

Waste Water Treatment by Liquid-Solid Adsorption Using Calcined Sand-Clay Mixture Adsorbent

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Abstract

Effluent from incompetent wastewater treatment plants (WWTPs) contains a great variety of pollutants so support water treatments are essential. The present work studies the removal of phosphate species from aqueous solutions by adsorption on to spherical Calcined Sand -Clay mixture (CSCM) used a natural, local and low-cost adsorbent. Batch experiments were performed to estimate removal efficiency of phosphate. The adsorption experiments were carried out as function of pH, dose of adsorbent, initial concentration, temperature and time of adsorption. The efficient removal was accomplished for pH between 10 and 12. The experimental results also showed that the removal of phosphate by (CSCM) was rapid (the % removal 98.9%, 92%, 90%, 89% in 60 min) when the initial phosphate concentrations were at 5, 10, 15, 20 mg/l, respectively at optimum PH 10-12 and optimum dose was 5 gm/200ml. The adsorption process is time dependent. Thermodynamic studies showed that phosphate adsorption was exothermic. The effect of temperature range of 15-30 °C has been investigated. The results indicated that the temperature significantly affected phosphate adsorption on (CSCM) adsorbent. Langmuir and Freundlich isotherms models indicated that both isotherms were proper to describe the adsorption characteristics of (CSCM), with Langmuir being more fit. Adsorption capacity of phosphate had equal to 0.835 mg phosphorous/g adsorbent. The study reveal that calcined sand-clay mixture is an excellent low cost material for phosphate removal in wastewater treatment process .

Key words: Adsorption, Wastewater, Phosphate, Calcined sand-clay mixture.

Introduction

Environmental problem has a serious consequences on public health due to inefficient treatment of domestic, municipal and industrial wastewater. Nutrient discharged in the surface water and ground water bear a great deal of responsibility on water bloom and eutrophication that adversely affects on surface water [1]. The

concentrations of phosphorus between 3 and 15 mg/L mostly brought together from domestic and industrial wastewaters [2]. According to the requirement of American state environmental agencies and the U.S. Environmental Protection Agency (EPA) the total phosphorus effluent concentrations from dischargers must

be as far as 0.05 mg/L to deal with water quality problems [3]. Biological, chemical, or combined biological and chemical processes are common methods for phosphorus removal performance. A specific group of polyphosphate-accumulating microorganisms play a great deal of consuming excessive phosphorus as intracellular storage through biological treatment, and then phosphorus is removed from the liquid by sludge wasting. Chemical phosphorus technique is established to precipitate phosphate as form of sparingly soluble metal phosphate complexes by adding salts of multivalent metal ions (e.g. FeCl_3 , $\text{Fe}_2(\text{SO}_4)_3$, $\text{Al}_2(\text{SO}_4)_3$, or $\text{Ca}(\text{OH})_2$). Biological and chemical processes are similar in target to take out only soluble orthophosphates or transform those forms in the influent into ortho-P during the treatment process then in to solids phase by subsequent solid and liquid separations. Once P effluent level observed within permitted limits indicate both the effectiveness of chemical and/or biological P treatment processes in achieving goals as well as efficient final solid and liquid separation [4]. Adsorption has been tested as an alternative to conventional method for phosphate removal in wastewater treatment for a long time. For several reasons, inorganic adsorbents are offered to use as promising alternative [5]. Adsorption process was chosen especially for some advantages such as less production of sludge and easy operation, but it has not been applied widely since the suspended solids contained in the feed water accumulate in and clog the adsorbent bed and most adsorbents cannot be reused [6]. Various adsorbents were improved for phosphate removal such as alum sludge [7], red mud [8], fly ash [9], calcite [10], dolomite mineral [11],

Clay soil [12], Bentonite Clay [13]. The purposes of this study were to determine the following: (1) the feasibility of using calcined sand-clay mixture (CSCM) to adsorb phosphate; and (2) the optimal conditions of using calcined sand-clay mixture for phosphorus removal.

Material and Method

Adsorbate

Synthetic Phosphate stock solutions were prepared in the laboratory by dissolving an amount of anhydrous potassium dihydrogen phosphate KH_2PO_4 (0.2195 g) in 1 liter distilled water. Further dilution was conducted on the stock solution to get the desired concentrations of the experimental solutions using distilled water. To determine Phosphate concentration the Vanadomolybdo phosphoric Acid Colometric Method was followed with a UV-Vis spectrophotometer and measured at 470 nm according to [14].

Adsorption Media (Adsorbent Preparation)

Sand and clay materials have been brought from the sea of Najaf region and mixed at different volume percent ages to form spherical particles about 10 mm in diameter by hand. After that they have been dried and then calcined at 800 C to prevent their dissolution in the water.

Chemical Properties

The chemical analysis of the adsorption media was achieved using (XRF) in the University of Baghdad / College of Science /Department of Geological Survey and Mining. The results of the composition of each material used in this study are presented as given in Table 1.

