Adsorption isotherms and kinetics of phosphate on waste mussel shell

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INTRODUCTION

Phosphorus (P) is an important element to all living organisms. However, high concentration of P released into natural water strongly accelerates eutrophication (Mezner & Bensmaili, 2009). Eutrophication is the aging process for water bodies, which causes algal blooms, aquatic life death, and decrement in water quality (Song et al., 2011). The principal forms of P in water are orthophosphate, polyphosphate, and organically bound phosphate (Caravelli et al., 2010). The most common P compound in wastewater is orthophosphate (Hussain et al., 2011). The effects of the discharge of P to receiving water has led to legislations such as those by the European Union (EU) and United State Environmental Protection Agency (USEPA). The EU permits the effluent limit of total phosphorus (TP) ranging from 1 to 2 mg L⁻¹ for 10,000–100,000 population equivalent. Meanwhile, the USEPA follows a TP limit of 0.5–0.8 mg L⁻¹ to control eutrophication (Abdul Salim et al., 2018).

Many water treatment methods are used to remove P from water, such as biological phosphorus removal, chemical precipitation, and adsorption. The biological process to treat wastewater can be highly variable due to operational difficulties (Oladaja et al., 2012). Furthermore, the chemical treatment entails high chemical costs and increased sludge amount (Fulazzaky et al., 2015). Among these treatment methods, the adsorption process is superior to other methods. This technique has a simple operation and produces small volume of sludge. Nowadays, considerable attention has been paid on economical and environmental concerns to the study of using different types of low-cost adsorbents such as rice straw (Luo et al., 2019), oyster shell (Nam et al., 2017), eggshell (Torit & Phihusut, 2018), and cockle shell (Kim et al., 2018).

In this study, the selection of mussel shell as a low-cost alternative adsorbent for PO₄³⁻ removal was favourable due to its high availability in Malaysia. WMS contains calcium carbonate, which enables it to adsorb PO₄³⁻ from water (Kim et al., 2018). The objectives of this work were to determine the adsorption kinetic and isotherm for the adsorption of PO₄³⁻ onto WMS based on the data of batch experiments and to elucidate how basic adsorption isotherm (i.e., Langmuir isotherm model) combined with simple mass/material balance could be applied to estimate removal efficiency or required adsorbent amount according to a given set of initial conditions.

ADSORPTION KINETICS AND ISOTHERMS

Kinetic adsorption models

Graphical abstract

ION EXCHANGE

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The adsorption kinetic is of interest for many aspects of surface chemistry, from understanding adsorption/desorption mechanisms to more practical problems such as purification of water (Abdul Salim et al., 2018; Singh et al., 2018), food processing (Zhong et al., 2019), flue gas separation (Wang et al., 2018) and catalysis (Dzade & De Leeuw, 2018).

Pseudo-first-order model

The first-order rate equation is commonly expressed as (Ho & McKay, 2000):

$$\ln(q_e - q_t) = \ln(q_e) - k_1 t_i$$

where $q_t$ is the equilibrium amount of PO\(_4^{3-}\) adsorbed (mg g\(^{-1}\)), $q_e$ is the amount of PO\(_4^{3-}\) adsorbed at adsorption time (mg g\(^{-1}\)), $k_1$ is a rate constant of PFO equation (min\(^{-1}\)) and $t_i$ is the adsorption time (min).

The values of $k_1$ and $q_e$ can be evaluated from the intercept and slope of plot ln($q_e - q_t$) versus $t_i$, respectively (Table 1). When the curve of plotting ln($q_e - q_t$) versus $t_i$ shows a straight line, the adsorption kinetic follows a PFO model.

Pseudo-second-order model

The second-order rate equation can be expressed in the linear form of (Ho, 2006):

$$\frac{t_i}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t_i}{q_e}$$

where $q_t$ (mg g\(^{-1}\)) is the amount of PO\(_4^{3-}\) adsorbed at adsorption time, $q_e$ is the amount of PO\(_4^{3-}\) adsorbed at equilibrium time (mg g\(^{-1}\)), $k_2$ is a rate constant of PSO model (min\(^{-1}\)) and $t_i$ is the adsorption time (min).

