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# Study the Feasibility of Alumina for the Adsorption of Metal Ions from Water

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## Abstract

The present work describes the adsorption of $Ba^{2+}$ and $Mg^{2+}$ions from aqueous solutions by activated alumina in single and binary system using batch adsorption. The effect of different parameters such as amount of alumina, concentration of metal ions, pH of solution, contact time and agitation speed on the adsorption process was studied. The optimum adsorbent dosage was found to be 0.5 g and 1.5 g for removal of $Ba^{2+}$ and $Mg^{2+}$, respectively. The optimum pH, contact time and agitation speed, were found to be pH 6, 2h and 300 rpm, respectively, for removal of both metal ions. The equilibrium data were analyzed by Langmuir and Freundlich isotherm models and the data fitted well to both isotherm modes as indicated by higher correlation of determination $R^2$> 0.87 in both single and binary systems. Pore diffusion model for batch adsorption was used to predict the concentration decay curve for adsorption of $Ba^{2+}$ and $Mg^{2+}$ onto activated alumina. There was a good agreement between the experimental data and the predicted decay curves using pore diffusion model.

**Keywords:** Adsorption, magnesium, barium, diffusion model

## Introduction

The presence of heavy metals in the environment is of major concern because of their toxicity, bio-accumulating tendency and threat to human life and the environment [1, 2]. These metal ions are presented in wastewater from industrial activities such as mining, metal processing, pharmaceuticals, pesticides, organic chemicals, rubber and plastics, etc [3, 4].

The removal of metals in wastewater has been an important issue for many years due to environmental harm [5]. Many methods are used for the removal of heavy metal ions from wastewater including: precipitation, electrolytic process, ultra-filtration, reverse osmoses, ion exchange, solvent extraction, adsorption and biological system [6, 7, 8].

Adsorption is an important, highly effective, cheap and easy method among the physicochemical treatment process [9, 10]. A number of materials have been used to remove heavy metals from wastewater such as activated carbon, charcoal, lignite, titanium dioxide, calcium carbon, alumina and clay [11]. Alumina can be used as an alternative for activated carbon [12]. Alumina is a fine weight material similar in appearance to common salt and it is highly porous and exhibits tremendous surface area, resulting in superior adsorbent capabilities. It is more preferable than activated carbon especially for removing inorganic compounds [13, 14].

Barium and magnesium can end up in water and soil due to a number of activities. These activities include the discharge and disposal of drilling wastes, copper smelting, motor vehicle parts, plastic and accessories manufacturing. The presence of these metals in drinking water may cause stomach irritation, muscle weakness, increased blood pressure, or cardiovascular disease. They can be removed by several ways like: reverse somosis, filtration, adding softeners and coagulation.

The aim of the present work is to examine environment friendly material like alumina as an adsorbent for removal of Magnesium and Barium ions from aqueous solution, the effect of different experimental parameters such as adsorbent dosage, concentration of the adsorbate, contact time and pH of the solution under study single and binary systems were investigated, as well as to study the isotherms model and pore model ions to predict the concentration decay curve for the adsorption of Ba and Mg onto activated alumina.

## Adsorption Isotherm

Adsorption isotherm is defined as the ratio between the amount of material adsorbed per unit weight of adsorbent ($q_e$) and the material concentration in the solution ($C_e$) at equilibrium constant temperature [15]. Adsorption isotherm models are used to describe the adsorption isotherm data. Several models have been published in the literature to describe experimental data of adsorption isotherm. The Langmuir and Frundlich models are the most frequently employed models.

### Langmuir Isotherm

Langmuir isotherm was derived in 1916 by Irving Langmuir [16, 17]. It is one of the most known models which are frequently employed for the determination of adsorption parameter [18]. The Langmuir equation is represented by:

$$q_e = \frac{abC_e}{1+bC_e} \qquad \ldots(1)$$

And the equation may be linearized as:

$$\frac{C_e}{q_e} = \frac{1}{a}C_e + \frac{1}{ab} \qquad \ldots(2)$$

### Freundlich Isotherm

The Freundlich isotherm is the earliest known relation presented by Herbert Freundlich in 1906 [19]. The Freundlich equation is represented by:

$$q_e = K_f C_e^{1/n} \qquad \ldots(3)$$

The linear form of the equation obtained by taking the logarithm as follows

$$\log q_e = \log K_f + \frac{1}{n}\log C_e \qquad \ldots(4)$$

## Materials and Experimental Work

### 1. Materials

#### 1.1. Adsorbent

The adsorbent used was aluminum oxide 90 standardized for column chromatography adsorption analysis, supplied by MERCK chemical company; the properties of the alumina are listed in Table 1:

Table 1: Properties of alumina

| Product name | ,Aluminum oxide 90 standardized |
|---|---|
| Formula | $Al_2O_3$ |
| Particle size range | 60-200 µm (70% in this range) |
| Specific surface area | Approx. 120-160 $m^2/g$ |
| Specific pore volume | Approx. 0.7-0.3 ml/g |
| Mean pore size | 6 – 15 nm |
| pH (10% aq. Suspension) | 8.5 – 10.5 |
| Bulk density | Approx. 83.6 g/100 ml |

**Ref. MERCK Chemical Company**

### 1.2. Adsorbate

Metal ions used in the present work were barium nitrate $Ba(NO_3)_2$ and magnesium nitrate $Mg(NO_3)_2$. 1000 mg/l standard stock solutions of $Ba^{2+}$ and $Mg^{2+}$ were prepared by dissolving 1.902 g and 10.540 g, respectively, in one liter of distilled water.