Table 1: Chemical Composition of adsorbent

Constituent	Clay Wt. %	Sand Wt. %
SiO ₂	27.90	27.03
Al ₂ O ₃	7.251	0.6517
Fe ₂ O ₃	6.734	0.6288
MgO	3.116	0.486
CaO	13.44	32.43
K ₂ O	1.13	0.0516

Physical Properties

The physical properties of the adsorbent was analyzed in the Oil Research and Development Center-Ministry of Oil. The tests conducted were: particle surface area, using BET method, pore volume and bulk density, according to ASTM B527. The results of surface area measurements are listed as given in Table 2.

Table 2: Physical Properties of Calcined Sand-Clay Mixture

Surface Area, m ² /g	Pore Volume cm ³ /g	Bulk Density g/cm ³
20.33	0.0303	0.9799

Adsorption Experiment

Batch experiments were implemented to achieve the equilibrium data. Artificial wastewater was prepared from KH₂PO₄ at different concentrations 5, 10, 15 and 20 mg/L. Adsorbent ranging in weight 5, 10, 15 and 20 g with 10 mm in diameter were placed in individual 200 ml distilled water of 500 ml glass bottle capacity. The bottles were placed at fixed positions in a shaker. The bottles were left for a suitable time ranging from 15 min to 240 min to allow adsorption to reach equilibrium conditions. The shaker speed controller was at constant speed of 100 rpm. After shaking, the mixture was filtered through a 0.45 μm filter. Vanadate-molybdate reagent of 10 ml and 5 ml of distilled water were added to 35 ml of filtered sample. After 15 min the mixed solution was analyzed for phosphate concentration by a UV-Vis spectrophotometer at the detection wavelength of 470 nm

according to [14] The adsorbed amount, q_t was calculated from Equation 1

$$q_t = (C_o - C_e)V/m \quad \dots(1)$$

where q_t is the amount adsorbed per unit gram of adsorbent (mg/g) in t time, C_o the initial concentration (mg/L), C_e the equilibrium concentration (mg/L), V the volume of solution (200 mL), and m the weight of the adsorbent (g). The following equation was used to determine the percentage removal of phosphate at any time:

$$R(\%) = \frac{C_i - C_e}{C_i} \times 100 \quad \dots(2)$$

Where: C_i , C_e mg/l is the initial and equilibrium concentration of each phosphate.

The shaker provided with a digital temperature sensor and speed controller. The experiments were conducted at 15, 20 and 30 °C and the shaker speed controller was at constant speed of 100 rpm. Two types of isotherm batches, were conducted, one of controlled experiments at pH 4, 7 and the other are uncontrolled experiments pH 11. Buffer solutions, 0.1M of HCl and 0.1M NaOH were added drop wise to the water to control the pH. In these runs the pH was controlled at 4, 7. Buffer solutions were not added for the runs conducted without a pH control.

Results and Discussion

Effect of Initial Phosphate Concentration and Contact Time

The effect of the initial concentrations (5-20 mg/L) on the adsorption by (CSCM) at constant adsorbent weight, 5 g is as shown in Figure 1. A fast initial sorption capacity of phosphate at the beginning 30 min was noticed and,

next, the sorption capacity was further increased but with a much slower rate till it reached equilibrium in about 60 min. The equilibrium adsorption increased from 0.188 to 0.375 mg/g with increase in the initial phosphate concentration from 5-20 mg/L.

Upon investigating the effect of contact time, rapid removal of P was observed in the first 30 minutes, with 89.4% P removal in this period at 5 mg/L as shown in Figure 2.

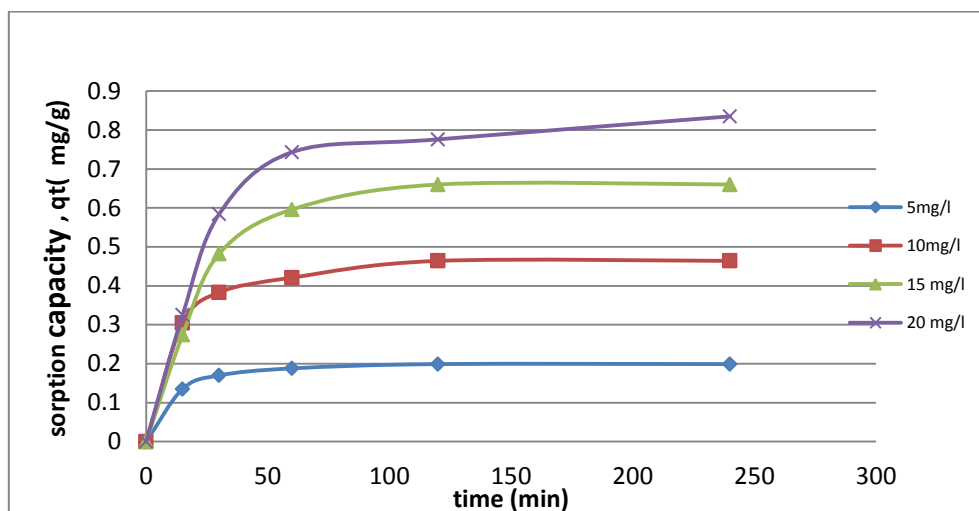


Fig. 1: Effect of initial concentration and contact time for the adsorption of phosphate on sand clay adsorbent weight=5 gm; pH 11, temperature =20 °C

