adsorption has been investigated by many workers.[5,9] However, the use of activated carbon is limited because of its high cost. This has led to a search for cheaper substitutes. Several wastes and residues have been investigated for the adsorption of dyes with varying success: Annadurai et al. investigated the removal of dyes using cellulose-based wastes from aqueous solutions.[10] Malik studied the use of activated carbons prepared from sawdust and rice husk for the adsorption of acid dyes.[11] Doğan et al. investigated the kinetics and mechanism of the removal of methylene blue by adsorption onto perlite.[12] Karaca et al. considered the applicability of various adsorption models to methylene blue adsorption at the lignite/water interface.[13] Mittal et al. studied the removal of the coloring agent phenol red from wastewater using waste materials as adsorbents.[14] Gupta et al. investigated the removal of vertigo blue 49 and orange DNA 13 from aqueous solutions using carbon slurry developed from a waste material,[15] as well as the electrochemical removal of the hazardous dye reactofix red 3 BFN from industrial effluents.[16] In addition, Gupta et al. studied the adsorption of safranin-T from wastewater using waste materials,[17] the interaction of some azo dyes with nontronite mineral,[18] and the adsorption treatment and recovery of a hazardous dye.[19] Moreover, Gupta et al. performed adsorption studies of quinonline yellow using waste materials,[20] as well as studies on the removal of lindane and malathion from wastewater using bagasse fly ash.[21] Likewise, Gupta et al. considered the removal and recovery of the hazardous azo dye acid orange 7 through adsorption over waste materials[22] and the removal of rhodamine B, fast green, and methylene blue from wastewater using red mud.[23] New economical, easily available and highly effective adsorbents are still needed.

Clays have been used as promising low-cost adsorbents. There are several types of clays such as smectites, mica (Illite), kaolinite, serpentine, pylophyllite, vermiculite, and sepiolite.[24–26] These materials are classified based on differences in their layered structures. Clay materials have high surface areas, layered structures, and high porosities. Also, they have a net negative charge, and hence, they have the capacity to adsorb

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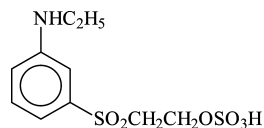[‡] Balikesir University.

NHC$_2$H$_5$

SO$_2$CH$_2$CH$_2$OSO$_3$H

Figure 1. Structure of RB221.

Table 1. Some Physicochemical Properties of Kaolinite

property	value
color	white
cation-exchange capacity (mequiv/100 g)	13.00
density (g/mL)	2.18
pH	7.90
specific surface area (m^2/g)	17
hardness	2−3

positively charged materials.[27,28] Kaolinite, a low-costly material, is the most abundant phyllosilicate mineral in highly weathered soils. Kaolinite is a 1:1 alumina silicate comprising a tetrahedral silica sheet bonded to an octahedral alumina sheet through the sharing of oxygen atoms between silicon and aluminum atoms in adjacent sheets. Kaolinite is found as a common constituent of soils and sediments. Successive 1:1 layers are held together by hydrogen bonding of adjacent silica and alumina layers.[29] Therefore, in this work, kaolinite, which is both low-cost and abundant in nature, was selected as an adsorbent for the investigation of the adsorption of reactive blue 221 (RB221) from aqueous solution. Reactive blue 221 was chosen as the adsorbate because it is widely used in the textile industry. This article reports the results of adsorption equilibrium studies of RB221 onto kaolinite. The effects of pH, ionic strength, temperature, and acid activation on adsorption equilibrium were evaluated. The isosteric heat of adsorption was also calculated and is discussed. The equilibrium data were fitted with the Langmuir and Freundlich equations to determine the correlation between the isotherm models and the experimental data.