## 2. Experimental Work

Experiments of single and binary system were carried out in batch model. In general, the adsorption experiments were achieved by agitation of 20 ml of metal ion solution (single or binary system solution) of a given mass of adsorbent. The agitation speed was 300 rpm for 30 min. the contact time was 24 h at 20 ˚C. After that the alumina was separated from the liquid phase by filtration through membrane filter 0.45 µm. The filtrate was analyzed to find the remaining metal ion concentration by Atomic Absorption Spectrometer (AAS). The pH of the initial solution was adjusted using diluted solution of either 0.1 M HCl or NaOH. The following parameters were studied.

### 2.1. Adsorbent Dose

The effect of adsorbent weight on the adsorption was studied by agitating 20 ml of 50 mg/l of metal ion ($Ba^{2+}$, $Mg^{2+}$ or mixture of them) with different adsorbent weight (0.1 – 2 g) at equilibrium time. These experiments were conducted for single and binary system.

### 2.2. pH of the Solution

The effect of pH was studied by adjusting the pH of metal ion solutions ($Ba^{2+}$ and $Mg^{2+}$) from 3 to 10 by using dilute 0.1 M of HCl and NaOH solutions. The experiments were conducted for the single system.

### 2.3. The Concentration of Metal Ion and Adsorption Isotherm

The effect of metal ion concentration was studied for both single and binary systems. This was carried out by agitating 20 ml of metal ion concentration (50-200 ppm) with 0.5 g alumina for $Ba^{2+}$ and 1.5 g alumina for $Mg^{2+}$. The amounts of metal ion adsorbed by alumina were calculated experimentally using the following equation:

$$q_e = \frac{V}{W}(C_o - C_e) \qquad \ldots(5)$$

The percentage of adsorption of metal ion was calculated using the following equation:

$$\%\,\mathrm{Re}\,moval = \left(\frac{C_o - C_e}{C_o}\right) * 100 \qquad \ldots(6)$$

## Result and Discussion

## 1. Single System

### 1.1. Effect of Adsorbent Dosage

The effect of alumina dosage for adsorption of $Ba^{2+}$ and $Mg^{2+}$ was examined. Alumina dosage was varied from 0.1 g to 2 g. This experiment was carried out using fixed volume of metal ion solution of 20 ml and constant metal ion concentration of 50 mg/l, pH of 6, contact time 24 h, 300 rpm agitation speed and at room temperature of 25 ˚C. The results are presented in Fig. 1 for both metal ions.

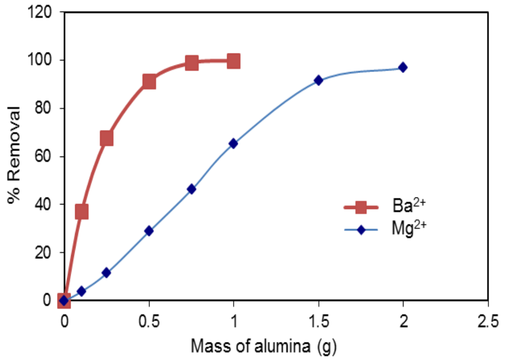


Fig. 1: The effect of alumina dose on the adsorption of $Ba^{2+}$ and $Mg^{2+}$ in single system, T=20 ˚C, pH= 6, $C_O$= 50 mg/l, V= 20 ml solution

Fig. 1 indicates that metal ion removal increases with increasing weight of alumina. Increasing weight of alumina leads to an increase in the number of active sites available for adsorption [20]. Also, this figure shows the difference between the adsorption of alumina for both $Ba^{2+}$ and $Mg^{2+}$ used. Fig. 1 shows the removal of $Ba^{2+}$ and $Mg^{2+}$ attained maximum removal at adsorbent dosage of 1 g and 2 g, respectively, with 100% removal. Hence 0.5 g and 1.5 g was chosen as the optimum adsorbent dosage for removal of $Ba^{2+}$ and $Mg^{2+}$, respectively.

## 1.2. Effect of pH

The pH of aqueous solution is an important controlling parameter in the adsorption process [21]. The influence of pH on the adsorption of$Ba^{2+}$ and $Mg^{2+}$ onto alumina at 30 $^{o}$C and metal ion concentration of 50 mg/l was studied and it is shown in Figs. 2 and 3, respectively. The pH range used was (3-10). These figures show that the percentage removal of $Ba^{2+}$ and $Mg^{2+}$increased with increasing pH of the solution. Similar behavior has been reported by [22]. The most effective pH was found to be 6 for both metal ions.

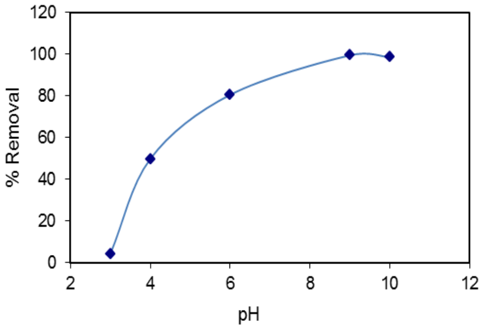


Fig. 2: The effect of pH on the adsorption of $Ba^{2+}$ in single system, T= 20 ˚C, $C_o$= 50 mg/l, W= 0.5 g alumina, V= 20 ml solution