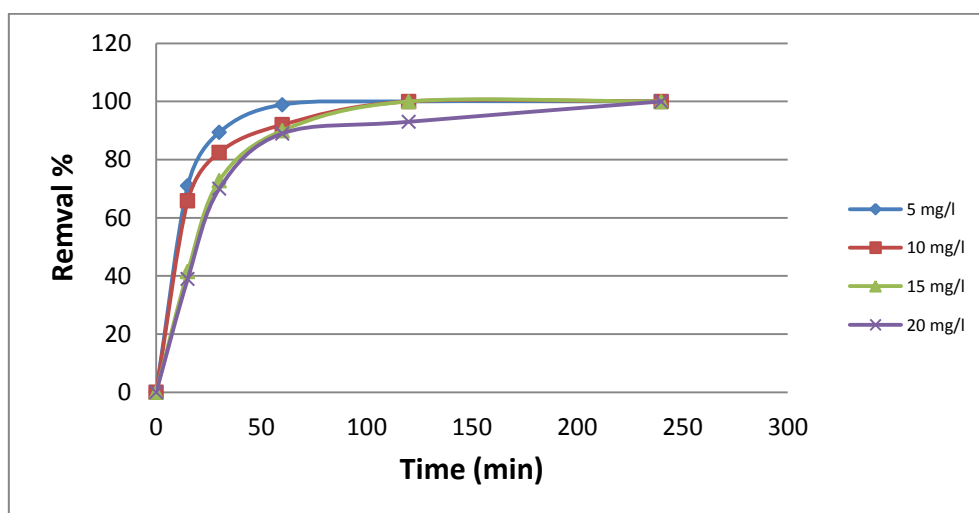


Fig. 2: Effect of initial concentration and contact time on percentage removal of phosphate contact time on percentage removal of phosphate at constant adsorbent dose 5 g and pH10-12, temperature =20 °C

Effect of Sorbent Dosage

The effect of sorbent dosage on percentage removal of phosphate is as shown in Figure 3. It was observed that the percentage removal increased from 98.9% to 100% with increase in adsorbent dose from 5 to 20 g at 5 mg/L, increase from 92% to 99% at 10 mg/L, increase from 90% to 96% at 15

mg/L, and increase from 89% to 92.7% at 20 mg/L. With a dose of 5 g (CSCM) /200 ml of simulated solution resulting in a 95%, 92%, 90%, 89% removal in P concentration at 5, 10, 15, 20 mg/L, respectively. Above this dosage of adsorbent, any increase in P removal is small. A dosing rate of 5 g was therefore recommended.

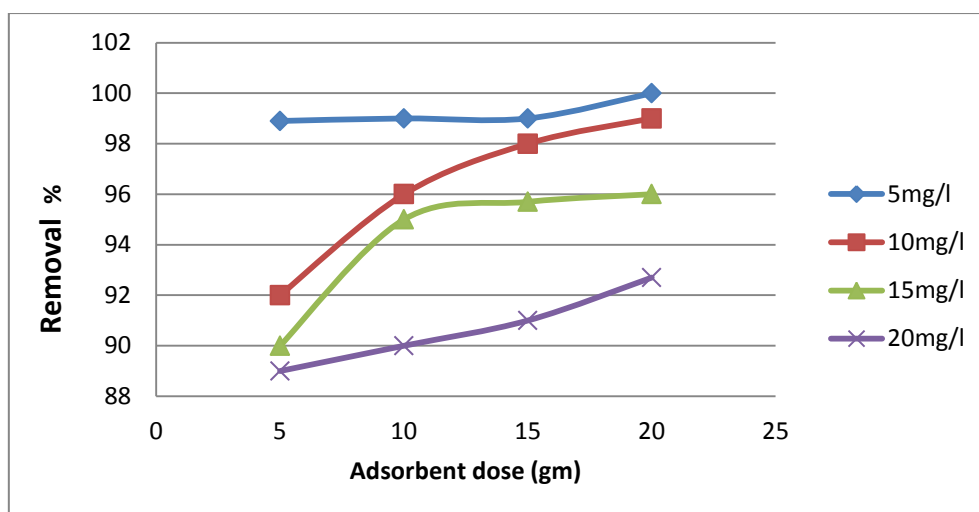


Fig. 3: Effect of amount of adsorbent for the removal on phosphate using calcined sand clay mixture: temperature =20 °C, pH 11; time =60 min

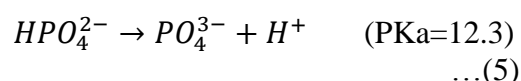
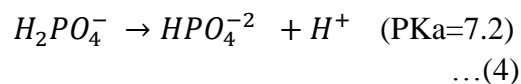
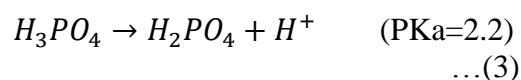
Effect of pH Value