2. Material and Methods

2.1. Materials. The kaolinite was obtained from Balikesir in the Marmara region of Turkey. Reactive blue 221 was obtained from Setaş and Eksoy Textile Co. (Bursa, Turkey). All other chemicals used in this study were of analytical grade and were used without further purification. The kaolinite sample was treated before use in the experiments as follows: A suspension containing kaolinite (10 g/L) was mechanically stirred for 24 h, and after being allowed to stand for about 2 min, the supernatant suspension was filtered through filter paper ($\Phi = 12.5$ cm) under a vacuum. The solid sample was dried at 110 °C for 24 h, ground, and then sieved with a 100-μm sieve. The particles under 100 μm were used in further experiments.[30] The chemical structure of RB221 is illustrated in Figure 1. The cation-exchange capacity (CEC) of kaolinite was determined as 13 mequiv/100 g by the ammonium acetate method, and its density was determined as 2.18 g/mL using the picnometer method.[31] Some physicochemical properties of kaolinite are listed in Table 1.[32]

2.2. Instruments. pH measurements were made using an Orion 920A pH meter. The concentration of dye was determined using a Perkin-Elmer Lamda 25 UV−visible spectrophotometer. The chemical composition of kaolinite determined by X-ray florescence (XRF) is 53.00% SiO$_2$, 26.71% Al$_2$O$_3$, 0.62% Na$_2$O, 0.37% Fe$_2$O$_3$, 0.57% CaO, 1.39% K$_2$O, 0.28% MgO, and 17.20% loss ignition.

2.3. Equilibrium Study. Adsorption studies were performed by the batch technique to obtain equilibrium data. The batch technique was selected because of its simplicity. Batch sorption studies were performed with different initial pH values, ionic strengths, temperatures, and acid activation treatments on kaolinite samples to obtain equilibrium isotherms and data required for the design of the treatment of dye-bearing wastewater. Dye solutions were prepared by dissolving dye in deionized water to the required concentrations. Adsorption experiments were carried out by adding a fixed amount of sorbent (0.5 g) into 100 mL polyethylene flasks and adjusting the pH to the desired value (pH range 3−9). Polyethylene flasks containing a definite volume (50 mL in each case) of different initial concentrations [(1−25) × 10^{-5} mol/L] of dye solution at a temperature of 30 °C were shaken for the desired time periods in a GFL model incubator orbital shaker at a constant speed of 180 rpm. The contact time and other conditions were selected on the basis of preliminary experiments, which demonstrated that the equilibrium was established in 3 h. Equilibration for longer times, that is, between 3 and 24 h, gave practically the same uptakes. Therefore, a contact period of 3 h was finally selected for all of the equilibrium tests. After agitation, the dye solutions were separated from the adsorbent by centrifugation for 15 min. The dye removal was determined spectrophotometerically using a UV−vis spectrophotometer by monitoring the absorbance changes at the wavelength of maximum absorbance (601 nm). The absorbance measured was then converted to a concentration. The amount of adsorption at equilibrium, q_e (mol/g), was calculated as

$$q_e = (C_0 - C_e)\frac{V}{W} \qquad (1)$$

where C_0 and C_e (mol/L) are the initial and equilibrium liquid-phase concentrations of dye, respectively; V is the volume of the solution (L); and W is the mass of dry sorbent used (g). Duplicate experiments were performed in parallel to check the results. The results showed that the error was below 5%.[33]

2.4. Parameters. 2.4.1. Effect of Initial pH. Because the solution pH has a considerable effect on dye removal, the pH of the solution was also changed to monitor the adsorption behavior of dyes on kaolinite samples. The effect of pH on dye removal was studied over the pH range of 3−9. The pH of the dye solution was adjusted by the addition of dilute (0.1 M) HCl or NaOH solutions using an Orion 920A pH meter with a combined pH electrode. The pH meter was standardized with NBS buffers before every measurement. Changes in absorption were then used to calculate the concentration and adsorption.

2.4.2. Effect of Ionic Strength. The effect of salt on adsorption equilibrium was studied at KCl concentrations of 1 × 10^{-3}, 1 × 10^{-2}, and 1 × 10^{-1} mol/L.