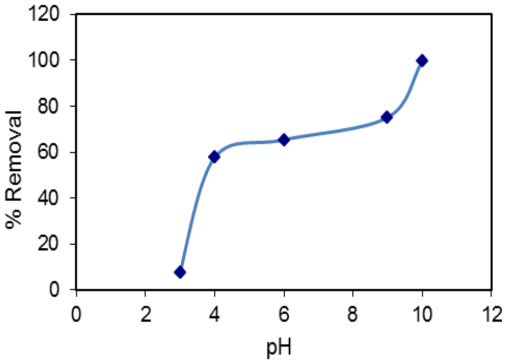


Fig. 3: The effect of pH on the adsorption of $Mg^{2+}$ in single system, T= 20 ˚C, , $C_o$= 50 mg/l, W= 0.5 g alumina, V= 20 ml solution

At low pH values, there is high concentration of $H^+$ in the solution; a competition exists between the positively charged hydrogen ions and metal ions for available adsorption sites. The high percentage removal at high pH values is due to the metal precipitation as hydroxides and therefore the removal takes place by adsorption as well asprecipitation. This can be explained by the fact that as pH of solution increases, the $OH^-$ ions in the solution increase and form some complexes with metal ions and precipitate as metal hydroxide [23, 24]. The optimum conditions for both metal ions were found to be at pH 6.

## 1.3. Effect of Initial Metal Ion Concentration

The effect of initial concentration of $Ba^{2+}$ and $Mg^{2+}$ on adsorption was studied and is shown in Figs. 4 and 5, respectively.

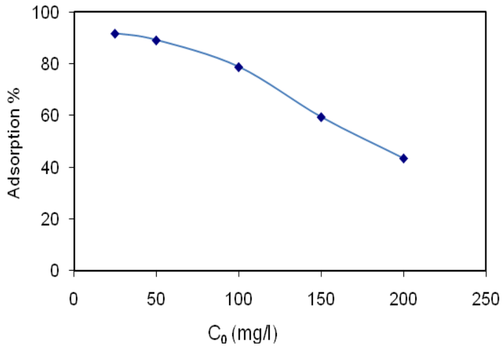


Fig. 4: The effect of initial concentration of $Ba^{2+}$ on the adsorption of $Ba^{2+}$ in single system, onto alumina T=20 °C, pH= 6, M= 0.5 g alumina, V= 20 ml solution

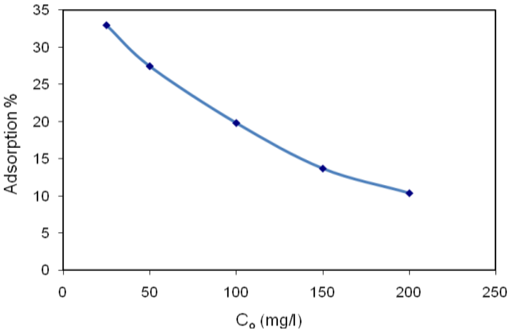


Fig. 5: The effect of initial concentration of $Mg^{2+}$ on the adsorption of $Mg^{2+}$ in single system, onto alumina T=20 °C, pH= 6, M= 1.5 g alumina, V= 20 ml solution

It is clear from these figures that the percentage removal of $Ba^{2+}$ and $Mg^{2+}$ decreased as the initial concentration of the metal ions increased from 25-200 mg/l; this was due to the saturation of the active adsorption sites of the adsorbent with the initial metal ions concentration. In other words, the lower concentration of metal ion solution was fully adsorbed at the active sites present in the alumina and then as the concentration increased the number of active site decreased and later no free sites were available to adsorb.

### 1.4. Equilibrium Isotherm Studies

Equilibrium isotherm studies were performed to obtain equilibrium isotherm curves. The adsorption isotherm curves were obtained by plotting the amount of solute ($Ba^{2+}$ and $Mg^{2+}$) adsorbed per unit weight adsorbent ($q_e$) against the equilibrium concentration of the solute ($C_e$) in the solution. The values of qe for each metal ion were calculated using Equation 5.

Figs. 6 and 7 show the experimental and theoretical adsorption isotherm curve for $Ba^{2+}$ and $Mg^{2+}$ at 20 °C. The theoretical data for both metal ions were obtained by using Langmuir and Freundlich models.

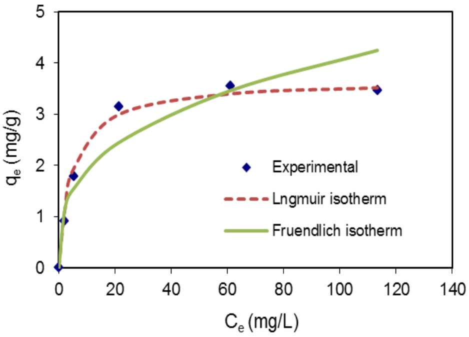


Fig. 6: Adsorption isotherm for adsorption of $Ba^{2+}$ onto alumina in single system, T=20 °C, pH= 6, M= 0.5 g alumina, V= 20 ml solution

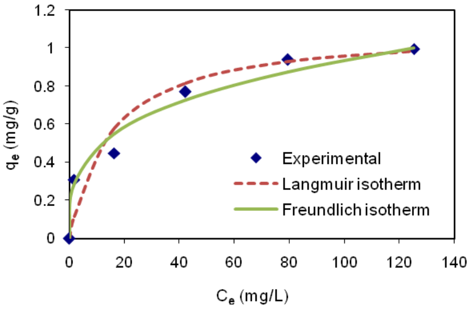


Fig. 7: Adsorption isotherm for adsorption of $M^{2+}$ onto alumina in single system, T=20 °C, pH= 6, M= 1.5 g alumina, V= 20 ml solution

Figs. 6 and 7 show that the experimental data fitted the Langmuir model better than Freundlich model with $Ba^{2+}$ and $Mg^{2+}$. The corresponding Langmuir and Freundlich parameters along with the correlation coefficients are given in Table 2.

