How to Calculate Adsorption Isotherms of Particles Using Two-Parameter Monolayer Adsorption Models and Equations

Risti Ragadhita, Asep Bayu Dani Nandiyanto*

Departemen Kimia, Universitas Pendidikan Indonesia
Correspondence: E-mail: nandiyanto@upi.edu

ABSTRACTS

Adsorption isotherm is the most important calculation to predict and analyze the various possible mechanisms that occur in adsorption process. However, until now, most studies only presented the adsorption isotherm theory, and there are no studies that explain the adsorption isotherm thoroughly and in detail from theory to calculation. Therefore, this study contains guidelines for selecting the type of adsorption isotherm to describe the entire adsorption data set, which is featured by the ten most common adsorption isotherms. The steps of how to analyze the two-parameter monolayer adsorption are presented. This study is expected to provide clear and useful information for researchers who are working and studying on the adsorption process.

ARTICLE INFO

Article History:
Received 15 Nov 2020
Revised 30 Jan 2021
Accepted 20 Feb 2021
Available online 24 Feb 2021

Keyword:
Adsorption Isotherms, Carbon, Curcumin, Education, Silica, Tungsten.
1. INTRODUCTION

Adsorption is a surface phenomenon that involves adhesion of atoms, ions or molecules from a gas, liquid, or dissolved solid on a surface of substance. The atoms, ions or molecules that attached on the solid surface is the adsorbate, and the place where the adsorbate accumulates is called the adsorbent. This process creates a film of the adsorbate on the surface of the adsorbent. Definition of adsorption is different from absorption. The absorption involves a fluid (as the absorbate) is dissolved by or permeates a liquid or solid (the absorbent), and the process involves the whole volume of the material. Illustration from the definition of adsorbate and adsorbent is presented in Figure 1.

Adsorption divided into two types based on molecular interactions: physical and chemical adsorptions (Al-Ghouti & Da’ana, 2020; Kong & Adidharma, 2019). Adsorption process is widely applied and well-practiced in water treatment, purification, and separation processes. This process is also one of the most effective and promising techniques, supported by facile, technically feasible, and economical processes (Rahmani & Sasani, 2016; Hegazi, 2013).

One of the important factors in the adsorption is adsorption isotherm. The relationship in the adsorption isotherm explains the phenomena and interactions between adsorbate and adsorbent. Generally, the adsorption performance can be predicted by modeling the adsorption isotherm data because the adsorption isotherm model can provide information about the adsorbent capacity, the adsorption mechanism, and the evaluation of the adsorption process performance (Nandiyanto et al., 2020a; Anshar & Raya, 2016). In previous studies, we have performed isotherm analysis on various adsorbent systems (Nandiyanto et al., 2020a; Nandiyanto et al., 2020b; Nandiyanto et al., 2020c; Nandiyanto et al., 2020d). In this study, we used the most widely applied isotherm models to evaluate adsorption performance, such as Langmuir, Freundlich, Temkin, Dubinin-Radushkevich, Florry-Huggins, Fowler-Guggenheim, Hill-Deboer, Jovanovic, Harkin-Jura, and Halsey, while other researches only described the theory and the calculation method was not discussed deeply. This study was also completed with the calculation strategies for getting the parameters in the adsorption isotherm.

Figure 1. Illustration of monolayer (a) and multilayer (b) adsorption process (Rina Maryanti et al., 2020)
2. ADSORPTION ISOTHERM THEORY

2.1. Langmuir Isotherm

Langmuir isotherm defines that the maximum adsorbent capacity occurs due to the presence of a single layer (monolayer) of adsorbate on the adsorbent surface. There are four assumptions in this type of isotherm, namely (Langmuir, 1918):

a. The molecules are adsorbed by a fixed site (the reaction site at the adsorbent surface).
b. Each site can "hold" one adsorbate molecule.
c. All sites have the same energy.
d. There is no interaction between the adsorbed molecules and the surrounding sites. Adsorption process form monolayer. Illustration of monolayer formation during adsorption is shown in Figure 1 (a).

Langmuir isotherm model is represented by equation (1):

\[ \frac{1}{Q_e} = \frac{1}{Q_{max}K_L} C_e + \frac{1}{Q_{max}} \]  

(1)

where \( Q_e \) is the amount of adsorbed adsorbate molecule per gram of adsorbent (mg/g), \( Q_{max} \) is the capacity of the adsorbent monolayer (mg/g), \( C_e \) is the adsorbate equilibrium concentration (mg/L), and \( K_L \) is the Langmuir adsorption constant.

The important factor in the Langmuir isotherm is the dimensionless constant or separation factor \( R_L \) (Langmuir, 1918) which is expressed by equation (2):

\[ R_L = \frac{1}{1+K_L C_e} \]  

(2)

This separation factor has the following values:

(i) \( R_L > 1 \), unfavorable adsorption process (allows the adsorption process to occur, most desorption processes occur).
(ii) \( R_L = 1 \), linear adsorption process (depending on the amount adsorbed and the concentration adsorbed).
(iii) \( R_L = 0 \), Irreversible adsorption process (strong adsorption).

2.2. Freundlich Isotherm

Freundlich isotherm describes a physical type of adsorption in which the adsorption occurs in several layers and the bonds are not strong (multilayer). Multilayer formation is illustrated in Figure 1 (b). Freundlich isotherm also assumes that the sites of adsorption are heterogeneous (Dada et al., 2012). The empirical relationship for expressing Freundlich isotherm is given in equation (3):

\[ \ln Q_e = \ln K_f + \frac{1}{n} \ln C_e \]  

(3)

where \( K_f \) is Freundlich constant, \( C_e \) is the concentration of adsorbate under equilibrium conditions (mg/L), \( Q_e \) is the amount of adsorbate absorbed per unit of adsorbent (mg/g), and \( n \) is the value indicating the degree of linearity between the adsorbate solution and the adsorption process (Dada et al., 2012). The value of \( n \) is described as follows:

(i) \( n = 1 \), linear adsorption.
(ii) \( n < 1 \), adsorption process with chemical interaction.
(iii) \( n > 1 \), adsorption process with physical interaction.
(iv) Favorable adsorption process is declared when \( 0 < 1/n < 1 \), and a cooperative adsorption process occurs when \( 1/n > 1 \).

2.3. Temkin Isotherm

Temkin isotherm assumes three postulates, namely that the adsorption heat decreases linearly with increasing surface adsorbent coverage, the adsorption process assumes a uniform binding energy distribution on the adsorbent surface, and the adsorption interaction involves the interaction between adsorbate-adsorbent (Romero-Gonzales et al., 2005). Temkin isotherm is given in equation (4):

\[ 0 < R_L < 1 \], Favorable adsorption process (normal adsorption). \]
The linear correlation of the Jovanovic model is shown in equation (8):

\[
\ln Q_e = \ln Q_{\text{max}} - K_J C_e
\]  

where \( Q_e \) is the amount of adsorbate in the adsorbent at equilibrium (mg/g), \( Q_{\text{max}} \) is the maximum uptake of adsorbate, and \( K_J \) is the Jovanovic constant.

2.6. Halsey Isotherm

Halsey isotherm evaluates a multilayer adsorption system (Dada et al., 2012). The Halsey model follows equation (9):

\[
Q_e = \frac{1}{n_H} \ln K_H - \left( \frac{1}{n_H} \right) \ln C_e
\]  

where \( K_H \) dan \( n \) are the Halsey model constants.

2.7. Harkin-Jura Isotherm

Harkin-Jura isotherm describes that the adsorption occurring on the adsorbent surface is a multilayer adsorption because the adsorbent has a heterogeneous pore distribution (Ayawei et al., 2017). This model is expressed by equation (10):

\[
\frac{1}{q_e^2} = \beta_{HJ} A_{HJ} - \left( \frac{1}{A} \right) \log C_e
\]  

where \( \beta_{HJ} \) value is related to specific surface area of adsorbent and \( A_{HJ} \) are the Harkin Jura isotherm constants.

The modification of the Harkin-Jura equation (equation 10) is used to determine the surface area of the adsorbent. The modified Harkin-Jura equation is written in equation (11).

\[
\beta_{HJ} = \frac{-q(S^2)}{4.606RTN}
\]  

Where \( q \) is the constant independent of the nature of the adsorbent, \( S \) is the specific surface area \( \left( \frac{m^2}{g} \right) \), \( R \) is the universal gas constant \( \left( 8.314 \frac{1}{\text{mol} \cdot \text{K}} \right) \), \( T \) is the absolute temperature, and \( N \) is the Avogadro number.
Then, the specific surface area of adsorbent is determined by equation (12).

\[ S^2 = -\frac{\beta_{HJ} \times 4.606 \times RTN}{q} \]  

(12)

For surface area calculations, Table 1 shows several of q value.