Experiments were conducted under varying pH between 4 and 12. The pH of the solution was adjusted with 0.1 mol/L HCl or 0.1 mol/L NaOH for only acidic and neutral solution. There is no need for controlling pH under usual case, since the adsorption process was spontaneously occurred in basic solution once the solution was added to adsorbent. The experiments were achieved at 5, 10, 15, 20 g each adsorbent dose with 5, 10, 15, 20 mg/L initial concentrations, respectively. Figure 4 removal efficiency increased from 16% to 53.4% to 98.9% when pH increased from 4 to 7 to 10 respectively. Solution pH is an important controlling parameter in determining the dominant phosphorus removal mechanism, as well as the existing ionic species in solution are responsible for a given mechanism [15]. Aqueous phosphate exists in four forms depending on the pH of a given solution. These are:

1. Phosphate ion (PO_4^{3-}), which predominates in strongly basic conditions;
2. Hydrogen phosphate ion (HPO_4^{2-}), which is the dominant form at weakly basic conditions;

3. Dihydrogen phosphate ion (H_2PO_4^-), which predominates in weakly acidic conditions; and

4. Trihydrogen phosphate (H_3PO_4) which is the main form at strongly acidic conditions.



The logarithmic constant, pKa, is given as

$$\text{PK}_a = -\log K_a \quad \dots(6)$$

A smaller pKa value (i.e., a larger Ka value). A strong acid does not change pH and is therefore vital to understanding the possible removal mechanisms associated with phosphate. In sorption studies involving the uptake of phosphorus on to calcined sand-clay mixture (CSCM), it was found that the highest phosphorus removal occurred at pH 10-12. There was three different forms of phosphate, e.g., H_2PO_4^- , HPO_4^{2-}

and PO_4^{3-} in the solution as described in Equations 3-5. Generally, governing species in the PH region between 4 and 10, HPO_4^{2-} and $H_2PO_4^-$ with notice that HPO_4^{2-} species were governed in slightly alkaline conditions, but $H_2PO_4^-$ species governed in slightly acidic conditions. HPO_4^{2-} dominated over PO_4^{3-} species between pH 10-pH 12, while PO_4^{3-} species governed at pH higher than 12.5, [16]. There are several factors that controls the phosphate adsorption: Phosphate speciation in solution, pH_{ZPC} (zero point charge) of the adsorbent and the affinity of phosphate ions towards the adsorbent [17]. The pH at which the net surface charge zero on the adsorbent is called pH_{ZPC} . The surface charge of the adsorbent become negative when pH is less than pH_{ZPC} value, therefor a higher repulsion between the binding sites and phosphate ions resulting lower phosphate uptake, while the surface become a net positive charge when the pH is greater than pH_{ZPC} that improve coulombic attraction between the sites and the phosphate ions leading an increase in phosphate adsorption. The

solution begins to donate more protons than hydroxide groups, When the pH is less than pK_a , that cause the sorbent surface positively charged attracting negatively charged species [18]. In this study, the higher removal of phosphates at pH 10-12 (less than pK_a value of 12.3) indicates that the species involved in adsorption were affected by pH. Maximum phosphate sorption took place when it was higher than pH_{ZPC} of the (CSCM) surface, and less pK_a value 12.3 of HPO_4^{2-} , the conditions that facilitated (CSCM) surface to be positively charged. This observations have revealed that HPO_4^{2-} was the key species involved in range of adsorption process. The phenomenon may be explained another mechanism via precipitation. Hydrolysis of metal oxides generate metal cation and hydroxyl anion (OH^-) as the following equation.

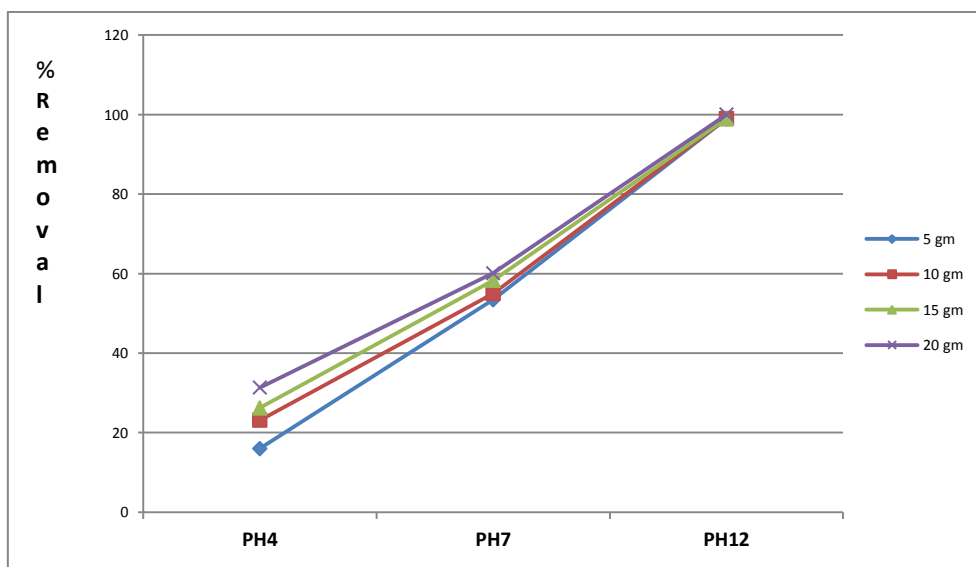
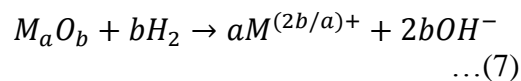
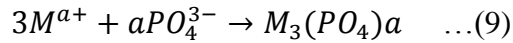