As shown in Table 2, the correlation coefficient $R^2$ for Langmuir model for both metal ions is slightly greater than that for Freundlich model. This indicates that the experimental data gives best fitting with the Langmuir model than the Freundlich model for both metal ions.

The values of Langmuir parameter (a) are the monolayer adsorption capacity and (b) are constant related to the free energy of adsorption and that of Freundlich parameter ($K_f$) are constant indicative ofthe relative adsorption capacity of the adsorbent and (b) and(1/n) are constant indicative of the intensity of adsorption. As given in Table 2, these parameters vary in the following order:

$Ba^{2+} > Mg^{2+}$ for a and $K_f$
$Ba^{2+} > Mg^{2+}$ for b and 1/n

The values of the models parameters indicate that the capacity of alumina for these metals followed the order $Ba^{2+} > Mg^{2+}$.

Table 2: Model isotherm parameters for single metal ion adsorption system

| Metal ion | Langmuir Model | | | Freundlich Model | | |
|---|---|---|---|---|---|---|
| | a | b | $R^2$ | $K_f$ | 1/n | $R^2$ |
| $Ba^{2+}$ | 3.665 | 0.210 | 0.998 | 0.889 | 0.331 | 0.877 |
| $Mg^{2+}$ | 1.098 | 0.069 | 0.981 | 0.244 | 0.292 | 0.946 |

## 2. Binary System

### 2.1. Effect of Adsorbent Dose

The effect of alumina dose on the adsorption of both $Mg^{2+}$ and $Ba^{2+}$ in binary system is shown in Fig. 8.

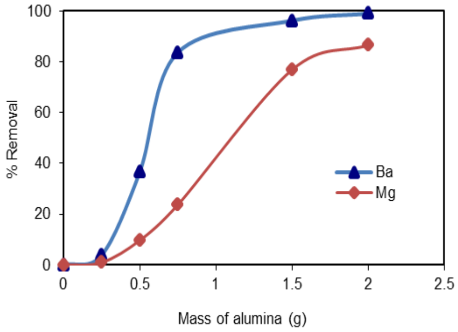


Fig. 8: The effects of alumina dose on the adsorption of both $Mg^{2+}$ and $Ba^{2+}$in binary system. Initial concentration of both ions $C_o$= 50mg/l, pH=6, V= 20ml solution

A similar behavior was obtained for the effect of alumina dose on the percentage removal for the single and binary system; i.e. the percentage removal of both metal ion increases gradually with the amount of absorbent up to a certain value. Also, the percentage removal of $Ba^{2+}$ is greater than that for $Mg^{2+}$ at the same amount of alumina. This indicates that alumina is more efficient for adsorption of $Ba^{2+}$ than $Mg^{2+}$.

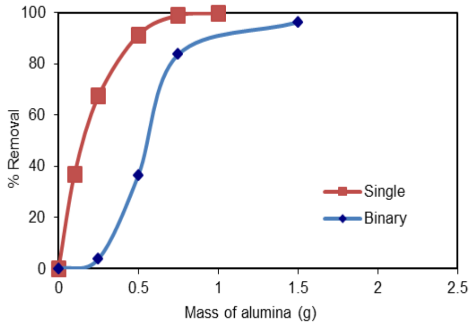


Fig. 9: The effect of alumina dose on the adsorption of $Ba^{2+}$ in single and binary system. Initial concentration of $Ba^{2+}$and $Mg^{2+}$ in single and binary system i $C_o$= 50 mg/l, pH= 6, V= 20 ml solution

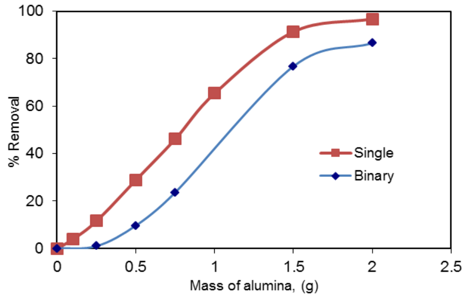


Fig. 10: The effect of alumina dose on the adsorption of both $Mg^{3+}$ in single and binary system. Initial concentration of both ions $C_o$= 50 mg/l, pH= 6, V= 20 ml solution

A comparison between the percentage removal for both $Ba^{2+}$ and $Mg^{2+}$ in single and binary system is shown in Figs. 9 and 10. It can be observed from these figures that the percentage removal in single phase is higher than that in multi-phase; this behavior may be attributed to the competition between these two components to sorption; hence, the chance for getting for both of them will be lowered in multi component system.

## 2.2. Effect of Initial Metal Ion Concentration

The effect of initial concentration of $Ba^{2+}$ and $Mg^{2+}$in binary system was studied and the results are shown in Figs. 11a, 11b, 12a and 12b.