Table 1. List of q value various material. Recalculated from reference (Shanavas et al., 2011; Nandiyanto et al., 2020g)

| Material       | T (K) | \( q(\frac{m^2}{g}) \) |
|----------------|-------|-------------------------|
| Carbon         | 298   | 1.053 \times 10^{21}    |
|                | 308   | 1.760 \times 10^{21}    |
|                | 313   | 1.727 \times 10^{21}    |
|                | 318   | 1.677 \times 10^{21}    |
|                | 323   | 1.662 \times 10^{21}    |
|                | 328   | 1.664 \times 10^{21}    |
| Titanium       | 308   | 1.011 \times 10^{24}    |
| Dioxide        | 313   | 6.631 \times 10^{23}    |
|                | 318   | 4.552 \times 10^{23}    |
|                | 323   | 4.553 \times 10^{23}    |
|                | 328   | 2.633 \times 10^{23}    |
| Silica         | 298   | 3.436 \times 10^{22}    |
| Tungsten Trioxide (WO\(_3\)) | 298 | 1.141 \times 10^{24} |

2.8. Flory-Huggins Isotherm

Flory-Huggins isotherm takes into account the degree of surface coverage of the adsorbate on the adsorbent. This isotherm also assumes that the adsorption process occurs spontaneously (Saadi et al., 2015). Flory-Huggins isotherm is expressed by equation (13):

\[ \log \frac{\theta}{C_e} = \log K_{FH} + n \log(1 - \theta) \]  

(13)

where \( \theta = (1 - \frac{C_e}{C_\theta}) \) is the degree of surface coverage, \( K_{FH} \) is the Flory–Huggins model equilibrium constant and \( n_{FH} \) is the number of adsorbates occupying adsorption site. Furthermore, the Gibbs free energy of spontaneity \( (\Delta G^0) \) is calculated from the equilibrium constant \( (K_{FH}) \). The value of \( \Delta G^0 \) corresponds to the \( K_{FH} \) value as shown in equation (14):

\[ \Delta G^0 = -RT \ln K_{FH} \]  

(14)

The negative sign on the value \( \Delta G^0 \) confirms that the adsorption process is spontaneous, which is a function of temperature \( (T) \).

2.9. Fowler-Guggenheim Isotherm

Fowler-Guggenheim isotherm suggests that there is a lateral interaction at a set of localized sites with weak interactions (Van der Waals interaction effect) between adsorbed species at neighboring sites (Hamdaoui and Naffrechoux, 2007). The empirical relationship of Fowler-Guggenheim model is expressed by equation (15):

\[ \ln \left( \frac{C_e(1-\theta)}{\theta} \right) - \frac{\theta}{1-\theta} = -\ln K_{FG} + \frac{2W\theta}{RT} \]  

(15)

where \( K_{FG} \) is the constant, \( W \) (kJ/mol) for the adsorbed adsorbate at the active site representing the interaction between the adsorbate and the adsorbent, \( C_e \) is the equilibrium constant, \( W \) is the empirical interaction energy between two adsorbed molecules at the adjacent neighboring site (kJ/mol), and \( \theta \) is the fractional coverage of the surface. The empirical interaction energy \( (W) \) has the following value:

(i) If \( W > 0 \) kJ/mol, attractive interaction between adsorbed molecule.
(ii) If \( W < 0 \) kJ/mol, repulsive interaction between adsorbed molecule.
(iii) If \( W = 0 \) kJ/mol, no interaction between adsorbed molecule.
2.10. Hill-Deboer Isotherm

Hill-Deboer isotherm describes mobile adsorption and bilateral interactions between adsorbed molecules (Hamdaoui and Naffrechoux, 2007). Hill-Deboer isotherm approach is written in equation (16):

\[
\ln \left[ \frac{C_e(1-\theta)}{\theta} \right] - \frac{\theta}{1-\theta} = -lnK_1 - \frac{K_2 \theta}{RT} \tag{16}
\]

where \(K_1\) is the Hill-Deboer constant (L/mg) and \(K_2\) is the energetic constant of the interactions between adsorbed molecules (kJ/mol):

(i) \(K_2 > 0\) kJ/mol, attraction between adsorbed molecules.

(ii) \(K_2 < 0\) kJ/mol, repulsion between adsorbed molecules.

(iii) \(K_2 = 0\) kJ/mol, no interaction between adsorbed molecules.

The quantity adsorbed by the unit mass of the adsorbent at equilibrium \((Q_e)\) is calculated using equation (17):

\[
Q_e = \frac{C_0 - C_e}{m} \times V \tag{17}
\]

where \(C_0\) is the initial concentration (mg/L), \(C_e\) is the concentration at equilibrium (mg/L), \(m\) is the mass of the adsorbent (grams), and \(V\) is the volume of the adsorbate solution (L).

3. MATERIAL AND METHOD

There were several materials used as adsorbents which were the result of conversion from agricultural waste such as carbon converted from peanut shells (CPS), carbon obtained from rice husks (CRH), silica from rice husks (SRH). Inorganic materials such as tungsten (WO\(_3\)) was also used as adsorbents in this study. Detailed information on how the process of converting agricultural waste into carbon and silica and fabrication process of WO\(_3\) was presented in our previous studies (Ragadhita et al., 2019; Faindini et al., 2020; Nandiyanto et al., 2020a; Nandiyanto et al., 2020e). The adsorbate solution used as an experimental model was curcumin solution. Information on curcumin production was carried out in the same manner as provided in our previous study (Ragadhita et al., 2019; Nandiyanto et al., 2020f).

In general, the adsorption process was carried out in the following steps: specific mass amount of each CPS, CRH, SRH, and WO\(_3\) adsorbents were put into 200 mL of curcumin solution with variations concentrations of 20, 40, 60, 80 ppm at constant pH and temperature. The solution mixture was mixed in a borosilicate batch (glass reactor) with a capacity of 400 mL and has dimensions of 10 and 8 cm, respectively, for height and diameter.

Then, the solution mixture was stirred at 1000 rpm for 1 h. Next, the solution mixture was filtered. The filtrate was measured and analyzed with a UV-VIS spectrophotometer (Model 7205; JENWAY; Cole-Parmer; US; analyzed at wavelengths between 200 and 600 nm).

After the adsorption process was completed, the next step was to evaluate the adsorption process. Several adsorption isotherm models were used for the analysis of the adsorption process including Langmuir, Freundlich, Temkin, Dubinin-Radushkevich, Flory-Huggins, Fowler-Guggenheim, Hill-Deboer, Jovanovic, Halsey, and Harkin-Jura isotherms.

4. RESULTS AND DISCUSSION

4.1. Linearization and Curve Plotting to Obtain Two-Parameter Adsorption Isotherms from Several Models

The adsorption process includes a series of adsorption experiments to calculate the adsorption parameters used to express the adsorption equilibrium model. Several adsorption isotherm models were used to evaluate the adsorption process in this study are Langmuir, Freundlich, Temkin, Dubinin-Raduschkevich, Flory-Huggins, Fowler-
Guggenheim, Hill-Deboer, Jovanovic, Harkin-Jura, and Halsey isotherms. The calculation of the adsorption isotherm is carried out through data fitting to obtain a linear equation \( y = mx + c \). Then, we also need to consider the value of \( R^2 \). The greater \( R^2 \) relates to similarity data to the model proposed. The fitting of this data is adjusted to the linear expression of the mathematical model of each adsorption isotherm. From the results of the data fitting, several parameters in the adsorption process were obtained. The phenomena occurring during the adsorption were predicted. Information regarding curve data fitting, calculations, and parameters of the adsorption isotherm model that must be analyzed is presented in Table 2.

4.2. Experimental Results from The Adsorption Process

Data from the adsorption process of curcumin solution using CPS, CRH, SRH, and \( \text{WO}_3 \) adsorbents are presented in Table 3. Table 3 shows the adsorption data of curcumin solution for data fitting using two-parameter isotherm adsorptions: Langmuir, Freundlich, Temkin, Dubinin-Radushkevich, Jovanovic, Halsey, Harkin-Jura, Flory-Huggins, Fowler-Guggenheim, and Hill-Deboer isotherm.