Fig. 4: Effect of pH value on the phosphate removal efficiency at different concentration, Dose = 5 g and equilibrium time of 60 min

The cationic species participate in phosphate uptake through electrostatic interaction, while the anionic species used inner sphere ligand exchange mechanism. Likewise phosphate metal precipitation took place as the equation given below [19]:



The presence of calcium oxides and silicates oxides in relatively large quantities as shown in Table 2.1 may support the precipitation mechanism. Thus phosphorus-removal pathway in the (CSCM) surface are adsorption on to the (CSCM) surface by precipitation of metallic phosphate salts. The orthophosphates which is particularly form of phosphorus, was indicated that able to be absorbed by clay minerals and various organic soils fraction in the soil matrix and chemically precipitate with Ca (at neutral to alkaline pH values) [20].

Effect of Temperature

The effect of temperature on the phosphate adsorption rate (q_e) was also

examined over temperature range of 15- 30 °C. Figure 5 shows the effect of temperature on the adsorption rate. It can be seen that the phosphate adsorption rate on calcined sand-clay mixture (CSCM) decreases with increasing temperature from 15 to 30 °C. The maximum adsorption rate was 0.63 mg/g at 15 °C decreased to 0.47 mg/g at 30 °C. This means that the adsorption of phosphate ions was improved at lower temperatures. The sorption of phosphate is exothermic. A similar observation was reported for removal of phosphate using dolomite mineral [21]. Thus the amount of adsorption decreased with increasing temperature. In contrast, the sorption of phosphate was endothermic used alginate-calcium carbonate composite beads [22]. It is noticed that removal efficiency decreased from 95% to 79%, 89% to 70%, 78% to 66%, 75% to 60% when temperature raised from 15 °C to 30 °C, at varying concentrations 5, 10, 15, 20 mg/l, respectively. As shown in Figure 6.

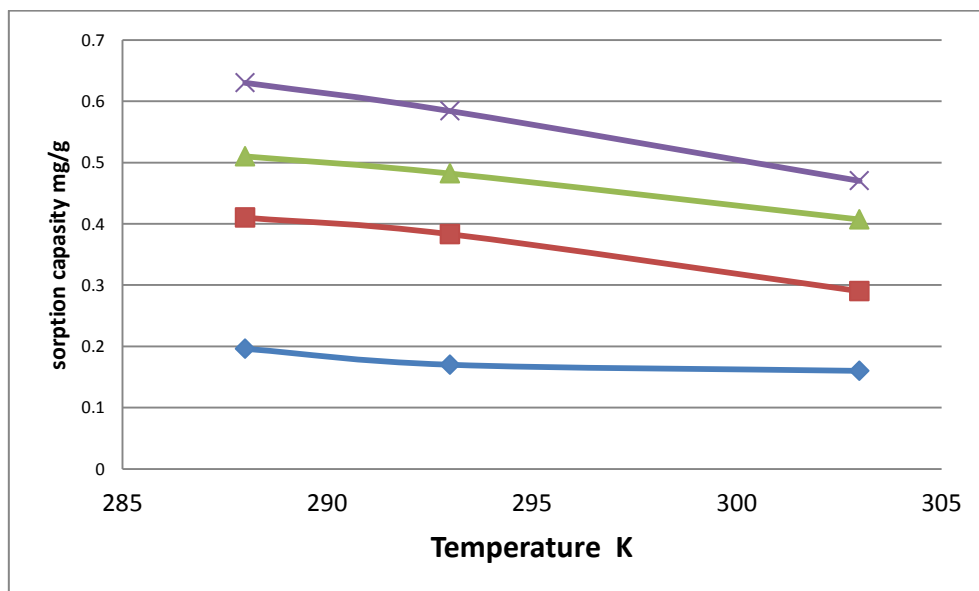


Fig. 5: Effect Of the temperature on the sorption capacity pH=10-12; amount adsorbent=5 gm; contact time =30 min; at different concentrations