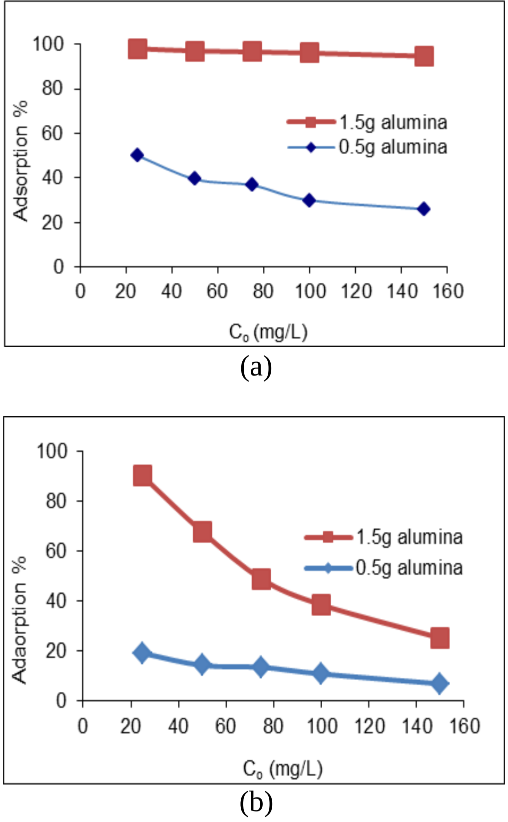


Fig. 11: The effect of initial ion concentration of (a) $Ba^{2+}$ and (b) $Mg^{2+}$ and dose of alumina on the percentage removal of $Ba^{2+}$ and Mg(II) in binary system

These Figures show that the percentage removal of $Ba^{2+}$ and $Mg^{2+}$ decreases with increasing the initial concentration and increases with the increasing of mass of adsorbent. This is similar to the results obtained by single component system. These figures also show that the percentage removal of $Ba^{2+}$ is greater than that for $Mg^{2+}$. This is because in the case of binary system when the $Ba^{2+}$ and $Mg^{2+}$ ions exist in the same solution, competition occurs between them for the active adsorption sites on the adsorbent surface and one of them will occupy the larger number of active sites. In this work, $Ba^{2+}$ will occupy the greater amount of active sites than $Mg^{2+}$ and therefore the percentages removal of $Ba^{2+}$ are greater than $Mg^{2+}$. As explained in the single system, the alumina is more efficient for the removal of $Ba^{2+}$ than $Mg^{2+}$. Figs. 13 and 14 illustrate the comparison between the adsorption rate of metal ions in single and binary system.

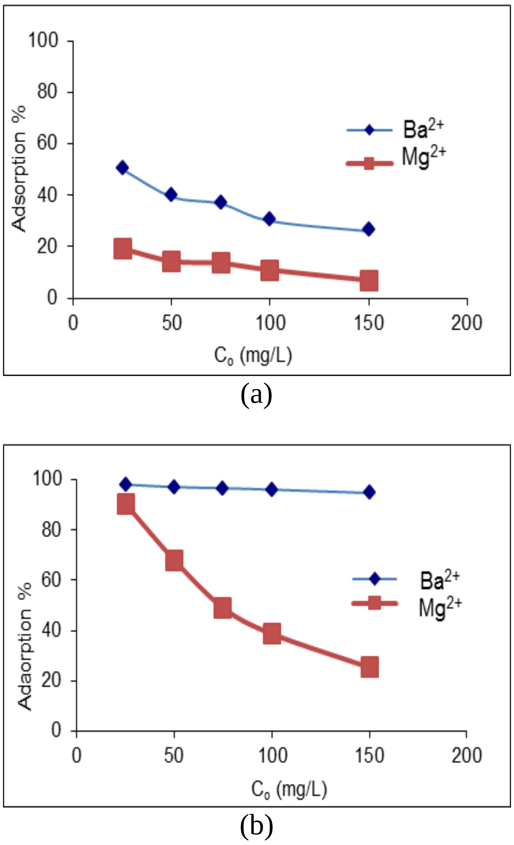


Fig. 12: The effect of initial ion concentration of $Ba^{2+}$ and $Mg^{2+}$ on the percentage removal of Ba(II) and Mg(II) in binary system using (a) 0.5 g alumina and (b) 1.5 g alumina

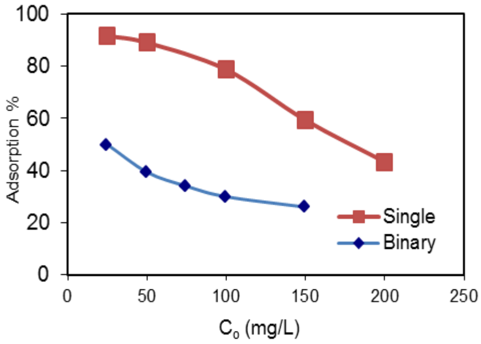


Fig. 13: The effect of initial ion concentration of $Ba^{2+}$on the percentage removal of $Ba^{2+}$ in single and binary system