The adsorption kinetic obeys a PSO model when the plot of $t_i/q_t$ versus $t_i$ gives a straight line (Köse & Kivanç, 2011). The values of $k_2$ and $q_e$ can be evaluated from the intercept and slope of plot $t_i/q_t$ versus $t_i$, respectively (Table 1). The PFO and PSO models have been successfully applied for the adsorption of PO\(_4^{3-}\) from aqueous solution (Abdul Salim et al., 2018; Chen et al., 2013; Chen et al., 2012; Köse & Kivanç, 2011; Mezenner & Bensmaila, 2009; Oladoja et al., 2012).

Table 1 List of adsorption kinetics models.

| Kinetic models | Linear form | Plot | Parameters |
|----------------|-------------|-----|------------|
| PFO            | ln($q_e - q_t$) = ln($q_e$) - $k_1$ $t_i$ | ln($q_e - q_t$) vs. $t_i$ | $q_e$ (mg g\(^{-1}\)) $k_1$ (min\(^{-1}\)) |
| PSO            | $\frac{t_i}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t_i}{q_e}$ | $t_i$ vs. $q_t$ | $q_e$ (mg g\(^{-1}\)) $k_2$ (min\(^{-1}\)) |

Isotherm adsorption models

The Freundlich and Langmuir equations are commonly used to describe adsorption isotherms. The Freundlich model describes that a heterogeneous surface of adsorbates forms on the surface of adsorbent with multilayer sorption of different energies of adsorption (Boopathy et al., 2013). The Langmuir model assumes that the adsorbent is being saturated when the monolayer adsorbate coverage of adsorbent has attached with a homogenous surface without interactions between the adsorbed molecules (Song et al., 2011).

Freundlich model

The linear form of the Freundlich isotherm can be written as:

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

where $K_F$ is the Freundlich constant (mg g\(^{-1}\)), $n$ (dimensionless) is the heterogeneity factor which has a lower value for more heterogeneous surfaces, and $C_e$ is the concentration of the adsorbate in the equilibrium solution (mg L\(^{-1}\)).

The Freundlich isotherm suggests that a plot of ln $q_e$ versus ln $C_e$ should give a straight line, the adsorption process is satisfied to follow the Langmuir isotherm. Consequently, two parameters ($K_L$ and $q_{max}$) should be obeyed by the following expression:

$$q_{max} = \frac{1}{K_L} q_{max} C_e$$

The isotherm equation is combined with a mass/material balance (Chung et al., 2015). In a batch studies, the mass balance expression should be obeyed by the following expression:

$$C_i = C_e + C_s^i$$

where $C_i$ is the initial solute concentration in the solution and $C_s^i$ is the concentration of solute adsorbed onto the adsorbent at equilibrium. The $q_e$ in Eq. (5) can be written by the following equation (Chung et al., 2015):
\[ q_e = \left( \frac{V \cdot C_i}{m} \right) = \frac{V (C_i - C_e)}{m} \]  

(9)

Substituting Eq. (9) into Eq. (5) gives the second order function, in which \( C_e \) is one argument variable as follows (Chung et al., 2015):

\[ K_L \cdot C^2 + \left( 1 + \frac{K_L \cdot q_{max} \cdot m}{V} - K_L \cdot C_i \right) \cdot C_e - C_i = 0 \]  

(10)

The following expression is in the form of quadratic equation whereby all variables are treated as constants except for \( C_e \). Therefore, by applying the quadratic formula, the value of \( C_e \) can be identified as follows (Chung et al., 2015):

\[ C_e = \frac{-1 \pm \sqrt{1 + \frac{4K_L \cdot q_{max} \cdot m}{V} - K_L \cdot C_i}}{2K_L} \]  

(11)

The resulting \( C_e \) is a function of \( C_i \) and \( m \) for a specific \( V \) with parameters \( K_L \) and \( q_{max} \). Therefore, when \( K_L \) and \( q_{max} \) are gained through the batch adsorption experiments, \( C_e \) can be estimated for the given \( C_i \) and \( m \) in a fixed volume. Furthermore, the removal efficiency \( (E) \) can be expressed as:

\[ E = \frac{C_i - C_e}{C_i} \]  

(12)

and thus, \( E \) is also a function of \( C_i \) and \( m \) for a specific \( V \).