4.3. Plotting Analysis for Adsorption Isotherms using a Two-Parameter Adsorption Isotherm

4.3.1 Langmuir

Langmuir model adsorption parameters were obtained using equation (1) as presented as \( \frac{1}{Q_e} = \frac{1}{Q_{\text{max}} K_L} \frac{1}{c_e} + \frac{1}{Q_{\text{max}}} \). To get the Langmuir model parameters, we need to convert \( c_e \) and \( Q_e \) values into the form of \( \frac{1}{c_e} \) and \( \frac{1}{Q_e} \), which are used for fitting data (see Table 2).

The curves of fitting data result from equation (1) are presented in Figures 2 (a-d). The result of fitting data was used to determine the adsorption parameters. The result of data fitting in the form of a gradient obtained is the \( \frac{1}{Q_{\text{max}} K_L} \) value and the intercept is the \( \frac{1}{Q_{\text{max}}} \) value. Table 4 show parameters of the Langmuir model using CPS, CRH, SRH, and \( \text{WO}_3 \) adsorbents.

\( Q_{\text{max}} \) and \( K_L \) in Table 4 are the maximum monolayer adsorption capacity and Langmuir adsorption constant, respectively. Based on \( Q_{\text{max}} \) value, adsorption process using CRH adsorbent is very good due to it has the highest maximum monolayer adsorption capacity \( (Q_{\text{max}}) \) value than others. Langmuir adsorption constant \( (K_L) \) shows the degree adsorbate-adsorbent interaction. Higher \( K_L \) value indicating strong adsorbate-adsorbent interaction while smaller \( K_L \) value indicating weak interaction between adsorbate molecule and adsorbent surface. The \( K_L \) value for all adsorption systems show a relatively small value means weak interaction between the absorbent and adsorbate molecules due to the active site only adsorb one molecule. Plotting analysis shows that CPS, SRH, and \( \text{WO}_3 \) have relatively high correlation value \( (R^2 > 0.70) \) than CRH, informing that CPS, SRH, and \( \text{WO}_3 \) are good represented by Langmuir isotherm.
Table 2. Information regarding curve data fitting, calculation, and isotherm parameters

| Isotherm Type | Linier Equation | Plotting | Parameter |
|---------------|----------------|----------|-----------|
| Langmuir      | \( \frac{1}{Q_e} = \frac{1}{q_{max}K_0} + \frac{1}{q_{max}} \) | \( \frac{1}{C_e} vs \frac{1}{Q_e} \) | \( \frac{1}{q_{max}} = \text{intercept} \)<br>\( q_{max} = \frac{1}{\text{intercept}} \)<br>\( K_0 = \frac{1}{q_{max} \times \text{slope}} \) |
| Freundlich    | \( \ln Q_e = \ln k_f + \frac{1}{n} \ln C_e \) | \( \ln C_e \text{vs} \ln Q_e \) | \( \ln K_F = \text{intercept} \)<br>\( k_F = e^{\text{slope}} \)<br>\( \frac{1}{n_F} = \text{slope} \)<br>\( n_F = \frac{1}{\text{slope}} \) |
| Temkin        | \( q_e = B_T \ln A_T + B_T \ln C_e \) | \( \ln C_e \text{vs} Q_e \) | \( B = \text{slope} \)<br>\( \ln A_T = \frac{\text{intercept}}{B_T} \)<br>\( B_T = \frac{RT}{B} \) |
| Dubinin-Radushkevich | \( \ln q_e = \ln q_s - \left( \beta E^2 \right) \) | \( e^2 \text{vs} \ln Q_e \) | \( \beta = K_{DR} = \text{slope} \)<br>\( E = \frac{1}{\sqrt{k_{DR}}} \) |
| Flory Huggins | \( \log \frac{\theta}{C_e} = \log K_{FH} + n \log (1 - \theta) \) | \( \log \left( \frac{\theta}{C_0} \right) \text{vs} \log (1 - \theta) \) | \( n_{FH} = \text{slope} \)<br>\( \log k_{FH} = \text{intercept} \)<br>\( K_{FH} = e^{- \text{intercept}} \)<br>\( \Delta G = RT \ln (K_{FH}) \)<br>\( \theta = 1 - \frac{C_0}{C} \) |
| Fowler-Guggenheim | \( \ln \left( \frac{C_e (1 - \theta)}{\theta} \right) - \frac{\theta}{1 - \theta} = -\ln K_{FG} + \frac{2W \theta}{RT} \) | \( \theta \text{vs} \ln \left[ \frac{C_e (1 - \theta)}{\theta} \right] \) | \( W = \text{slope} \)<br>\( -\ln K_{FG} = \text{intercept} \)<br>\( K_{FG} = e^{-\text{intercept}} \)<br>\( \alpha (\text{slope}) = \frac{2W \theta}{RT} \)<br>\( W = \frac{RT}{2 \theta} \)<br>\( \theta = 1 - \frac{C_0}{C} \) |
| Hill-Deboer   | \( \ln \left[ \frac{C_e (1 - \theta)}{\theta} \right] - \frac{\theta}{1 - \theta} = -\ln K_1 - \frac{k_2 \theta}{RT} \) | \( \theta \text{vs} \ln \left[ \frac{C_e (1 - \theta)}{\theta} \right] \) | \( -\ln k_1 = \text{intercept} \)<br>\( \alpha (\text{slope}) = \frac{k_2 \theta}{RT} \)<br>\( k_2 = \frac{RT}{\theta} \)<br>\( \theta = 1 - \frac{C_0}{C} \) |
| Jovanovic     | \( \ln q_e = \ln q_{max} - K_f C_e \) | \( C_e \text{vs} \ln Q_e \) | \( K_f = \text{slope} \)<br>\( \ln q_{max} = \text{intercept} \)<br>\( Q_{max} = e^{\text{intercept}} \) |
| Harkin-Jura   | \( \frac{1}{q_e} = \frac{\beta}{A} - \left( \frac{1}{A} \right) \log C_e \) | \( \log C_e \text{vs} \frac{1}{q_e^2} \) | \( A_H = \frac{1}{\text{slope}} \)<br>\( \frac{\beta H}{A_H} = \text{intercept} \) |
| Halsey        | \( \ln Q_e = \frac{1}{n_H} \ln K_H - \frac{1}{n_H} \ln C_e \) | \( \ln C_e \text{vs} \ln Q_e \) | \( \frac{1}{n_H} = \text{slope} \)<br>\( \frac{1}{n_H} = \text{slope} \)<br>\( n_H = \text{slope} \)<br>\( \ln K_H = \text{intercept} \)<br>\( K_H = e^{\text{intercept}} \) |

DOI: https://doi.org/10.17509/ijnst.v6i1.32354
Table 3. Curcumin solution adsorption data using CPS, CRH, SRH, and WO₃ adsorbents

| Adsorbent | Cᵢ (ppm) | Cₑ (ppm) | qₑ (mg/L) | ε²  | θ    |
|-----------|----------|----------|-----------|-----|------|
| CPS       | 15       | 15       | 1.45      | 14.43 | 0.045 |
|           | 47       | 45       | 3.93      | 6.31  | 0.042 |
|           | 62       | 61       | 2.38      | 3.65  | 0.019 |
|           | 80       | 73       | 13.40     | 3.06  | 0.084 |
| CRH       | 21       | 18       | 4.80      | 11.85 | 0.114 |
|           | 41       | 39       | 3.60      | 7.19  | 0.044 |
|           | 59       | 55       | 8.50      | 4.06  | 0.072 |
|           | 78       | 62       | 32.90     | 3.61  | 0.209 |
| SRH       | 24       | 22       | 3.40      | 9.796 | 0.069 |
|           | 40       | 35       | 7.50      | 7.930 | 0.096 |
|           | 50       | 42       | 13.00     | 5.233 | 0.132 |
|           | 76       | 64       | 22.70     | 3.473 | 0.149 |
|           | 91       | 78       | 42.50     | 2.862 | 0.135 |
| WO₃       | 20       | 19       | 2.00      | 11.64 | 0.049 |
|           | 37       | 35       | 4.00      | 8.086 | 0.054 |
|           | 62       | 58       | 8.60      | 3.859 | 0.069 |
|           | 78       | 73       | 10.60     | 3.079 | 0.068 |