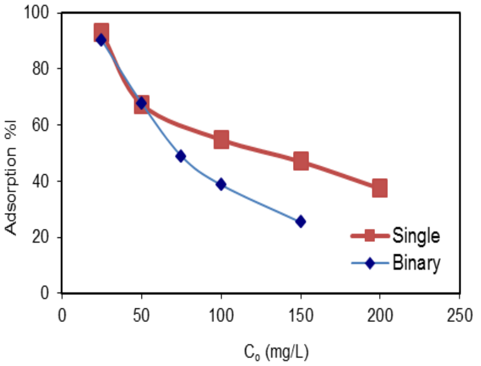


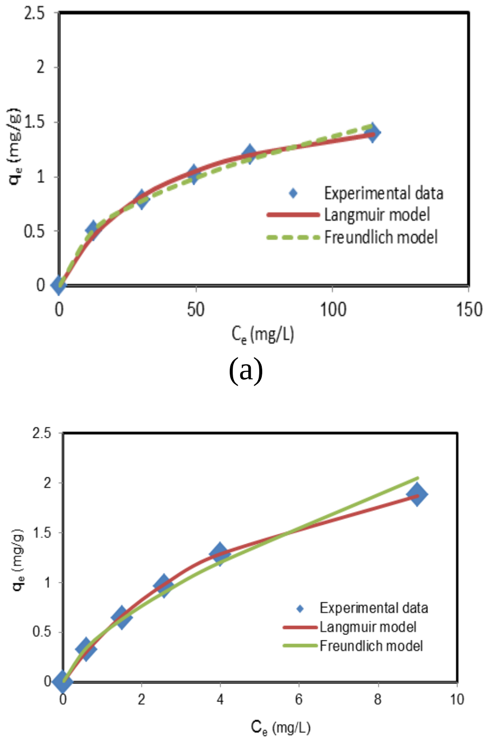
Fig. 14: The effect of initial ion concentration of $Mg^{2+}$ on the percentage removal of $Mg^{2+}$ in single and binary system

It can be seen from these figures that the adsorption rate in single component system is greater than that in binary system due to the competition effect in the binary system on the adsorption process as explained above.

### 2.3. Equilibrium Isotherm Studies

The Langmuir and Freundlich isotherm models were used to describe the adsorption equilibrium data for $Ba^{2+}$ and $Mg^{2+}$ onto alumina for binary system as shown in Figs. 15 and 16 for $Ba^{2+}$ and $Mg^{2+}$, respectively.

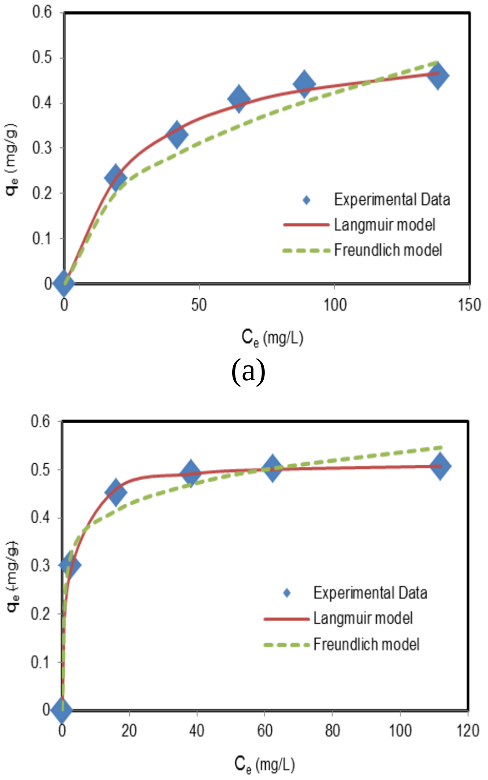
It is clear from these figures that the experimental isotherm data for $Ba^{2+}$ gives good fitting with both Langmuir and Freundlich isotherm models and the experimental isotherm data for $Mg^{2+}$ gives better fitting with the Langmuir model than that with the Freundlich model.



(a)

(b)

Fig. 15: The adsorption isotherm of $Ba^{2+}$ in binary system of $Ba^{2}$using (a) 0.5g alumina, (b) 1.5g alumina



(a)

(b)

Fig. 16: The adsorption isotherm of $Mg^{2+}$ in binary system of $Mg^{2+}$ using (a) 0.5g alumina, (b) 1.5g alumina

Table 3 shows the adsorption isotherm parameters. It can be seen from Table 2 that the value of adsorption capacity a and $K_f$ for Langmuir model and Freundlich model respectively and the correlation coefficient $R^2$ varies in the following order:

$Ba^{2+} > Mg^{2+}$ for a, $K_f$ and $R^2$

Table 3: Model isotherm parameters for binary metal ion adsorption system

| Mass alumina g | Metal ion | Langmuir Model | | | Freundlich Model | | |
|---|---|---|---|---|---|---|---|
| | | a | b | $R^2$ | $K_f$ | 1/n | $R^2$ |
| 0.5 | $Ba^{2+}$ | 1.840 | 0.027 | 0.995 | 0.155 | 0.475 | 0.992 |
| | $Mg^{2+}$ | 0.553 | 0.039 | 0.997 | 0.054 | 0.446 | 0.873 |
| 1.5 | $Ba^{2+}$ | 2.932 | 0.196 | 0.997 | 0.485 | 0.656 | 0.989 |
| | $Mg^{2+}$ | 0.516 | 0.516 | 0.999 | 0.281 | 0.141 | 0.907 |

Figs. 17 and 18 show the adsorption isotherm for $Ba^{2+}$ and $Mg^{2+}$ in single and binary system. It can be seen from these figures that the adsorption capacity of alumina for adsorption of both metals in single system is greater than that in binary system. This is due to the competition among the metals for activation sites in case of binary system which lowered the adsorption capacity for both metals. It can be noticed from the values of a and $K_f$ which take the following order:

Single>Binary for a and $K_f$

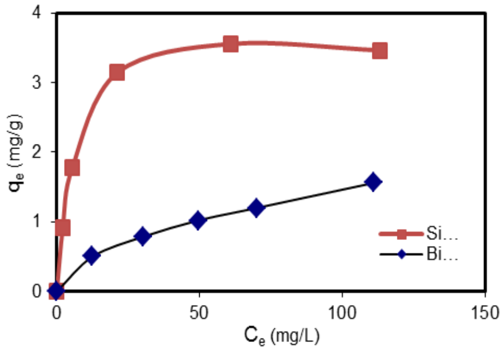


Fig. 17: The adsorption isotherm of $Ba^{2+}$ in single and binary system, M= 0.5 g alumina

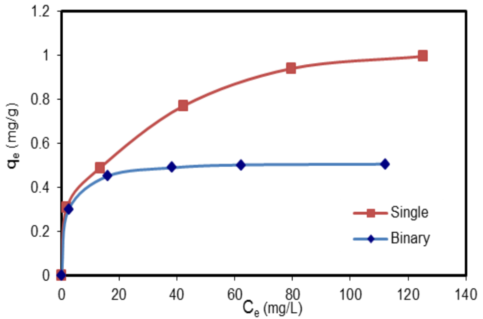


Fig. 18: The adsorption isotherm of $Mg^{2+}$ in single and binary system

## Mathematical Model for Batch Adsorption

Pore diffusion model was used in the present work to describe the adsorption of metal ion in batch system through predicting the concentration decay curve. The mathematical model using pore diffusion model [25] is:

- External mass transfer can be obtained by mass balance in the bulk fluid outside the particle:

$$-V\frac{dC_b}{dt}=\frac{3Wk_f}{\rho_p R_p}(c_b-c_{p,r=Rp}) \qquad \ldots(7)$$

- Interpartical diffusion can be obtained from the mass balance of metal ion inside the porous adsorbent particle:

$$\rho_p\frac{\partial q}{dt}+\varepsilon_p\frac{\partial c_p}{\partial t}=\varepsilon_p D_p\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\frac{\partial^2 c_p}{\partial r}\right] \qquad \ldots(8)$$

The initial and boundary conditions are:

I.C.:

$$c_b=c_o\,,\ c_p=0\,,\ q=0\,,\ t=0 \qquad \ldots(9)$$

BC: $$\frac{\partial c_p}{\partial t}\bigg|_{r=0}=0\,,\ \frac{\partial q}{\partial r}\bigg|_{r=0}=0\quad r=0\,, \qquad \ldots(10)$$

$$\varepsilon_p D_p\frac{\partial C_p}{\partial r}\bigg|_{r=R_p}=k_f(C_b-C_{p,r=Rp})\quad r=R_p \qquad \ldots(11)$$

Where $C_b$ and $C_p$ are the solute concentration in the bulk liquid and particle phase, respectively.

Local equilibrium was assumed between the solute in the pore and the solute adsorbed in the pore surface. This local equilibrium was represented by the Langmuir:

$$q = \frac{q_e b C_p}{1 + b C_p} \qquad \ldots(12)$$

The external mass transfer coefficient can be correlated in term of dimensionless correlation. The following correlation was developed based on the experimental data [26]:

$$Sh = 0.046 \mathrm{Re}_m^{0.283} Ga^{0.173} U^{-0.011} \left( \frac{T^{/}}{d_p} \right)^{0,019} Sc^{0.461} \qquad \ldots(13)$$

Equation (11) is valid for: 104 < Rem < 3×104; 1.1×105 < Ga < 106; 300 <sc<2000 and 27 < U < 2900, where U is a group characterizing the solid concentration. This correlation has a deviation between experimental and calculated value of 2.5%.

The external mass transfer coefficient can be obtained by the analytical solution for Equation 6 and where at t = 0, $C_{P,r=Rp} = 0$ and $C_b = Co$ , hence:

$$k_f = \frac{R_p \rho_p V}{3Wt} \ln\left( \frac{C_t}{C_o} \right) \qquad \ldots(14)$$

The set of partial differential Equations 7-12 were first solved by reduction to a set of ordinary differential equation, ODE, using the Finite element, FE, and Orthogonal collocation, OC, methods, respectively. The resulting ODE system was solved using an existing ODE solver provided by MATLAB v-7. The mathematical model was developed to obtain the theoretical concentration decay curve. The experimental concentration decay curves for each metal ion ($Ba^{+2}$ and $Mg^{+2}$) were obtained by plotting Ce/Co versus time, at different agitation speeds.

Figs. 19 and 20 show the experimental concentration decay curve at different agitation rates and that is predicted by the mathematical model for $Ba^{2+}$ and $Mg^{2+}$, respectively, at different agitation rates. The mathematical model used was the pore diffusion model. These figures show a good fitting between the experimental and predicted results. The results for adsorption for both metals slightly change with agitation speed.