For the given \( C_i \) and target \( E \), the model equation to estimate the value of \( m \) can be gained. The value of \( m \) can be obtained by substituting Eq. (9) and Eq. (12) into Eq. (5) to give:

\[ m = \frac{V \cdot E}{K_L \cdot q_{max} \cdot (1 - E)} + \frac{V \cdot E}{q_{max} \cdot C_i} \]  

(13)

Eq. (13) is an explicit equation, whereby \( m \) is a function of \( C_i \) and \( E \) for a specific \( V \) with parameters \( K_L \) and \( q_{max} \), and thus, the required \( m \) can be estimated under a set of \( C_i \) and a desired \( E \) (Fig. 1).

Therefore, when \( m_{\text{Predicted}} \) and \( E_{\text{Predicted}} \) are obtained, adsorption capacity \( (q_{\text{Predicted}}) \) can be estimated by substituting Eq. (12) into Eq. (9), giving:

\[ q = \frac{E \cdot C_i \cdot V}{m} \]  

(14)

**Langmuir isotherm parameter evaluation and model calculation**

The Langmuir isotherm was fitted to experimental data for PO4\(^{3-}\) with Eq. (6) to evaluate isotherm parameters. The application tool for user form was created using Excel, which allowed input of the Langmuir isotherm parameters and the set of initial experimental conditions. When the parameters and the set of initial experimental conditions were filled in, the removal efficiency and/or the required adsorbent mass for a target efficiency were calculated by the system.

**EXPERIMENTAL**

**Materials**

WMS was collected from Pasir Gudang, Johor. The WMS was rinsed with deionized water and then dried in an oven at a temperature of around 28-30 °C for 48 h. The dried WMS was ground by a grinder (Panasonic, Model MX-AC400W, Malaysia) and sieved at 1.18 mm. The dried adsorbent was used for the adsorption of PO4\(^{3-}\) from aqueous solution.

**Analytical methods and characterization techniques**

The analysis of PO4\(^{3-}\) was performed using HACH DR 6000 UV–Vis Spectrophotometer in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, 2005) based on the amino acid method. The measurements of pH were made using a portable pH meter (Jenway Model 350 pH meter).

In this work, the adsorbent was previously sputter-coated with gold (Sputter Coater, Bio-Rad Instruments, USA) for surface morphology analysis of the unmodified adsorbents using a scanning electron microscope (SEM, Hitachi, Model TM3000, Japan). The EDX instrument was used to identify the chemical composition of WMS (Energy-Dispersive X-Ray Spectroscopy, Bruker, Model X Flash 6110, German). An in-depth analysis for the crystal phase composition of adsorbent was carried out using XRD (High Resolution X-Ray Diffractometer, Bruker D8 Advance, German).

**Batch experiments**

Batch experiments were conducted to determine adsorption isotherm and kinetics. The experiments of kinetic adsorption were conducted by adding 2, 6, and 10 g of the adsorbents into an Erlenmeyer flask containing 100 mL of PO4\(^{3-}\) 5 mg L\(^{-1}\) and shaken at 140 rpm. The concentrations of PO4\(^{3-}\) in each sample solution were monitored at appropriate time intervals until the adsorbent was saturated. The residual concentrations of PO4\(^{3-}\) presented in each Erlenmeyer flask were determined using HACH DR 6000 UV–Vis Spectrophotometer. The PO and PSO models were used to study the kinetics of the adsorption of PO4\(^{3-}\) onto the adsorbent.

The isotherm experiments were carried out by adding 2, 4, 6, 8, and 10 g of the adsorbent into different Erlenmeyer flasks containing 100 mL of synthetic solution. Each solution was shaken for 1 to 6 days, depending on time period of the isotherm equilibrium of PO4\(^{3-}\). Sample solution was monitored at appropriate time intervals and then centrifuged at 6000 rpm for 10 min (Hettich, EBA 21, German). The supernatant of PO4\(^{3-}\) concentration was determined using HACH DR 6000 UV–Vis Spectrophotometer. The Freundlich and Langmuir isotherm models were used to study the adsorption isotherm of PO4\(^{3-}\).

Each batch adsorption experiment was conducted twice. The adsorption capacity \( (q) \) and the removal efficiency \( (E) \) were calculated by using Eq. (15) and Eq. (16), respectively.