2.4.3. Effect of Temperature. The sorption studies were also carried out at different temperatures, namely, 30, 40, 50, and 60 °C, to determine the effect of temperature and to evaluate the heat of adsorption.

2.4.4. Effect of Acid Activation. The acid treatment was carried out using a glass reactor with a boiler−reflux condenser and a magnetic stirrer/hot plate. The kaolinite sample was slowly added to solutions with H$_2$SO$_4$ concentrations of 0.2, 0.4, and 0.6 N, which were then stirred and maintained at the solution temperature of 90 °C during the activation period of 2 h. Afterward, the sample solution was first cooled to room temperature, then filtered off using a centrifugal separator, and washed sequentially with deionized water three times to remove the ions and other residues. The resulting products were finally
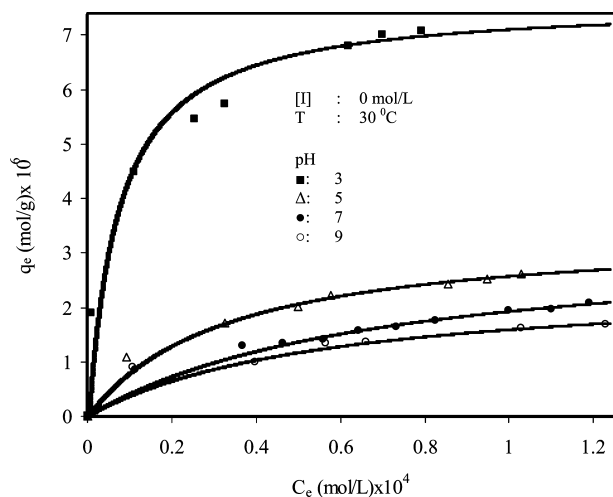
Figure 2. Effect of initial solution pH on the adsorption of RB221 onto kaolinite.

Figure 3. Effect of ionic strength on the adsorption of RB221 onto kaolinite.

dried at 110 °C for 24 h and stored in a desiccator.[31] The removal of RB221 on acid-activated kaolinite samples was investigated under constant experimental conditions.

3. Results and Discussion

3.1. Adsorption Equilibrium. The adsorption of RB221 dye on kaolinite from aqueous solutions was investigated as a function of pH, ionic strength, temperature, and acid activation.

3.1.1. Effect of pH. Solution pH is an important factor controlling the surface charge of the adsorbent and the degree of ionization of the materials in the solution.[34,35] The effect of pH on the adsorption of RB221 was studied in the range of 3−9, and the adsorption was found to decrease with increasing pH (Figure 2). The pH effect on dye adsorption can be explained in terms of electrostatic interactions between the kaolinite and the dye molecules. As the pH of the system decreases, the number of negatively charged sites decreases, and the number of positively charged sites increases. In our previous study, we investigated the ζ potential of kaolinite suspensions as a function of pH and found that kaolinite has an isoelectrical point at pH 2.35.[36] As the pH of the suspension decreases, the number of positively ionizable sites on kaolinite increases. In this case

$$SOH + H^+ = SOH_2^+ \tag{2}$$
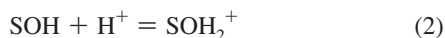
The surface of kaolinite was positively charged, and the dye was negatively charged, indicating an electrostatic attraction between the kaolinite and the dye molecules. Positively charged sites favor the adsorption of dye anions through electrostatic attraction.[37] As the pH of the dye solution decreased, the association of dye anions with more positively charged kaolinite surface could more easily take place

$$SOH_2^+ + dye^- = SOH_2^+dye^- \tag{3}$$

Furthermore, it can be said that some forces or interactions such as van der Waals and acid−base interactions also contribute the adsorption of reactive blue 221 onto kaolinite. The lower adsorption of RB221 at basic pH is due to the presence of excess OH⁻ ions competing with the dye anions for the adsorption sites. Similar results have been reported in the literature for the adsorption of RB221 on sepiolite.[38,39]