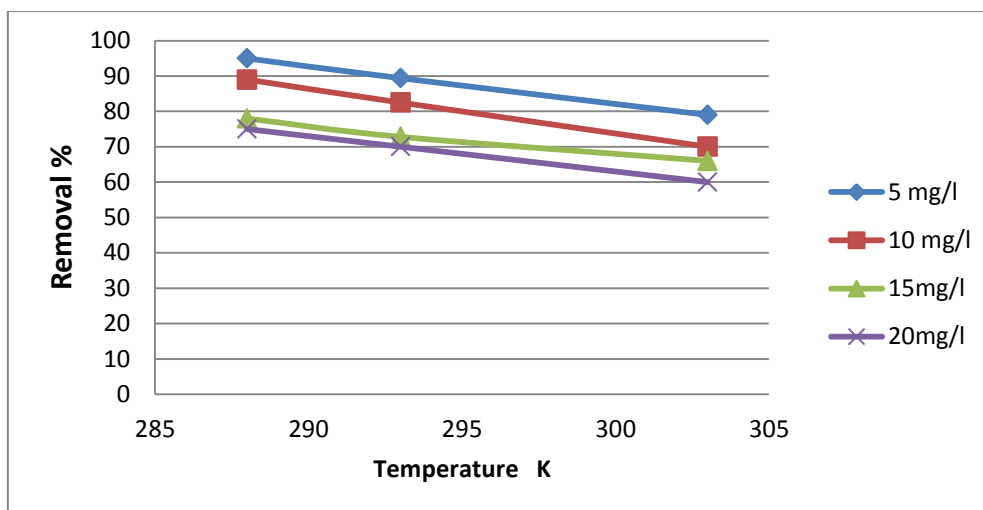


Fig. 6: Effect Of the temperature on the phosphate removal pH=10-12; amount adsorbent=5 gm; contact time =30 min; at different concentrations

Isotherm Equations for Single-Solute Adsorption

Two-Parameter Isotherms

The well-known equations proposed by Langmuir (1918) and Freundlich (1906) are typical representatives of the group of two-parameter isotherms. They belong to the most frequently used isotherm equations. The Langmuir isotherm has the form:

$$q = \frac{q_m + bc}{1 + bc} \quad \dots(10)$$

A linear regression is also possible because all two-parameter equations can be linearized. For Langmuir isotherm, different types of linearization are possible as follows:

$$\frac{1}{q_e} = \frac{1}{q_m} + \frac{1}{q_m b} \cdot \frac{1}{c_e} \quad \dots(11)$$

The Langmuir equation is valid for monolayer sorption onto the surface and energetic homogeneity of the adsorption sites. On the other hand, the Langmuir isotherm equation was also found to be applicable in cases where the underlying assumptions obviously not fulfilled. q_m and b are Langmuir parameters related to maximum adsorption capacity (mg of solute per g

of adsorbent) and free energy of adsorption, respectively. c_e is the concentration of solute at equilibrium (mg/l) and q_e is the amount of solute adsorbed per unit weight of adsorbent at equilibrium (mg of adsorbate per g of adsorbent). It is possible to estimate q_m and b from both intercept and slope, respectively through linear plot of the experimental data of $\frac{1}{q_e}$ versus $\frac{1}{c_e}$ as illustrated in Figure 7 and tabulated in Table 3. The higher values of the correlation coefficient (R^2) for both isotherms indicates that obviously best fit to experimental data. It is possible to explain good fitness in terms of surface nature of the adsorbent and affinities to towards phosphate concerning of various mineralogical forms exist in the adsorbent. The Freundlich isotherm is given by:

$$q = KC^{1/n} \quad \dots(12)$$

Where K and n are the isotherm parameters. The Freundlich isotherm can describe neither the linear range at very low concentrations nor the saturation effect at very high concentrations. By contrast, the medium concentration range is often

very well represented. Freundlich isotherm is a common used to describe the characterization of adsorption from aqueous solutions. It has been applied for the prediction of multi solute adsorption, the equilibrium relationship in the most kinetic and breakthrough curve models. It is convenient to convert Freundlich isotherm into the logarithmic form as:

$$\log q = \log k + \frac{1}{n} \log c \quad \dots(13)$$

Where K describe the strength of adsorption. High K value means high the adsorbent loading. The exponent n value indicate the degree of isotherm curvature as well as the energetic heterogeneity of the adsorbent surface. The isotherm becomes the more concave when the lower the n value is. If the concentration has a value of 1 in the respective unit, the loading equals the value of K. In experiments the exponent n is possible take any value.

In practice, however, mostly n values lower than 1 are found. With n = 1, the isotherm becomes linear. Freundlich isotherms are characterized as favorable with n < 1 that display relative high adsorbent loadings at low concentrations, whereas are recognized as unfavorable with n > 1. The value of K and n that represent intercept and slope, respectively be estimated from the linearization equation of 13 through taking logarithm of both sides equation 12 as illustrated in Figure 8 and tabulated in Table 3 .As shown in Figures 7-8 the (R^2) value for Langmuir model (0.9975) is slightly higher than of the Freundlich model (0.9821) which may denote the control of monolayer adsorption process over intra-molecular interactions among the adsorbed phosphate [19]. From both figures it can be seen that Langmuir model showed a better fit of the data than the Freundlich model.

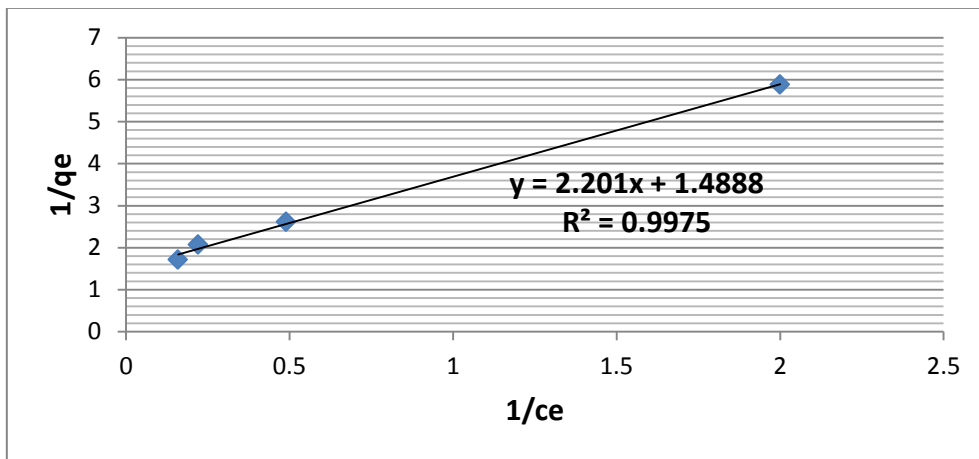


Fig. 7: Langmuir adsorption isotherm for phosphate on calcined sand clay mixture: temperature=20 °C; pH 10-12; adsorbent dose =5 gm; time =30 min