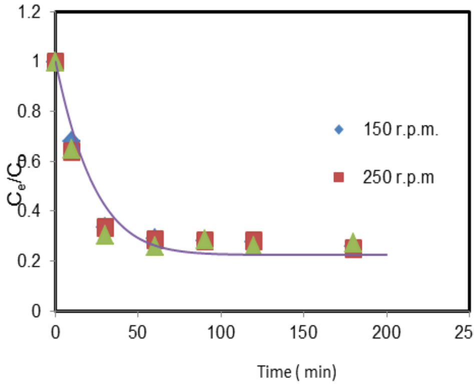


Fig. 19: The experimental concentration decay curve and that predicted by pore diffusion model for adsorption $Ba^{2+}$ in single component system at different agitation speed

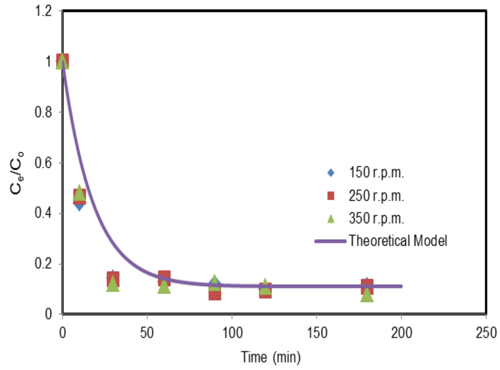


Fig. 20: The experimental concentration decay curve and that predicted by pore diffusion model for adsorption $Mg^{2+}$ in single component system at different agitation speed

### 1. The External Mass Transfer Coefficient $k_f$ and the Pore Diffusion Coefficient Dp

The principal parameters required for using the program were the external mass transfer coefficient $k_f$ and the pore diffusion coefficient Dp. By minimizing the differences between the theoretical and experimental decay curves for the batch adsorption, it was possible to obtain the individual Dp and $k_f$ for each metal ion using the Langmuir isotherm equation [27] as presented in the Table 4.

There was a good agreement between the batch experimental data and the predicted decay curves using pore diffusion model for batch operation and the pore diffusion coefficient for each metal ion were found to be:

Table 4: Model isothermal parameters for binary material ions adsorption system

| Metal ion | $D_p$, m2/s | $k_f$ .m/s |
|---|---|---|
| $Ba^{2+}$ | $8.0 \times 10^{-9}$ | $3.600 \times 10^{-5}$ |
| $Mg^{2+}$ | $4.5 \times 10^{-9}$ | $0.573 \times 10^{-6}$ |

## Conclusions

1- The metal ion removal of $Ba^{2+}$ and $Mg^{2+}$ increased with increasing the alumina dosage for single and binary system. The optimum dosage of alumina was found to be 0.5 g and 1.5 g for removal of $Ba^{2+}$ and $Mg^{2+}$, respectively.

2- The percentage removal of $Ba^{2+}$ and $Mg^{2+}$ decreased as the initial concentration of metal ion increased for single and binary system.

3- In single system, the percentage removal of $Ba^{2+}$ and $Mg^{2+}$ increased with increasing the alkalinity of the solution. The optimum pH was found to be pH 6.

4- The experimental adsorption data fitted well with both Langmuir and Freundlich isotherm model in single system.

5- In binary system, the percentage removal of $Ba^{2+}$ was greater than that of $Mg^{2+}$ at the same weight of alumina and initial concentration of metal ion.

6- The percentage removal of metal ion in singular system is greater than that in binary system.

7- In binary system, the experimental data of $Ba^{2+}$ was fitted by both Langmuir and Freundlich isothermal model while $Mg^{2+}$ results showed better fitting with Langmuir model.

8- The experimental data were modeled using pore diffusion mathematical model with good agreement.

## Nomenclature

| | | |
|---|---|---|
| a | External surface area per unit volume of the particle | $m^2/m^3$ |
| b | Langmuir constant related to energy of adsorption | l/mg |
| C | Fluid phase concentration | mg/l |
| $C_b$ | The solute concentration in the bulk fluid. | Mg/l |
| $C_e$ | Equilibrium liquid phase concentration | mg/l |
| $C_o$ | Initial liquid phase concentration | mg/l |
| $C_p$ | The solute concentration in the particle phase | mg/l |
| $D_p$ | Pore diffusion coefficient | $m^2/s$ |
| $D_m$ | Molecular diffusivity | $m^2$ |
| $d_p$ | Particle diameter | m |
| g | Gravitational force (9.8) | $m/s^2$ |
| $K_f$ | Concentration in Freundlich relating to adsorption capacity | $(mg/g)(l/mg)^{1/n}$ |
| $k_f$ | External film mass transfer coefficient | m/s |

| | | |
|---|---|---|
| n | Freundlich constant relating to adsorption intensity | - |
| $q_e$ | Equilibrium solid phase adsorbate concentration | mg/g |
| r | Radial coordinate | m |
| S | Surface area | $m^2$ |
| R | Correlation coefficient | - |
| $R_p$ | Radius of particle | m |
| t | time | s |
| T | Temperature | K |
| V | Volume of solution | $m^3$ |
| v | Superficial velocity | m/s |
| W | mass of adsorbent | g |

*Creek symbols*

| | | |
|---|---|---|
| $\varepsilon_p$ | Porosity of adsorbent particle | - |
| $\mu_c$ | Kinematics viscosity | $m^2/s$ |
| $\mu_w$ | Water viscosity | $m^2/s$ |
| $\rho$ | Density | $Kg/m^3$ |
| $\rho_w$ | Density of water | $Kg/m^3$ |

*Dimensionless group*

| | | |
|---|---|---|
| Sh | Sherwood number | $\frac{k_f d_p}{D_m}$ |
| Re | Reynolds number | $\frac{\rho_w v d_p}{\mu_w}$ |
| $Re_m$ | Reynolds number | $\frac{P d_p^4}{\mu_c^3}$ |
| Sc | Schmidt number | $\frac{\mu_w}{\rho_w D_m}$ |
| Ga | Galileo number | $\frac{g d_p^3}{\mu_c^2}$ |
| U | Solid concentration group | $\frac{W}{\rho S d_p}$ |

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