Table 4. Langmuir isotherm parameters using \( \frac{1}{Q_e} = \frac{1}{Q_{max}} + \frac{1}{Q_{max}K_L C_e} \)

| Adsorbent | \( \frac{1}{C_e} \) | \( \frac{1}{Q_e} \) | \( Q_{max} \) (mg/g) | \( K_L \) (L/mg) | \( R_L \) | \( R^2 \) | Note |
|-----------|----------------------|----------------------|-----------------------|-----------------|---------|--------|------|
| CPS       | 0.066                | 0.689                | 11.037                | 0.009           | 0.992-0.996 | 0.7374 | • 0 < \( R_L \) < 1, favorable adsorption  
 |           | 0.022                | 0.254                |                       |                 |         |        |       |
|           | 0.016                | 0.420                |                       |                 |         |        |       |
|           | 0.013                | 0.075                |                       |                 |         |        |       |
| CRH       | 0.053                | 0.208                | 14.684                | 0.021           | 0.954-0.988 | 0.2664 | • 0 < \( R_L \) < 1, favorable adsorption  
 |           | 0.025                | 0.278                |                       |                 |         |        |       |
|           | 0.018                | 0.117                |                       |                 |         |        |       |
|           | 0.016                | 0.030                |                       |                 |         |        |       |
| SRH       | 0.044                | 0.297                | 11.274                | 0.010           | 0.948-0.988 | 0.958  | • 0 < \( R_L \) < 1, favorable adsorption  
 |           | 0.028                | 0.133                |                       |                 |         |        |       |
|           | 0.023                | 0.077                |                       |                 |         |        |       |
|           | 0.015                | 0.044                |                       |                 |         |        |       |
|           | 0.013                | 0.041                |                       |                 |         |        |       |
| WO₃       | 0.053                | 0.500                | 14.164                | 0.006           | 0.213-0.520 | 0.9876 | • 0 < \( R_L \) < 1, favorable adsorption  
 |           | 0.028                | 0.250                |                       |                 |         |        |       |
|           | 0.021                | 0.125                |                       |                 |         |        |       |
|           | 0.017                | 0.116                |                       |                 |         |        |       |
|           | 0.014                | 0.094                |                       |                 |         |        |       |
4.3.2. Freundlich

The Freundlich model adsorption parameters were obtained using equation (3) as presented as \( \ln Q_e = \ln k_F + \frac{1}{n} \ln C_e \). To get the Freundlich model parameters, we need to convert \( C_e \) and \( Q_e \) values into the form of \( \ln C_e \) and \( \ln Q_e \), which are used for fitting data (see Table 2). The curves of data fitting result are presented in Figures 3 (a-d). The result of fitting data also used to determine adsorption parameters. The result of data fitting in the form of a gradient obtained is \( \frac{1}{n} \) value, and the intercept is \( \ln k_F \) value. Table 5 shows parameter results of Freundlich model using CPS, CRH, SRH, and WO\(_3\) adsorbents. Freundlich isotherm is good represent of SRH and WO\(_3\) adsorption systems than CPS and CRH adsorption system, this is confirmed by the \( R^2 \) value of higher than 0.70. Thus, SRH and WO\(_3\) adsorption system were assumed that adsorption process occurs in heterogeneous surface in multilayer form with weak adsorbate and adsorbent interaction.
Table 5. Freundlich isotherm parameters using $\ln Q_e = \ln k_f + \frac{1}{n} \ln C_e$

| Adsorbent | $\ln C_e$ | $\ln Q_e$ | $\frac{1}{n}$ | $n$ | $R^2$ | Note |
|-----------|-----------|-----------|-------------|-----|-------|------|
| CPS       | 2.723     | 0.371     | 1.0068      | 0.993 | 0.5567 | $\frac{1}{n} > 1$, cooperative adsorption |
|           | 3.819     | 1.369     |             |      |       | $n < 1$, chemical interaction between adsorbate molecules |
|           | 4.121     | 0.867     |             |      |       | $R^2 < 0.70$, monolayer adsorption |
|           | 4.301     | 2.595     |             |      |       |                          |
| CRH       | 2.926     | 1.568     | 1.1841      | 0.844 | 0.4286 | $\frac{1}{n} > 1$, cooperative adsorption |
|           | 3.676     | 1.281     |             |      |       | $n < 1$, chemical interaction between adsorbate molecules |
|           | 4.013     | 2.140     |             |      |       | $R^2 < 0.70$, monolayer adsorption |
|           | 4.132     | 3.493     |             |      |       |                          |
| SRH       | 3.121     | 1.214     | 1.6486      | 0.606 | 0.9687 | $\frac{1}{n} > 1$, cooperative adsorption |
|           | 3.567     | 2.015     |             |      |       | $n < 1$, chemical interaction between adsorbate molecules |
|           | 3.758     | 2.565     |             |      |       | $R^2 > 0.70$, multilayer adsorption |
|           | 4.172     | 3.122     |             |      |       |                          |
|           | 4.367     | 3.199     |             |      |       |                          |
| WO$_3$    | 2.945     | 0.693     | 1.2962      | 0.771 | 0.9714 | $\frac{1}{n} > 1$, cooperative adsorption |
|           | 3.556     | 1.386     |             |      |       | $n < 1$, chemical interaction between adsorbate molecules |
|           | 3.865     | 2.080     |             |      |       | $R^2 > 0.70$, multilayer adsorption |
|           | 4.065     | 2.152     |             |      |       |                          |
|           | 4.293     | 2.361     |             |      |       |                          |

Figure 3. Freundlich isotherm model for adsorption system using a) CPS, b) CRH, c) SRH, and d) WO$_3$ adsorbents
4.3.4. Dubinin-Radushkevich

Dubinin-Radushkevich model adsorption parameters were obtained using equation (5) as follows: \( \ln q_e = \ln q_m - (\beta \varepsilon^2) \). To get the Dubinin-Radushkevich model parameters, we need to convert \( q_e \) and \( Q_e \) into the form of \( \ln Q_e \) value and looking for the \( \varepsilon^2 \) value which are used for data fitting (see Table 2). The curves of data fitting result are presented in Figures 5 (a-d). The result of data fitting also used to determine adsorption parameter. The result of data fitting in the form of a gradient obtained is the \( \beta \) value to calculate \( E \) value. Table 7 shows parameter results of Dubinin-Radushkevich using CPS, CRH, SRH, and WO\(_3\) adsorbents. Parameter \( \beta \) in Table 7 is Dubinin-Radushkevich isotherm constant related saturation capacity. High \( \beta \) value shows high adsorption capacity. Based on \( \beta \) parameter, WO\(_3\) has higher \( \beta \) value while CRH has smaller \( \beta \) value than others. \( \beta \) value influenced by pore volume. The larger pore volume impact on highest maximum binding energy value. Plotting data of Dubinin-Radushkevich show that SRH and WO\(_3\) adsorption system have the best correlation coefficient since correlation coefficient value is high \( (R^2 > 0.70) \). Thus, SRH and WO\(_3\) adsorption system are considered by Dubinin-Radushkevich have adsorbent size proportional to the micropore size.

4.3.5. Jovanovic

Jovanovic model adsorption parameters were obtained using equation (8) as presented as \( \ln q_e = \ln q_{max} - K_f C_e \). To get the Jovanovic model parameters, we need \( C_e \) data and we need to convert \( Q_e \) into the form of \( \ln Q_e \) which are used for data fitting (see Table 2). The curves of fitting data are presented in Figures 6 (a-d). The result of fitting data also used to determine adsorption parameter. The result of data fitting in the form of a gradient obtained is the \( K_f \) value and intercept is the \( \ln Q_{max} \) value. Table 8 shows parameters of Jovanovic using CPS, CRH, SRH, and WO\(_3\) adsorbents. \( K_f \) and \( Q_{max} \) in Table 8 are the Jovanovic constant and the maximum uptake of adsorbate molecule. \( Q_{max} \) related with how much adsorbates are absorbed by a particular adsorbent where the higher \( Q_{max} \) value shows better adsorbent capacity. CRH and SRH adsorbents showed identically small adsorption capacity \( (Q_{max}) \) value as well as CPS and WO\(_3\). Based on Dubinin-Radushkevich isotherm, WO\(_3\) and CPS adsorbent shows high adsorption capacity. This condition is possible due to surface active site is efficient in adsorbing the adsorbate molecule although it has small...
surface area and pore. The Jovanovic isotherm reflects well the entire adsorption system (i.e., CPS, CRH, SRH, and WO₃) which is shown from the relatively high correlation coefficient value of each adsorption system ($R^2 > 0.70$). Compatibility with Jovanovic’s model indicates that there is existence of monolayer adsorption.