3.1.2. Effect of Ionic Strength. Extensive investigations carried out on the adsorption of dyes have revealed that the
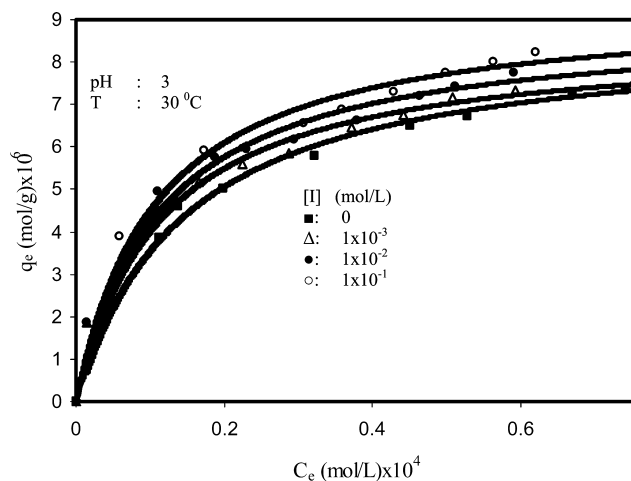
extent of dye uptake is strongly influenced by the concentration and nature of the electrolyte ionic species added to the dye bath.[40] In this study, we selected only KCl salt to determine the concentration effect of ionic type. The adsorption of RB221 on kaolinite was positively affected by the presence of KCl (Figure 3). Increasing KCl concentration enhanced the dye adsorption capacity of kaolinite. Reactive blue 221 can dissociate with increasing ionic strength according to eq 4. In this case, nitrogen atom in dye molecule has a positive charge. When the final pH is greater than the pH of the point of zero charge (pH_pzc = 2.35), physical interactions occur between negatively charged kaolinite and positively charged reactive blue 221. Therefore, dye adsorption onto kaolinite increases with increasing ionic strength. Janos et al.[41] and Al-Degs et al.[42] also found a positive effect or no effect of ionic strength on dye adsorption by activated carbon and coal fly ash, respectively.
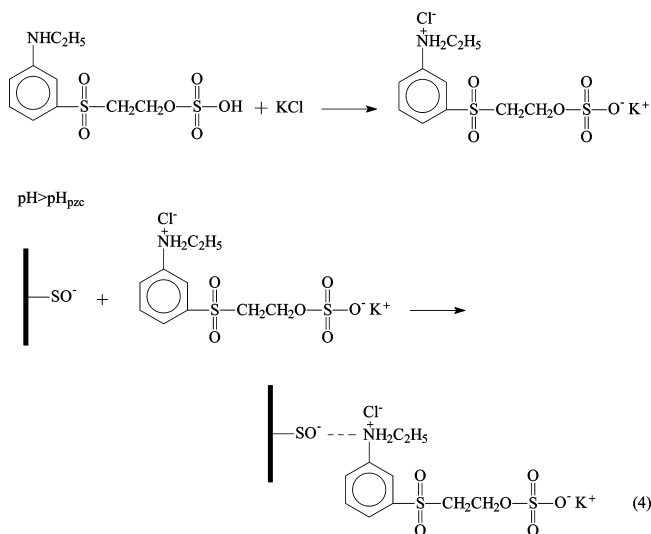
3.1.3. Effect of Temperature. The removal of RB221 was studied at 30, 40, 50, and 60 °C to determine the adsorption isotherms and thermodynamic parameters, which are presented in Figure 4. The extent of adsorption of RB221 was found to increase with temperature. The increase in the uptake of RB221 with temperature might be a result of an increase in the rate of diffusion of the adsorbate molecules across the external boundary layer because diffusion is an endothermic process. The increase in the adsorption behavior suggests that active surface
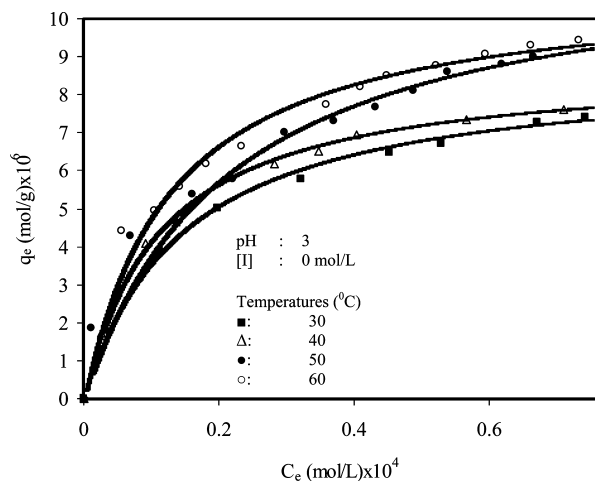
Figure 4. Effect of solution temperature on the adsorption of RB221 onto kaolinite.
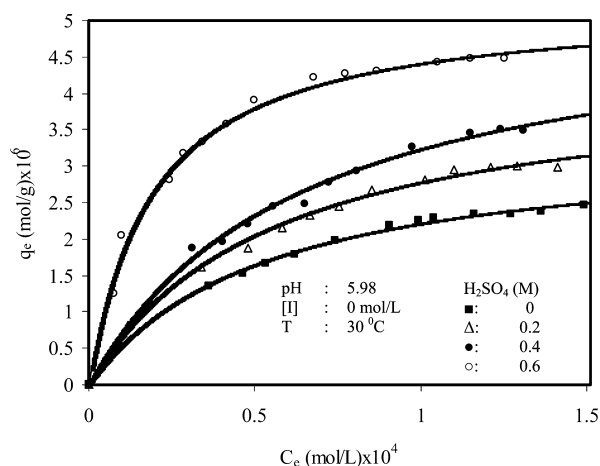