**Synthetic solution**

The PO4\(^{3-}\) stock solution (i.e., 100 mg L\(^{-1}\)) was prepared by dissolving 0.1435g of analytical grade potassium dihydrogen phosphate (KH2PO4) in 1 L deionised water. (Zapater-Pereyra et al., 2014). The synthetic solution was diluted with deionised water to attain the desired concentration. The pH of the synthetic solutions was set at 7.0 for all the batch experiments.
where $q$ is the adsorption capacity (mg g$^{-1}$), $C_i$ is the initial PO$_4^{3-}$ concentration (mg L$^{-1}$), $C_f$ is the PO$_4^{3-}$ concentration in the solution (mg L$^{-1}$), $V$ is the volume of solution (L) and $m$ is the mass of adsorbent (g).

RESULTS AND DISCUSSION

Physical and chemical characteristics of the WMS

Table 3 presents the elemental compositions of two natural WMS i.e., WMS from Pasir Gudang and WMS of Abonomar S.L., Spain. The major elemental composition of WMS was Ca and the minor compositions were Na, Fe, and Al, which were higher than those in WMS from Abonomar S.L. (Paradelo et al., 2016). This implied that WMS was mainly comprised of Ca and could be a potentially suitable material for PO$_4^{3-}$ removal from aqueous solution (Kim et al., 2018).

![X-ray diffraction spectra of WMS.](image)

Table 3 Elemental composition of the WMS.

| WMS of:          | Element composition (%) |
|------------------|-------------------------|
|                  | Ca | Na  | Fe  | Al  |
| Pasir Gudang$^a$ | 41.69 | 0.92 | 0.02 | 0.02 |
| Abonomar S.L.$^b$ | 28.00 | 0.52 | ND  | ND  |

(1) $^a$WMS of Pasir Gudang found in Johor, Malaysia, is the adsorbent used in this study; (2) $^b$WMS of Abonomar S.L. found in Pontevedra, Spain, is the WMS in the literature; (3) ND: not detected.

The SEM images were taken to examine the surface morphology of the WMS, as shown in Fig. 2. Fig. 2a (1004× magnification) shows that the WMS has a rough surface. The SEM micrograph image with 2003× magnification (Fig. 2b) exhibits a rough surface with some voids of different sizes presented on the surface of WMS, implying that the availability of high surface area could exhibit higher capability to adsorb PO$_4^{3-}$ from synthetic solution.

![SEM photomicrograph of WMS: (a) 1004× magnification, (b) 2003× magnification.](image)

Adsorption of PO$_4^{3-}$ from a synthetic solution onto the WMS

Fig. 4 illustrates the relationship of WMS dosage ($m$) on both $E$ and $q$ for PO$_4^{3-}$ adsorption onto WMS. Figs. 4a and b show that when the WMS dosage was increased from 2 to 10 g, $E$ for adsorption of PO$_4^{3-}$ was gradually increased from 43.8% to 83.4% while $q$ was gradually decreased from 0.11 to 0.04 mg·g$^{-1}$. Higher adsorbent amount used in a batch experiment has resulted in more adsorbent surface area that available to adsorb PO$_4^{3-}$ and thus, the percent removal of PO$_4^{3-}$ was increased (Hussain et al., 2011; Köse & Kivanç, 2011; Xiong et al., 2011). The decreasing amount of $q$ with increasing adsorbent dosage was a result of active sites on the WMS surface that remained unsaturated throughout the adsorption experiment (Aydın & Bulut, 2008). Hence, more adsorbent dosage used would appear to be difficult to attain at a saturation state (Abdul Salim et al., 2018). Besides that, the higher amount of adsorbent might cause particle aggregation and interference or repulsive forces between active binding sites and thus, reducing the interaction of PO$_4^{3-}$ with the adsorbent and decreasing the total surface area of the adsorbent (Abdul Salim et al., 2018; Mezenner & Bensmaili, 2009).

![Relationship between: (a) the removal efficiency and the WMS dosage and (b) the adsorption capacity and the WMS dosage.](image)

The XRD spectra of the WMS sample indicated that aragonite (CaCO$_3$) was the major component while sodium oxide (NaO) was the minor component of the WMS from Pasir Gudang (Fig. 3) and could have more favourable to chemically attract PO$_4^{3-}$ from aqueous solution (Panagiotou et al., 2018). Several researchers have noted that aragonite has good adsorption ability for PO$_4^{3-}$ ions (Vieira et al., 2019).
Adsorption kinetics of PO$_4^{3-}$ onto the WMS

In this study, the linear plots of PFO (Fig. 5a) and PSO (Fig. 5b) models were used to describe the adsorption kinetics of PO$_4^{3-}$ from synthetic solution (Ho & McKay, 1998). Table 4 shows the kinetic parameters $k_1$, $q_e$, and $q_e$ for PFO and PSO models.