Table 3: Isotherm constants for phosphate adsorption onto sand clay mixture

Parameters	Temperature, °C		
	15	20	30
Langmuir			
q _m mg/g	0.616	0.67	0.631
b (L/mg)	1.85	.678	0.312
R ²	0.9908	.9978	0.9907
Freundlich			
n	2.73	2.099	1.8
k _f (mgL ^{-1/n} g ⁻¹ L ^{1/n})	0.344	0.25	0.157
R ²	0.9771	0.9821	0.995

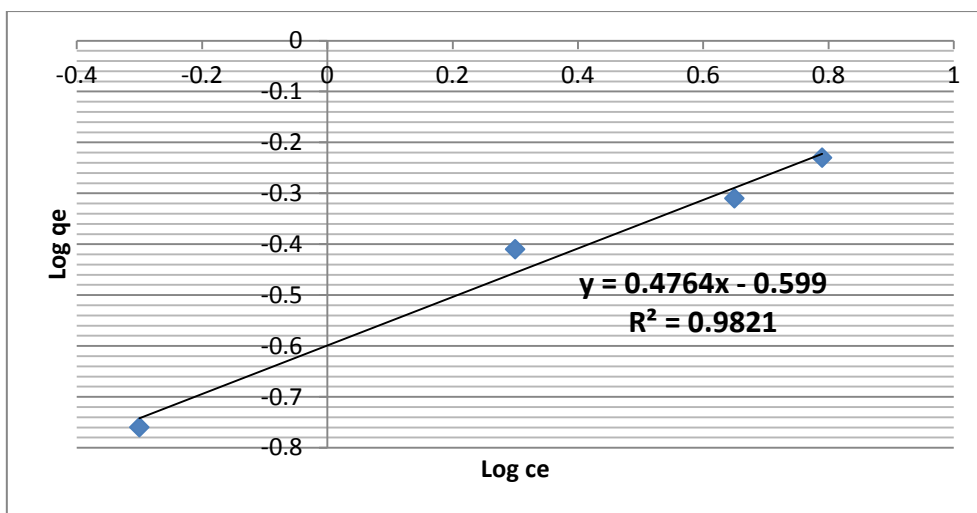


Fig. 8: Freundlich adsorption isotherm for phosphate on calcined sand clay mixture: temperature =20 °C; pH 10-12; adsorbent dose =5 gm; time =30 min

The mathematical expression of Langmuir isotherm of dimensionless constant which is commonly known as separation factor (R_L) can be defined as equation 14:

$$R_L = \frac{1}{1 + bc_0} \quad \dots(14)$$

In this regard R_L value can be considered as a preferential indicator of the adsorption. In deeper clarification, there are four values of the R_L , for favorable adsorption ($0 < R_L < 1$), for unfavorable ($R_L > 1$), for irreversible ($R_L = 0$) and for linear ($R_L = 1$). Values of R_L were proved that calcined sand clay mixture is favorable for adsorption of phosphate under conditions studied as shown in Table 5 where the values of R_L were in the range of 0-1at all temperatures studied.

Table 4: The maximum adsorption capacity of phosphate on different adsorbents

Adsorbent material	q_m mg/g	References
Modified bentonite	34.48	TANG yan-Kui et al., 2006
Burned kaolin	0.61	Majd I.Abdul Wahab et al., 2011
Calcined sand clay mixture	0.63	The present work

Table 5. The parameter R_L indicates the shape of isotherm as function of temperature.

Temperature 15, °C		
Nominal Concentration mg/l	Actual Concentration mg/l	R_L
5	5.18	0.094
10	11.65	0.044
15	16.6	0.0315
20	21	0.025
Temperature 20, °C		
	4.76	0.236
	11.61	0.112
	16.56	0.081
	20.88	0.065
Temperature 30, °C		
	5.1	0.385
	10.66	0.231
	15.33	0.172
	19.9	0.138

Thermodynamic of Phosphate Adsorption onto Calcined Sand Clay Mixture (CSCM)

The thermodynamic factors of phosphate adsorption onto sand-clay mixture including changes in standard enthalpy (ΔH°), standard entropy (ΔS°) were estimated by using the following Van't Hoff equation [21],

$$\log K = \frac{\Delta S^\circ}{2.303R} - \frac{\Delta H^\circ}{2.303RT} \quad \dots(15)$$

The Gibbs free energy (ΔG°) was evaluated by using equation 16:

$$\Delta G^\circ = -RT \ln K \quad \dots(16)$$

where R is gas constant (8.314 J.mol⁻¹.K⁻¹), K is the equilibrium constant at temperature T can be calculated from the ratio of amount adsorbed on solid at equilibrium C_i and the equilibrium concentration of phosphate C_e (mg/L) as expression: $K = C_i/C_e$.