Figure 5. Effect of acid activation on the adsorption of RB221 onto kaolinite.

centers available for adsorption increase with temperature. This might also be a result of an increase in the mobility of the large dye ion with temperature. An increasing number of molecules might also acquire sufficient energy to undergo an interaction with active sites at the surface.[43,44] The increase with temperature of the adsorption capacity of kaolinite implies that the enthalpy change has a positive value, indicating that the adsorption process of RB221 on kaolinite is endothermic, which is opposite to the exothermic adsorption usually encountered.

3.1.4. Effect of Acid Activation. The effects of acid activation on the adsorption of RB221 on kaolinite are presented in Figure 5. The adsorbed amounts of RB221 increased with increasing concentration of H_2SO_4 used for the acid activation. This might be due to the partial destruction of the kaolinite structure, as was shown by Gonzalez-Pradas et al.[45] and Lopez-Gonzalez and Gonzalez-Garcia[46] for bentonite, and also the specific adsorption of H^+ ions on the kaolinite surface.[32]

3.2. Adsorption Isotherms. The equilibrium adsorption isotherm is of importance in the design of adsorption systems. The purpose of the adsorption isotherm is to relate the adsorbate concentration in the bulk to the amount adsorbed at the interface. The two commonly used isotherms developed by Langmuir and Freundlich were selected for this study. The Langmuir isotherm is based on the assumptions that the molecules of the adsorbate are adsorbed at well-defined, energetically equal sites without interacting with each other and that each site can hold only one

molecule. The Langmuir adsorption isotherm has been successfully used to explain the adsorption of basic dyes from aqueous solutions. The linear form of the Langmuir model is

$$\frac{C_e}{q_e} = \frac{1}{q_m K} + \frac{1}{q_m} C_e \tag{5}$$

where q_e is the amount of dye adsorbed per unit weight of adsorbent (mol/g), C_e is the equilibrium concentration of the dye in the bulk solution (mol/L), q_m is the monolayer adsorption capacity (mol/g), and K is a constant related to the free energy of adsorption (L/mol).[2,47−49]