| Adsorbent | $\ln C_e$ | $Q_e$ | $A_T \frac{L}{g}$ | $B_T \frac{J}{mol}$ | $R^2$   | Note                                |
|-----------|-----------|-------|-------------------|---------------------|---------|-------------------------------------|
| CPS       | 2.723     | 1.45  | 0.025             | 144.97              | 0.4851  | • $B_T < 8$ kJ/mol, physical interaction between adsorbate molecules  
            | 3.819     | 3.93  |                   |                     |         | • $R^2 < 0.70$, no uniform distribution adsorbate to adsorbent surface   |
|           | 4.121     | 2.38  |                   |                     |         |                                     |
|           | 4.301     | 13.40 |                   |                     |         |                                     |
| CRH       | 2.926     | 4.80  | 0.026             | 46.528              | 0.6465  | • $B_T < 8$ kJ/mol, physical interaction between adsorbate molecules  
            | 3.676     | 3.60  |                   |                     |         | • $R^2 < 0.70$, no uniform distribution adsorbate to adsorbent surface   |
|           | 4.013     | 8.50  |                   |                     |         |                                     |
|           | 4.132     | 32.90 |                   |                     |         |                                     |
| SRH       | 3.121     | 3.40  | 0.038             | 99.573              | 0.9973  | • $B_T < 8$ kJ/mol, physical interaction between adsorbate molecules  
            | 3.567     | 7.50  |                   |                     |         | • $R^2 > 0.70$, uniform distribution adsorbate to adsorbent surface      |
|           | 3.758     | 13.00 |                   |                     |         |                                     |
|           | 4.172     | 22.70 |                   |                     |         |                                     |
|           | 4.367     | 24.50 |                   |                     |         |                                     |
| WO₃       | 2.945     | 2.00  | 0.045             | 264.64              | 0.9216  | • $B_T < 8$ kJ/mol, physical interaction between adsorbate molecules  
            | 3.556     | 4.00  |                   |                     |         | • $R^2 > 0.70$, uniform distribution adsorbate to adsorbent surface      |
|           | 3.865     | 8.01  |                   |                     |         |                                     |
|           | 4.065     | 8.60  |                   |                     |         |                                     |
|           | 4.293     | 10.60 |                   |                     |         |                                     |

**Table 6.** Temkin isotherm parameters using $q_e = B_T \ln A_T + B_T \ln C_e$
4.3.6. Halsey

Halsey model adsorption parameters were obtained using equation (9) as presented as $lnQ_e = \frac{1}{n_H}lnK_H - \frac{1}{n}lnC_e$. To get the Halsey model parameters, we need to convert $C_e$ and $Q_e$ data into the form of $lnC_e$ and $lnQ_e$, which are used for data fitting (see Table 2). The curves of data fitting result are presented in Figures 7 (a-d). The result of data fitting also used to determine the adsorption parameter. The result of data fitting in the form of a gradient obtained is the $\frac{1}{n}$ value and intercept is the $\frac{1}{n}lnK_H$ value. Table 9 shows parameter results of Halsey using CPS, CRH, SRH, and WO$_3$ adsorbents. $K_H$ and $n$ in Table 9 are the Halsey isotherm constants. Halsey isotherm reflect good adsorption system for SRH and WO$_3$ since ($R^2 > 0.70$) is relatively high. While, CPS and CRH adsorption system are not suitable with Halsey isotherm. Compatibility with Halsey model due to high $R^2$ indicates that there is existence of multilayer adsorption. From Halsey's parameter, we can identify that the higher the adsorption capacity ($Q_e$) correlates with the increase in the value of $n$. 

Figure 4. Temkin isotherm model for adsorption system using a) CPS, b) CRH, c) SRH, and d) WO$_3$ adsorbents

Table 9 shows parameter results of Halsey using CPS, CRH, SRH, and WO$_3$ adsorbents. $K_H$ and $n$ in Table 9 are the Halsey isotherm constants. Halsey isotherm reflect good adsorption system for SRH and WO$_3$ since ($R^2 > 0.70$) is relatively high. While, CPS and CRH adsorption system are not suitable with Halsey isotherm. Compatibility with Halsey model due to high $R^2$ indicates that there is existence of multilayer adsorption. From Halsey's parameter, we can identify that the higher the adsorption capacity ($Q_e$) correlates with the increase in the value of $n$. 

DOI: https://doi.org/10.17509/ijost.v6i1.32354
Table 7. Dubinin-Radushkevich isotherm parameters $ln q_e = ln q_s - (\beta \varepsilon^2)$

| Adsorbent | $ln Q_e$ | $\varepsilon^2$ | $\beta$ ($\text{mol}^2$/$\text{kJ}^2$) | $E$ ($\text{kJ/mol}$) | $R^2$ | Note |
|-----------|----------|----------------|---------------------------------|---------------------|-------|------|
| CPS       | 1.369    | 3.88328        | 0.358                           | 0.4996              |       | • $E < 8 \text{kJ/mol}$, physical interaction between adsorbate molecules |
|           | 0.867    | 6.31           |                                 |                     |       | • $R^2 < 0.70$, no micropore size is exist in adsorbent surface |
| CRH       | 2.595    | 3.65           | 1.568                           | 11.85               | 2.6092| 0.438 | 0.455 | • $E < 8 \text{kJ/mol}$, physical interaction between adsorbate molecules |
|           | 3.493    | 3.61           |                                 |                     |       | • $R^2 < 0.70$, no micropore size is exist in adsorbent surface |
| SRH       | 1.214    | 3.5364         | 1.281                           | 7.930               | 0.376 | 0.9829|       | • $E < 8 \text{kJ/mol}$, physical interaction between adsorbate molecules |
|           | 2.015    | 7.19           |                                 |                     |       | • $R^2 > 0.70$, micropore size is exist in adsorbent surface |
|           | 2.140    | 4.06           |                                 |                     |       |       |       | |
|           | 3.122    | 3.473          |                                 |                     |       |       |       | |
|           | 3.199    | 2.862          |                                 |                     |       |       |       | |
| WO₃       | 0.693    | 5.1626         | 2.015                           | 11.64               | 0.311 | 0.9976|       | • $E < 8 \text{kJ/mol}$, physical interaction between adsorbate molecules |
|           | 1.386    | 8.086          |                                 |                     |       | • $R^2 > 0.70$, micropore size is exist in adsorbent surface |
|           | 2.080    | 4.708          |                                 |                     |       |       |       | |
|           | 2.152    | 3.859          |                                 |                     |       |       |       | |
|           | 2.361    | 3.079          |                                 |                     |       |       |       | |

Figure 5. Dubinin-Radushkevich isotherm model for adsorption system using a) CPS, b) CRH, c) SRH, and d) WO₃ adsorbents

DOI: https://doi.org/10.17509/ijost.v6i1.32354
p- ISSN 2528-1410 e- ISSN 2527-8045
Table 8. Jovanovic isotherm parameter using \( \ln q_e = \ln q_{max} - K_f C_e \)

| Adsorbent | \( C_e \) | \( \ln Q_e \) | \( K_f \left( \frac{L}{mg} \right) \) | \( q_{max} \left( \frac{mg}{g} \right) \) | \( R^2 \) | Note |
|-----------|-------|-------------|-----------------|-----------------|-------|------|
| CPS       | 15    | 0.371       | 0.3331          | 1.508           | 0.936 | \( R^2 > 0.70 \), the existence of monolayer on the surface of adsorbent |
|           | 47    | 1.369       |                 |                 |       |      |
|           | 62    | 0.867       |                 |                 |       |      |
|           | 73    | 2.595       |                 |                 |       |      |
| CRH       | 18    | 1.568       | 0.139           | 3.502           | 0.9526| \( R^2 > 0.70 \), the existence of monolayer on the surface of adsorbent |
|           | 39    | 1.281       |                 |                 |       |      |
|           | 55    | 2.140       |                 |                 |       |      |
|           | 62    | 3.493       |                 |                 |       |      |
| SRH       | 22    | 1.214       | 0.1727          | 3.294           | 0.9357| \( R^2 > 0.70 \), the existence of monolayer on the surface of adsorbent |
|           | 35    | 2.015       |                 |                 |       |      |
|           | 42    | 2.565       |                 |                 |       |      |
|           | 64    | 3.122       |                 |                 |       |      |
|           | 78    | 3.199       |                 |                 |       |      |
| WO₃       | 19    | 0.693       |                 |                 |       | \( R^2 > 0.70 \), the existence of monolayer on the surface of adsorbent |
|           | 35    | 1.386       |                 |                 |       |      |
|           | 47    | 2.080       | 0.3755          | 1.614           | 0.9602|       |
|           | 58    | 2.152       |                 |                 |       |      |
|           | 73    | 2.361       |                 |                 |       |      |