![Figure 5](image)

**Table 4** Kinetic parameters obtained from the PFO and PSO models for the PO$_4^{3-}$ adsorption onto WMS.

| Medium            | Amount (g) | Pseudo-first-order model | Pseudo-second-order model |
|-------------------|------------|--------------------------|---------------------------|
|                   |            | $q_e$ (theo) (mg·g$^{-1}$) | $k_1$ (min$^{-1}$) | $R^2$ | $q_e$ (exp) (mg·g$^{-1}$) | $k_2$ (g·mg$^{-1}$·min$^{-1}$) | $R^2$ | $q_e$ (exp) (mg·g$^{-1}$) |
| Synthetic solution| 2          | 0.040                     | 0.0005                   | 0.919 | 0.110                  |
|                   | 6          | 0.030                     | 0.0004                   | 0.948 | 0.057                  |
|                   | 10         | 0.036                     | 0.0009                   | 0.959 | 0.042                  |
|                   | 2          | 0.112                     | 0.0481                   | 0.999 | 0.110                  |
|                   | 6          | 0.058                     | 0.0614                   | 0.996 | 0.057                  |
|                   | 12         | 0.043                     | 0.0643                   | 0.996 | 0.042                  |

The linear regression analysis of the kinetic models for the adsorption of PO$_4^{3-}$ from a synthetic solution by WMS was shown in Fig. 5. As shown in Table 4, the correlation coefficient for the PSO model ($R^2 > 0.996$) was higher than the for PFO model ($R^2 > 0.919$). This study verified that the PSO model is more suitable for the adsorption kinetic of PO$_4^{3-}$ from a KH$_2$PO$_4$ solution onto WMS compared to the PFO model (Table 4).

According to the results of this study, the adsorption between WMS and PO$_4^{3-}$ could be categorised as chemical adsorption. Chemical adsorption is based on chemical reactions between the adsorbate and the surface sites of the adsorbent (Worch, 2012), in which the adsorption process involves valence forces through sharing or exchanging of electrons between adsorbent and adsorbate through the replacement of OH$^-$ by PO$_4^{3-}$ (Xiong et al., 2017). Similar results have been reported for the adsorption of PO$_4^{3-}$ onto ferric sludge (Song et al., 2011) and molybdenum blue onto dehydrated peanut hull (Özer et al., 2007), where the value of $k_1$ increases while the value of $q_e$ decreases with increasing amount of adsorbent.

Adsorption isotherms of PO$_4^{3-}$ onto the WMS

Batch isotherm studies were performed in order to understand the relationship between the amount of the PO$_4^{3-}$ adsorbed per unit mass of WMS and the PO$_4^{3-}$ concentration in the solution at equilibrium. The experimental data for the adsorption of PO$_4^{3-}$ onto WMS was analysed using the linearised forms of the Freundlich (Fig. 6a) and Langmuir (Fig. 6b) models. The Langmuir and Freundlich parameters are listed in Table 5. The correlation coefficient for Langmuir model ($R^2 > 0.882$) was higher than for Freundlich model ($R^2 > 0.877$), indicating that PO$_4^{3-}$ adsorption was more likely a monolayer adsorption process with uniform distribution of energetic adsorption sites on its surface (Lü et al., 2009).

**Table 5** The parameters $n$, $K_r$, $q_{max}$, and $K_r$ for the adsorption of PO$_4^{3-}$ onto WMS.

| Sample                  | Freundlich model | Langmuir model |
|-------------------------|------------------|----------------|
| Synthetic solution      | $n$ | $K_r$ | $R^2$ | $q_{max}$ | $K_r$ | $R^2$ | (mg·g$^{-1}$) | (mg·g$^{-1}$) | (L·mg$^{-1}$) |
|                         | 1.41 | 0.044 | 0.877 | 0.157 | 0.412 | 0.882 |

Application of Langmuir isotherm to estimate adsorbate removal efficiency or required amount of adsorbent