The Freundlich isotherm is an empirical equation assuming that the adsorption process takes place on a heterogeneous surface and that the adsorption capacity is related to the concentration of RB221 at equilibrium. The linear form of the Freundlich equation is generally expressed as

$$\ln q_e = \ln K_F + \frac{1}{n} \ln C_e \tag{6}$$

where q_e is the amount of dye adsorbed per unit weight of adsorbent (mol/g), C_e is the equilibrium concentration of the dye in the bulk solution (mol/L), K_F is a constant indicative of the relative adsorption capacity of the adsorbent (mol/g), and $1/n$ is a constant indicative of the intensity of the adsorption. The magnitude of the exponent, $1/n$, gives an indication of the favorability of adsorption. Values of $n > 1$ represent favorable adsorption conditions. A plot of $\ln q_e$ versus $\ln C_e$ enables the constant K_F and the exponent $1/n$ to be determined from the intercept and slope of the line, respectively.[47−49]

The adsorption isotherm data of RB221 onto kaolinite were modeled using Langmuir and Freundlich equations (figures not shown). Table 2 reports the q_m and K values for the Langmuir isotherm, along with the regression coefficients (R^2) obtained from the linear regression equation between the values of C_e/q_e and C_e and $\ln q_e$ and $\ln C_e$, respectively, for the adsorption of RB221 dye onto kaolinite from aqueous solutions at different pH values, ionic strengths, temperatures, and acid activation treatments. The correlation coefficient R^2 for the Langmuir isotherm is comparatively higher than the R^2 value for the Freundlich isotherm. The Langmuir equation represents the adsorption process very well; the R^2 values were all higher than 0.99, indicating a very good mathematical fit. The fact that the Langmuir isotherm fits the experimental data very well might be due to a homogeneous distribution of active sites on kaolinite surface, because the Langmuir equation assumes that the surface is homogeneous.[43]

The shape of the isotherm can also be considered with a view toward predicting whether an adsorption system is "favorable" or "unfavorable". The essential characteristics of the Langmuir isotherm can be expressed by a dimensionless constant called the equilibrium parameter, R_L,[43] which is defined as

$$R_L = \frac{1}{1 + KC_e} \tag{7}$$

The value of R_L indicates the type of the isotherm as unfavorable ($R_L > 1$), linear ($R_L = 1$), favorable ($0 < R_L < 1$), or irreversible ($R_L = 0$). The fact that the R_L values reported in Table 2 are in the range of 0.108−0.9 shows that the adsorption of RB221 on kaolinite is favorable ($0 < R_L < 1$).

A comparison of the q_m value obtained from this study and those of other adsorbents is presented in Table 3. The q_m value obtained from this study was relatively low, when compared to those of materials used in other studies, such as activated carbon,

Table 2. Isotherm Constants for RB221 Adsorption on Kaolinite

	parameters				Langmuir isotherm				Freundlich isotherm
temp (°C)	H_2SO_4 (M)	pH	[I] (mol/L)	q_m (mol/g) $\times 10^5$	K (L/mol) $\times 10^{-5}$	R^2	R_L		R^2
30		3	0	0.87	0.68	0.996	0.5−0.163		0.981
40		3	0	0.88	0.90	0.999	0.8−0.135		0.953
50		3	0	1.18	0.46	0.993	0.9−0.242		0.991
60		3	0	1.09	0.78	0.994	0.9−0.148		0.989
30		3	0.001	0.86	0.88	0.997	0.8−0.160		0.998
30		3	0.010	0.89	0.90	0.996	0.8−0.158		0.978
30		3	0.100	0.94	0.93	0.993	0.6−0.147		0.965
30		5	0	0.34	0.30	0.996	0.7−0.241		0.996
30		7	0	0.32	0.14	0.990	0.8−0.370		0.982
30		9	0	0.24	0.17	0.994	0.8−0.317		0.867
30		5.98	0	0.34	0.19	0.994	0.5−0.262		0.970
30	0.2	5.98	0	0.43	0.18	0.990	0.8−0.280		0.980
30	0.4	5.98	0	0.53	0.16	0.991	0.8−0.325		0.961
30	0.6	5.98	0	0.52	0.53	0.997	0.7−0.132		0.903