Figure 6. Jovanovic isotherm model for adsorption system using a) CPS, b) CRH, c) SRH, and d) WO₃ adsorbents

DOI: https://doi.org/10.17509/ijost.v6i1.32354
p- ISSN 2528-1410 e- ISSN 2527-8045
Table 9. Halsey isotherm parameters using $lnQ_e = \frac{1}{nH}lnK_H - \frac{1}{n}lnC_e$

| Adsorbent | $lnC_e$ | $lnQ_e$ | $\frac{1}{n}$ | $n$ | $K_H$ | $R^2$ | Note |
|-----------|---------|---------|---------------|-----|-------|-------|------|
| CPS       | 2.723   | 0.371   | 1.0068        | 0.992 | 0.086 | 0.5567 | $R^2 < 0.70$, the existence of monolayer on the surface of adsorbent |
|           | 3.819   | 1.369   |               |      |       |       |      |
|           | 4.121   | 0.867   |               |      |       |       |      |
|           | 4.301   | 2.595   |               |      |       |       |      |
| CRH       | 2.926   | 1.568   | 1.1841        | 0.844 | 0.150 | 0.4286 | $R^2 < 0.70$, the existence of monolayer on the surface of adsorbent |
|           | 3.676   | 1.281   |               |      |       |       |      |
|           | 4.013   | 2.140   |               |      |       |       |      |
|           | 4.132   | 3.493   |               |      |       |       |      |
| SRH       | 3.121   | 1.214   | 1.6486        | 0.607 | 0.097 | 0.9687 | $R^2 > 0.70$, the existence of multilayer on the surface of adsorbent |
|           | 3.567   | 2.015   |               |      |       |       |      |
|           | 3.758   | 2.565   |               |      |       |       |      |
|           | 4.172   | 3.122   |               |      |       |       |      |
|           | 4.367   | 3.199   |               |      |       |       |      |
| WO₃       | 2.945   | 0.693   |               |      |       |       |      |
|           | 3.556   | 1.386   |               |      |       |       |      |
|           | 3.865   | 2.080   | 1.2962        | 0.771 | 0.090 | 0.9714 | $R^2 > 0.70$, the existence of multilayer on the surface of adsorbent |
|           | 4.065   | 2.152   |               |      |       |       |      |
|           | 4.293   | 2.361   |               |      |       |       |      |

Figure 7. Halsey isotherm model for adsorption system using a) CPS, b) CRH, c) SRH, and d) WO₃ adsorbents
4.3.7. Harkin-Jura

Harkin-Jura model adsorption parameters were obtained using equation (10) as presented as \( \frac{1}{q_e} = \frac{B}{A} - \left( \frac{1}{A} \right) \log C_e \). To get the Harkin-Jura model parameters, we need to convert \( C_e \) and \( Q_e \) data into the form of \( \log C_e \) and \( \frac{1}{q_e^2} \) which are used for data fitting (see Table 2). The curves of data fitting result are presented in Figures 8 (a-d). The result of data fitting also used to determine adsorption parameter. The result of data fitting in the form of a gradient obtained is the \( \frac{B}{A} \) value and intercept is the \( \frac{B}{A} \) value.

Table 10 shows parameter results of Harkin-Jura using CPS, CRH, SRH, and WO\(_3\) adsorbents. \( B \) and \( A \) in Table 10 are Harkin-Jura constants. Based on \( R^2 \) adsorption using CPS, SRH, WO\(_3\) adsorbent is suitable since \( R^2 > 0.70 \). From the Harkin-Jura parameter, we can identify that the higher values of parameters of \( A_{HJ} \) and \( \beta_{HJ} \), the worse the adsorption capacity (\( Q_e \)). The Harkin-Jura model also explains the theoretical surface area by using equation (12) as presented as \( S^2 = - \frac{\beta \times 6.606RTN}{q} \). For example, if we use the assumption of \( q \) value of carbon, silica, and WO\(_3\) as in Table 1, and the temperature used is room temperature (298 K), then the surface area value is presented in Table 11.

**Table 10.** Harkin-Jura isotherm parameters using \( \frac{1}{q_e} = \frac{B}{A} - \left( \frac{1}{A} \right) \log C_e \)

| Adsorbent | \( \log C_e \) | \( \frac{1}{q_e^2} \) | slope | intercept | \( \beta_{HJ} \) | \( A_{HJ} \) | \( R^2 \) | Note |
|-----------|----------------|-----------------|-------|------------|---------------|-------------|-------|------|
| CPS       | 1.183          | 0.476           |       | 1.2003     | 1.593         | 1.912       | 0.85  | \( R^2 > 0.70 \), the existence of multilayer on the surface of adsorbent |
|           | 1.659          | 0.065           |       |            |               |             |       |      |
|           | 1.790          | 0.176           | -0.6275 | 1.593     | 1.912         | 0.85        |       |      |
|           | 1.868          | 0.005           |       |            |               |             |       |      |
| CRH       | 1.270          | 0.043           |       | 0.0754     | 0.1545        | 13.262      | 0.1545 | 0.2747 | \( R^2 < 0.70 \), the existence of monolayer on the surface of adsorbent |
|           | 1.596          | 0.077           |       |            |               |             |       |      |
|           | 1.743          | 0.014           | -0.0754 | 0.1545    | 13.262        | 0.1545      | 0.2747 |       |
|           | 1.795          | 0.001           |       |            |               |             |       |      |
| SRH       | 1.355          | 0.088           |       | -0.1469    | 0.2654        | 6.807       | 0.3654 | 0.7261 | \( R^2 > 0.70 \), the existence of multilayer on the surface of adsorbent |
|           | 1.549          | 0.018           |       |            |               |             |       |      |
|           | 1.632          | 0.006           | -0.1469 | 0.2654    | 6.807         | 0.3654      | 0.7261 |       |
|           | 1.812          | 0.002           |       |            |               |             |       |      |
|           | 1.897          | 0.002           |       |            |               |             |       |      |
| WO\(_3\)  | 1.279          | 0.250           |       | -0.4226    | 0.7575        | 2.366       | 0.7575 | 0.8704 | \( R^2 > 0.70 \), the existence of multilayer on the surface of adsorbent |
|           | 1.544          | 0.062           |       |            |               |             |       |      |
|           | 1.679          | 0.015           | -0.4226 | 0.7575    | 2.366         | 0.7575      | 0.8704 |       |
|           | 1.766          | 0.013           |       |            |               |             |       |      |
|           | 1.864          | 0.009           |       |            |               |             |       |      |
Figure 8. Harkin-Jura isotherm model for adsorption system using a) CPS, b) CRH, c) SRH, and d) WO₃ adsorbent

Table 1. Calculation of the surface area with the Harkin-Jura model using equations $S^2 = \frac{-\beta \times 4.606RTN}{q}$

| Adsorbent | $\beta$ | $4.606RTN$ | $S(\frac{m^2}{g})$ |
|-----------|---------|------------|-----------------|
| CPS       | 1.593   | $2.3060 \times 10^2$ | 1000            |
| CRH       | 13.262  | $2.3060 \times 10^{24}$ | 3000            |
| SRH       | 6.807   | $2.3060 \times 10^{24}$ | 370             |
| WO₃       | 2.366   | $2.3060 \times 10^{24}$ | 37              |

4.3.8. Flory-Huggins

Flory-Huggins model adsorption parameters were obtained using equation (11) as presented as $\log \frac{\theta}{C_0} = \log KFH + n\log(1 - \theta)$. To get the Flory-Huggins model parameters, we need to convert $\theta$ data into the form of $\log \frac{\theta}{C_0}$ and $\log(1 - \theta)$ and which are used for data fitting (see Table 2). The curves of data fitting result are presented in Figures 9 (a-d). The result of data fitting also used to determine adsorption parameter. The result of data fitting in the form of a gradient obtained is the $n_{FH}$ value and intercept is the $\log KFH$ value. Table 12 shows parameter results of Flory-Huggins using CPS, CRH, SRH, and WO₃ adsorbents. $K_{FH}$ in Table
are the number of adsorbates occupying adsorption sites and the Flory-Huggins constant. Adsorbent SRH and WO$_3$ have good $K_{FH}$ value than CPS and CRH. This condition showed SRH and WO$_3$ have better adsorbent-adsorbate interaction. Moreover, SRH and WO$_3$ form multilayer adsorption which makes the adsorbate more attached to the adsorbent due to chemical bonds. Fowler-Huggins is poor suitable with all adsorption system (i.e., CPS, CRH, SRH, and WO$_3$) because $R^2 < 0.70$.