Experimental data of PO$_4^{3-}$ adsorption onto WMS was fitted to the linear forms of Freundlich and Langmuir isotherms in Eq. (3) and Eq. (4), which are depicted in Fig. 6. The results showed that the Langmuir isotherm model gave a better mathematical model to explain the adsorption equilibrium compared to the Freundlich isotherm model. From the slope and intercept of the plot of $1/q_e$ against $1/C_e$ in Fig. 6(b), the $K_r$ and $q_{max}$ values were attained as listed in Table 5. When the Langmuir isotherm parameters were identified, the removal efficiencies for any set of experimental conditions could be estimated. Eq. (11) was used to get the predicted removal efficiencies as a function of initial concentration of PO$_4^{3-}$ solution for different adsorbent masses of PO$_4^{3-}$ in the range of 2 to 10 g. The predicted data was compared to the experimental data for validation (Table 6a). This finding showed that the Langmuir isotherm model with mass balance was able to predict the removal efficiency by adsorption using initial solute concentration and different adsorbent masses. Furthermore, model verification was conducted to determine the required amount of adsorbent (Table 6b) by using Eq. (13). In addition, when $m_{predicted}$ and $E_{predicted}$ were obtained, adsorption capacity ($q_{predicted}$) could be estimated by using Eq. (14). Fig. 7 shows the practical application of Langmuir isotherm. According to the figure, the removal efficiency could be predicted with different amounts of WMS.
Table 6 Comparison of (a) removal efficiency, \(E\), and (b) required adsorbent mass, \(m\), predicted by Langmuir isotherm with mass balance to experimental data obtained from adsorption of \(\text{PO}_4^{3-}\) onto WMS.

(a) Initial conditions \(E_{\text{Experimental}}\) \(E_{\text{Predicted}}\)

| \(C_i\) (mg L\(^{-1}\)) | \(m\) (g) | 43.8 | 35.8 | 18.34 |
|------------------------|--------|------|------|-------|
| 5.0                    | 2.000  |      |      |       |
| 5.0                    | 4.000  | 54.6 | 58.1 | 6.50  |
| 5.0                    | 6.000  | 67.8 | 70.8 | 4.40  |
| 5.0                    | 8.000  | 76.8 | 78.1 | 1.69  |
| 5.0                    | 10.000 | 83.4 | 82.7 | 0.89  |

(b) Initial conditions \(E_{\text{Experimental}}\) \(E_{\text{Predicted}}\)

| \(C_i\) (mg L\(^{-1}\)) | \(m\) (g) | 2.194 | 9.70 | 0.088 | 20.23 |
|------------------------|--------|------|------|-------|-------|
| 5.0                    | 38.5   |      |      |       |       |
| 5.0                    | 61.0   | 4.361| 9.02 | 0.070 | 2.86  |
| 5.0                    | 73.2   | 6.554| 9.23 | 0.056 | 2.03  |
| 5.0                    | 80.0   | 8.732| 9.15 | 0.046 | 4.56  |
| 5.0                    | 84.1   | 10.855| 8.55 | 0.039 | 7.77  |

(1) \(E_{\text{Experimental}}\); (2) \(E_{\text{Predicted}}\); (3) \(m_{\text{Experimental}}\); (4) \(m_{\text{Predicted}}\); (5) \(q_{\text{Experimental}}\); (6) \(q_{\text{Predicted}}\;.

Fig. 6 Linear plots of: (a) Freundlich model and (b) Langmuir model for \(\text{PO}_4^{3-}\) adsorption.

Fig. 7 Relationship of: (dashed line) \(q_{\text{Predicted}}\) and \(m_{\text{Predicted}}\) for the adsorption of \(\text{PO}_4^{3-}\); (solid line) \(q_{\text{Experimental}}\) and \(m_{\text{Experimental}}\) for the adsorption of \(\text{PO}_4^{3-}\).

CONCLUSION

In this study, the verification of the isotherm and kinetic models was performed to understand the behaviour of the adsorption of \(\text{PO}_4^{3-}\) from synthetic solution onto WMS. The adsorption kinetic data was best described by the PSO model, suggesting that chemisorption was involved during the adsorption process. The adsorption of \(\text{PO}_4^{3-}\) onto WMS was best described by the Langmuir model, suggesting that the adsorption of \(\text{PO}_4^{3-}\) onto WMS was occurred as monolayer. The result proposed that WMS has a good potential to adsorb \(\text{PO}_4^{3-}\) from water and thus, improving environmental quality.

ACKNOWLEDGEMENT

The authors would like to acknowledge the Universiti Teknologi Malaysia and the Fundamental Research Grant Scheme provided by the Ministry of Higher Education (NO. 4F956).

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