Table 3. Comparsion with Other Adsorbents

adsorbent	dye	$q_m \times 10^4$ (mol/g)	ref
unexpanded perlite	methylene blue	1.804−7.118	31
expanded perlite	methylene blue	0.465−0.821	31
bentonite	methylene blue	1.12−2.27	45
zeolite	methylene blue	1.42	50
activated carbon	methylene blue	10	51
sepiolite	methylene blue	1.63−2.73	52
sepiolite	methyl violet	0.18−0.26	52
kaolinite	maxilon yellow 4GL	0.19−0.85	53
kaolinite	maxilon red GRL	0.10−0.26	53
kaolinite	reactive blue 221	0.03−0.12	this study

bentonite, sepiolite, and zeolite for different dyes. Despite the relatively low adsorption capacity of the studied kaolinite, the use of this adsorbent for dye removal is of interest because kaolinite is low in cost and readily available.

3.3. Adsorption Heat. The isosteric heat of adsorption, ΔH^0, can be estimated from adsorption data obtained at various temperatures as a function of coverage fraction ($\theta = q_e/q_m$) using the van't Hoff equation[43]

$$-\frac{\Delta H^0}{R_g} = \left[\frac{\partial (\ln C_e)}{\partial (1/T)} \right]_{\theta=0.5} \quad (8)$$

where R_g is the gas constant and C_e is the equilibrium concentration of dye in moles per liter at the absolute temperature T. Figure 6 shows a plot of $-\ln C_e$ versus $1/T$. The value of ΔH^0 was calculated at a specific coverage fraction of 0.5 as 6.8 kJ/mol. The positive value confirms the endothermic nature of the adsorption. The ΔH^0 value shows that the interactions

between kaolinite and RB221 are physical interactions. Because adsorption is an endothermic process, it would be expected that an increase in solution temperature would result in an increase in adsorption capacity. A similar result was found for the adsorption of methyl violet on perlite.[54]
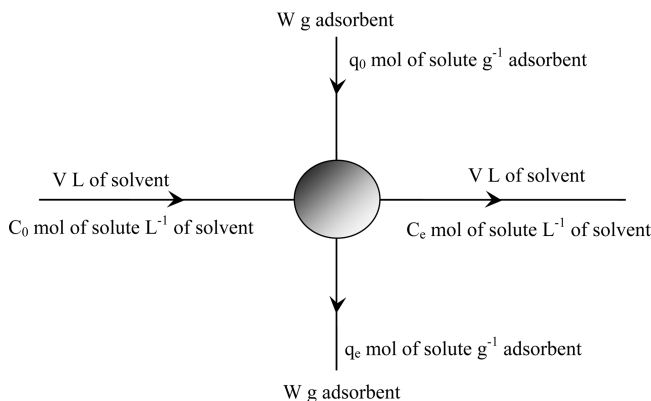
3.4. Single-Stage Batch Adsorption. Adsorption isotherms can be used to predict the design of single-stage batch adsorption systems.[43] A single-stage batch adsorption is design to predict the adsorber size and efficiency in the removal of pollutants from wastewaters by an adsorbent. The design objective is to reduce the amount of pollutants in a solution of volume V (L) from an initial concentration of C_0 to C_e. A schematic diagram for a single-stage adsorption process is shown in Figure 7. The solution to be treated contains V liters of water, and the dye concentration is reduced from C_0 to C_e in the adsorption process. In the treatment stage, W grams of adsorbent are added, and the dye concentration on kaolinite changes from $q_0 = 0$ to q_e. The mass balance that equates the dye removed from the liquid effluent to the that accumulated by kaolinite is