Table 12. Flory-Huggins isotherm parameters using $\log \frac{\theta}{C_i} = \log K_{FH} + n \log (1 - \theta)$

| Adsorbent | $\log(1 - \theta)$ | $\log \frac{\theta}{C_i}$ | $n_{FH}$ | $K_{FH}$ (l/mg) | $\Delta G^*$ | $R^2$ | Note |
|-----------|---------------------|--------------------------|---------|-----------------|-------------|-------|------|
| CPS       | -0.020              | -2.541                   | -0.014  | 0.863           | 2138        | 0.2068| $\Delta G^* > 0$, not spontaneously adsorption |
|           | -0.018              | -3.056                   |         |                 |             |       | $n_{FH} < 1$, represent more than one active adsorbent zone occupied by the adsorbate |
|           | -0.008              | -3.516                   |         |                 |             |       | $R^2 < 0.70$, the existence of monolayer on the surface of adsorbent |
|           | -0.038              | -2.982                   |         |                 |             |       |      |
| CRH       | -0.052              | -2.265                   | -0.0604 | 0.611           | 2155        | 0.3038| $\Delta G^* > 0$, not spontaneously adsorption |
|           | -0.019              | -2.975                   |         |                 |             |       | $n_{FH} < 1$, more than one active adsorbent zone occupied by the adsorbate |
|           | -0.032              | -2.919                   |         |                 |             |       | $R^2 < 0.70$, the existence of monolayer on the surface of adsorbent |
|           | -0.101              | -2.576                   |         |                 |             |       |      |
| SRH       | -0.031              | -2.547                   | 0.0874  | 1.507           | 3733        | 0.3992| $\Delta G^* > 0$, not spontaneously adsorption |
|           | -0.044              | -2.611                   |         |                 |             |       | $n_{FH} < 1$, more than one active adsorbent zone occupied by the adsorbate |
|           | -0.062              | -2.572                   |         |                 |             |       | $R^2 < 0.70$, the existence of monolayer on the surface of adsorbent |
|           | -0.070              | -2.708                   |         |                 |             |       |      |
|           | -0.062              | -2.829                   |         |                 |             |       |      |
| WO$_3$    | -0.022              | -2.605                   | 0.0184  | 1.056           | 3731        | 0.3267| $\Delta G^* > 0$, not spontaneously adsorption |
|           | -0.023              | -2.839                   |         |                 |             |       | $n_{FH} < 1$, more than one active adsorbent zone occupied by the adsorbate |
|           | -0.035              | -2.820                   |         |                 |             |       | $R^2 < 0.70$, the existence of monolayer on the surface of adsorbent |
|           | -0.031              | -2.955                   |         |                 |             |       |      |
|           | -0.030              | -3.062                   |         |                 |             |       |      |
4.3.9. Fowler-Guggenheim

Fowler-Guggenheim model adsorption parameters were obtained using equation (13) as presented as
\[
\ln \left( \frac{C_e(1-\theta)}{\theta} \right) - \frac{\theta}{1-\theta} = -\ln K_{FG} + \frac{2W\theta}{RT}.
\]
To get the Fowler-Guggenheim model parameters, we need to plot \( \theta \) vs \( \ln \left( \frac{C_e(1-\theta)}{\theta} \right) \) data (see Table 2). The curves of data fitting result are presented in Figures 10 (a-d). The result of data fitting also used to determine adsorption parameter. The result of data fitting in the form of a gradient obtained is the \( \frac{2W\theta}{RT} \) value and intercept is the \( \ln K_{FG} \) value. Table 13 shows parameter results of Fowler-Guggenheim using CPS, CRH, SRH, and WO3 adsorbents. \( K_{FG} \) in Table 13 is Fowler-Guggenheim constant represent adsorbent-adsorbate interaction. Higher \( K_{FG} \) value indicates a good interaction between adsorbent-adsorbate. All adsorbent system shows identically small \( K_{FG} \) value means weak interaction adsorbent-adsorbate since there are surface active site is less efficient in adsorbing the adsorbate molecules due to domination of physical interaction. Fowler-Guggenheim is poor suitable with all adsorption system (i.e., CPS, CRH, SRH, and WO3) because \( R^2 < 0.70 \).
Table 13. Fowler Guggenheim isotherm parameters using $ln\left(\frac{C_e(1 - \theta)}{\theta}\right) - \frac{\theta}{1 - \theta} = -lnK_{FG} + \frac{2W_\theta}{RT}$

| Adsorbent | $\frac{C_e(1 - \theta)}{\theta}$ | $\theta$ | $K_{FG}$ (L/mg) | $W$ (kJ/mol) | $R^2$ | Note |
|-----------|----------------|--------|----------------|-------------|------|------|
| CPS       | 5.757          | 0.045  | $4 \times 10^{-3}$ | -23403      | 0.2599 | $W < 0 \text{ kJ/mol}$, repulsive interaction between adsorbed molecule. $R^2 < 0.70$, the existence of monolayer on the surface of adsorbent. |
|           | 6.952          | 0.042  |                |             |       |      |
|           | 8.058          | 0.019  |                |             |       |      |
|           | 6.692          | 0.084  |                |             |       |      |
| CRH       | 4.973          | 0.114  | $1 \times 10^{-3}$ | -11595      | 0.4814 | $W < 0 \text{ kJ/mol}$, repulsive interaction between adsorbed molecule. $R^2 < 0.70$, the existence of monolayer on the surface of adsorbent. |
|           | 6.761          | 0.044  |                |             |       |      |
|           | 6.572          | 0.072  |                |             |       |      |
|           | 5.464          | 0.209  |                |             |       |      |
| SRH       | 5.722          | 0.069  | $3 \times 10^{-3}$ | 4028        | 0.1738 | $W < 0 \text{ kJ/mol}$, repulsive interaction between adsorbed molecule. $R^2 < 0.70$, the existence of monolayer on the surface of adsorbent. |
|           | 5.811          | 0.096  |                |             |       |      |
|           | 5.639          | 0.132  |                |             |       |      |
|           | 5.912          | 0.149  |                |             |       |      |
|           | 6.226          | 0.135  |                |             |       |      |
| WO$_3$    | 5.897          | 0.049  | $4 \times 10^{-3}$ | 22437       | 0.28  | $W < 0 \text{ kJ/mol}$, repulsive interaction between adsorbed molecule. $R^2 < 0.70$, the existence of monolayer on the surface of adsorbent. |
|           | 6.427          | 0.054  |                |             |       |      |
|           | 6.332          | 0.078  |                |             |       |      |
|           | 6.661          | 0.069  |                |             |       |      |
|           | 6.910          | 0.068  |                |             |       |      |

Figure 10. Fowler-Guggenheim isotherm model for adsorption system using a) CPS, b) CRH, c) SRH, and d) WO$_3$ Adsorbents
4.3.10. Hill-Deboer

Hill-Deboer model adsorption parameters were obtained using equation (14) as presented as
\[ \ln \left( \frac{C_0(1-\theta)}{\theta} \right) - \frac{\theta}{1-\theta} = -\ln K_1 - \frac{K_2 \theta}{RT} \]. To get the Hill-Deboer model parameters, we need to plot \( \theta \) vs \( \ln \left( \frac{C_0(1-\theta)}{\theta} \right) - \frac{\theta}{1-\theta} \) data. The curves of data fitting result are presented in Figures 11 (a-d). The result of fitting data also used to determine adsorption parameter. The result of data fitting in the form of a gradient obtained is the \( K_2 \theta / RT \) value and intercept is the \( \ln K_1 \) value. Table 14 shows parameter results of a Hill-Deboer using CPS, CRH, SRH, and WO\(_3\) adsorbents. \( K_1 \) in Table 14 is the Hill-Deboer constant interaction between adsorbent and adsorbate. Higher \( K_1 \) value indicates a good interaction between adsorbent-adsorbate. However, all adsorbents system indicate a small value of \( K_1 \) means poor interaction between adsorbent-adsorbate since active site is not effective in carrying out adsorption process. Hill-Deboer is poor suitable with all adsorption system (i.e., CPS, CRH, SRH, and WO\(_3\)) because \( R^2 < 0.70 \).