The negative values of ΔG° were (-2.63, -2.06, -1.021 kJ/mol) at 288, 293, 303 k, respectively as shown in Table 6 which indicate spontaneous process by (CSCM) as an adsorbent. Values of ΔH° and ΔS° were calculated from

the slope and intercept of the Van't Hoff linear plot of log K versus 1/T as shown in Figure 9.

The negative values of ΔH° (-33.8 kJ/mol) as shown in Table 5 prove the exothermic nature of adsorption. The negative values of ΔS° (-108.25 J/mol.K) reflect lower randomness at the solid/solution interface during the adsorption of phosphate. Thermodynamic factors were reported ΔH° (-5.85 kJ/mol), ΔS° (-10.17 J/mol.K) for the adsorption of phosphate on dolomite [21].

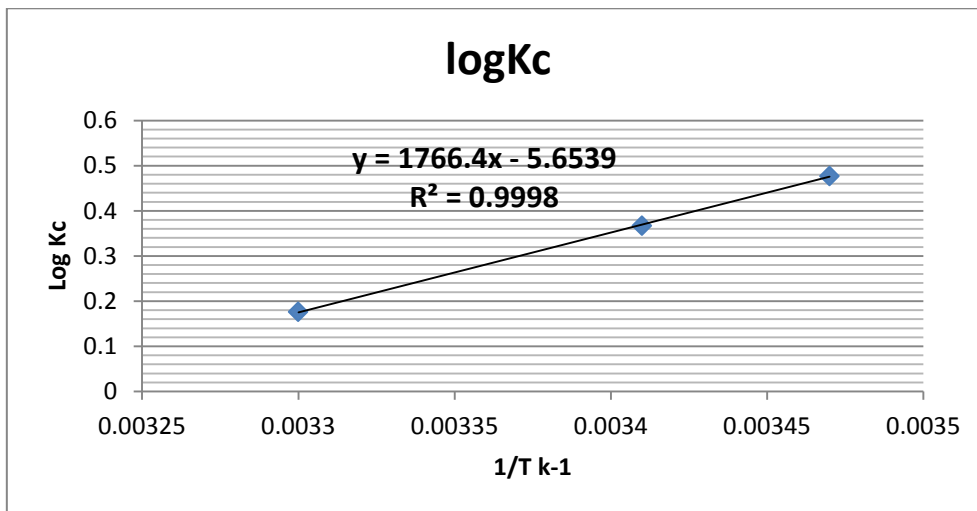


Fig. 9: Van't Hoff plot for the adsorption of phosphate onto calcined sand clay mixture adsorbent (pH=10-12)

Table 6: Thermodynamic parameters for the adsorption of PO_4^{3-} at various temperatures onto calcined sand clay mixture

Temp. (°C)	K_C	ΔG° kJ/mol	ΔH° kJ/mol	ΔS° J/mol.k
15	3	-2.63	-33.8	-108.25
20	2.33	-2.06		
30	1.5	-1.021		

Conclusions

The results of the present work can provide a process for developing a low-cost technology based on adsorption by calcined sand-clay mixture for phosphate removal from wastewater. The following points can be concluded from the present study: calcined sand-clay mixture (CSCM) removes phosphate from aqueous

solution rapidly. Phosphate may be removed by adsorption and/or by precipitation of calcium phosphate. Phosphate adsorption by (CSCM) increased with the increase in pH and reached spontaneously at the maximum adsorption in the pH range of 10-12. As the initial concentration of phosphate increases 5 to 20 mg/l, the amount of adsorbed phosphate on

the adsorbent increases. As the temperature increases 15-30 °C the adsorption rate decreases over the studied adsorbent which indicates that the adsorption of phosphate was favoured at lower temperature, since the adsorption of phosphate is exothermic. Equilibrium isotherm adsorption data obey both Langmuir and Freundlich models with slightly fit by Langmuir. The maximum adsorption capacity of (CSCM) is 0.835 mg/g P. (CSCM) can be used as an effective, low-cost, available and locally adsorbent for the removal of phosphate.

Nomenclature

b	Langmuir isotherm constant L/mg
CSCM	Calcined sand clay mixture
C	Concentration of adsorbate in feed mg/L
C _e	Equilibrium phosphate concentration mg/L
C ₀	Initial concentration of phosphate ions mg/L
C _f	Final concentration of phosphate ions mg/L
K _f	Freundlich isotherm constant mgL ⁻¹ /ng ⁻¹ L ¹ /n
n	Freundlich intensity parameter
q _m	The maximum amount of adsorbate per unit weight of adsorbent mg/g
q _e	Concentration of adsorbate in solid phase at equilibrium mg/g
q _t	Concentration of adsorbate in solid phase at time t mg/g
R _L	Separation factor
R ²	coefficient of determination
rpm	rotation per minute

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