$$V(C_0 - C_e) = W(q_e - q_0) = Wq_e \quad (9)$$

In the case of the adsorption of RB221 on kaolinite, the Langmuir isotherm provides the best fit to the experimental data. The Langmuir data can now be applied to eq 9. Substituting for q_e from eq 5 and rearranging gives

$$\frac{W}{V} = \frac{C_0 - C_e}{q_e} \equiv \frac{C_0 - C_e}{\left(\frac{q_m K C_e}{1 + K C_e} \right)} \quad (10)$$

Equation 10 permits an analytical calculation of the adsorbent solution ratio for a given change in solution concentration, from

Figure 6. Plot of $-\ln C_e$ versus $1/T$.
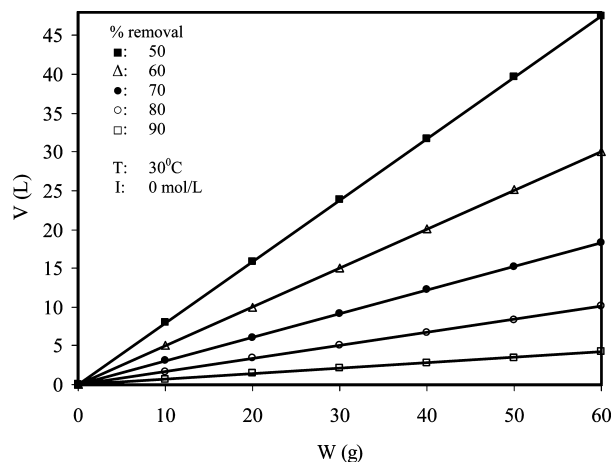

Figure 7. Single-stage batch adsorber.

Figure 8. Volume of effluent (*V*) treated as a function of adsorbent mass (*W*) for different percentage removals of RB221.

C_0 to C_e. Figure 8 shows a series of plots derived from eq 10 for the adsorption of RB221 on kaolinite. An initial RB221 concentration of 1×10^{-5} mol/L was assumed, and the figure shows the amount of effluent that can be treated to reduce the RB221 content by 90%, 80%, 70%, 60%, and 50% using various masses of kaolinite. These results suggest that kaolinite is an effective and efficient adsorbent for use in treatment plants for the adsorption of anionic dyes from aqueous solutions.

4. Conclusions

The results of this work, which examined the equilibrium adsorption of RB221 onto kaolinite under different conditions, can be summarized as follows:

(1) The adsorbed amount of RB221 increases with increasing ionic strength, temperature, and acid activation, but it decreases with increasing pH.

(2) The experimental data showed a perfect fit with the Langmuire isotherm, which confirms that the surface of kaolinite is homogeneous.

(3) The enthalpy change for the adsorption process is indicative of the endothermic nature of adsorption and a physical adsorption.

(4) The dimensionless separation factor (R_L) shows that kaolinite can be used for removal of dyes from aqueous solutions.

Nomenclature

C_0 = initial dye concentration in aqueous solution, mol/L
C_e = equilibrium dye concentration in solution, mol/L
K = adsorption constant, L/mol
K_F = Freundlich constant
n = Freundlich isotherm exponent
q_e = equilibrium dye concentration on the adsorbent, mol/g
q_m = monolayer capacity of the adsorbent, mol/g
R^2 = regression coefficient
R_g = gas constant, J/(K mol)
R_L = dimensionless separation factor
T = temperature, K
V = volume of aqueous solution to be treated, L
W = mass of adsorbent, g
ΔH^0 = heat of adsorption, kJ/mol

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