4.4. Approximately Isotherm Model

The experimental data of the adsorption process in Table 2 were analyzed through regression analysis to match the linear correlation of the adsorption isotherm mathematical models. Fitting data based on the plotted way in Table 1 for each adsorption model is used to determine the adsorption parameters that correspond to each adsorption model. The parameters obtained after the data fitting process are summarized in Tables 3-12. Figures 2-11 present the plotting of the experimental results.

Figures 2 (a-d) show the fitting data based on the Langmuir adsorption isotherm. The Langmuir isotherm for the study of the adsorption of curcumin solution with the and CRH show poor adsorption characteristics because it gives a low correlation coefficient value \( (R^2 < 1) \) is too far closer to the 0.90. Meanwhile, adsorption of CPS, SRH, and WO\(_3\) adsorbents matches the Langmuir model with a coefficient correlation \( (R^2 > 0.90) \). This means that the adsorption system using CRH does not allow monolayer formation. However, the reverse phenomenon is for the adsorption system using CPS, SRH, and WO\(_3\) adsorbents. The analysis of the separation factor \( (R_L) \) shows \( R_L \) value in the range between 0 and 1 for all cases which indicates that the adsorption process has favorable adsorption characteristics.

Figures 3 (a-d) show the Freundlich isotherm curve. Freundlich isotherm curve shows very small correlation coefficient value for adsorption system using CPS and CRH adsorbent compared to adsorption system with SRH and WO\(_3\) adsorbent. This model suggests that the adsorption system with SRH and WO\(_3\) fits into the Freundlich model, which allows the formation of a multilayer structure.

Figures 4 (a-d) are the linear curve of the Temkin adsorption. The adsorption system with CPS and CRH adsorbents does not match with the Temkin model isotherm because the \( R^2 \) value is less than 0.90. While, the adsorption system with SRH and WO\(_3\) adsorbents are compatible with Temkin isotherm model.
Ragadhita, R. *How to Calculate Isotherm Adsorption of Particles Using Two-Parameter...*  
DOI: [https://doi.org/10.17509/ijost.v6i1.32354](https://doi.org/10.17509/ijost.v6i1.32354)  
p- ISSN 2528-1410 e- ISSN 2527-8045

| Adsorbent | $\ln \frac{C_e(1-\theta)}{\theta} - \frac{\theta}{1-\theta}$ | $\theta$ | $K_1$ (L/mg) | $K_2$ (kJ/mol) | $R^2$ | Note |
|-----------|-------------------------------------------------|--------|-------------|--------------|------|------|
| CPS       | 5.709                                           | 0.045  | 4           | -49716       | 0.284| • $K_2 < 0$ kJ/mol, repulsive interaction between adsorbate molecules  
           | 6.901                                           | 0.042  | $1 \times 10^{-4}$ |              |      |      |
|           | 8.038                                           | 0.019  |             |              |      |      |
|           | 6.600                                           | 0.084  |             |              |      |      |
| CRH       | 4.844                                           | 0.114  | 1           | -26919       | 0.558| • $K_2 < 0$ kJ/mol, repulsive interaction between adsorbate molecules  
           | 6.715                                           | 0.044  | $1 \times 10^{-3}$ |              |      |      |
|           | 6.494                                           | 0.072  |             |              |      |      |
|           | 5.199                                           | 0.209  |             |              |      |      |
| SRH       | 5.647                                           | 0.069  | 3           | 4535         | 0.0625| • $K_2 < 0$ kJ/mol, attractive interaction between adsorbate molecules  
           | 5.704                                           | 0.096  | $1 \times 10^{-3}$ |              |      |      |
|           | 5.487                                           | 0.132  |             |              |      |      |
|           | 5.736                                           | 0.149  |             |              |      |      |
|           | 6.071                                           | 0.135  |             |              |      |      |
| WO$_3$    | 5.845                                           | 0.049  | 4           | 41858        | 0.2527| • $K_2 < 0$ kJ/mol, attractive interaction between adsorbate molecules  
           | 6.370                                           | 0.054  | $1 \times 10^{-3}$ |              |      |      |
|           | 6.247                                           | 0.078  |             |              |      |      |
|           | 6.587                                           | 0.069  |             |              |      |      |
|           | 6.838                                           | 0.068  |             |              |      |      |
Figures 5 (a-d) are an analysis fitting based on the Dubinin-Radushkevich model. Based on the correlation coefficient value, the adsorption system with SRH and WO₃ adsorbents are compatible with the Dubinin-Radushkevich model, whereas the adsorption system with CPS and CRH adsorbents does not. Therefore, the adsorption system with CPS and CRH adsorbents was not well reflected by the Dubinin-Radushkevich isotherm model. The Dubinin-Radushkevich isotherm reflects a good fit for the SRH and WO₃ adsorbent.

Figures 6 (a-d) are the isotherm curve of the Jovanovic model. Based on the analysis of the coefficient correlation value, the Jovanovic isotherm model is the most suitable and most reflective of all cases of adsorption systems because the value of $R^2 > 0.9$.

Figures 7 (a-d) are an analysis fitting based on the Halsey model. The adsorption system that is most suitable for this model is the adsorption system with SRH and WO₃ adsorbents. Meanwhile, the Halsey model is not suitable in representing the adsorption system with CPS and CRH.

Figures 8 (a-d) show the fitting analysis using the Harkin-Jura adsorption isotherm. The adsorption system with CPS and CRH adsorbent are the least suitable because the $R^2$ value is <0.9. The incompatibility with the Harkin-Jura isotherm represents that the adsorption process does not follow a multilayer adsorption model. On the other hand, the Harkin-Jura isotherm is compatible with the adsorption system with SRH, and WO₃ adsorbents because the $R^2$ value is close to 0.9 which allows the formation of multilayers on the adsorbent surface.

Figures 9 (a-d), 10 (a-d), and 11 (a-d) are the results of fitting data based on the Flory Huggins, Fowler Guggenheim, and Hill-Deboer models. These three models show poor correlation coefficient values for all adsorption systems.
adsorption cases (i.e., CPS, CRH, SRH, and WO₃), meaning that they reflect an adsorption system that is not suitable for all cases.

5. Discussion

Based on the $R^2$ value for each adsorption model, the adsorption system in CPS is compatible with Langmuir, Harkin-Jura, and Jovanovic isotherm models. CRH adsorbents is only compatible with the Jovanovic model. Langmuir and Jovanovic model have same assumption that adsorption process occurs by forming a monolayer structure without the presence of adsorbate-adsorbent lateral interactions for CPS and CRH adsorbents (Ayawei et al., 2017). Besides assuming the adsorption is monolayer, the adsorption system with the CPS adsorbent is also assumed to have adsorption by forming a multilayer. This is confirmed because it fits the Harkin-Jura model.

For adsorption systems with SRH and WO₃ adsorbents, both of them are incompatible with the Harkin Jura, Flory Huggins, Fowler Guggenheim, and Hill-Deboer models. Meanwhile, the other six models are suitable. The adsorption system with the SRH adsorbent followed suit with the order of the Temkin > Dubinin-Radushkevich > Freundlich > Halsey > Langmuir > Jovanovic models. Meanwhile, the order of compatibility of the adsorption system with the WO₃ adsorbent is summarized as follows Dubinin Radushkevich > Langmuir > Freundlich > Halsey > Jovanovic > Temkin models. The adsorption system with SRH and WO₃ adsorbents has a good correlation with the Langmuir model informing the monolayer adsorption process, in which the adsorbate molecules are distributed on all adsorbent surfaces (Langmuir, 1918). This monolayer adsorption process is also confirmed by the Jovanovic model, which describes monolayer adsorption without the presence of lateral interactions (Ayawei et al., 2017). In the Langmuir model, adsorption is advantageous or not explained by the $R_L$ value, where the resulting $R_L$ value is between 0 and 1, which indicates the adsorption process is favorable. Meanwhile, Freundlich, Temkin, Dubinin-Radushkevich, and Halsey isotherms support multilayer adsorption processes. The degree of linearization between adsorbate and adsobent is indicated by the values of $n < 1$ and $1/n > 1$ in the Freundlich model, the values show that adsorption follows cooperative adsorption with chemical interactions. Cooperative adsorption informs the occurrence of chemical and physical interactions at one time (Liu, 2015). The chemical interaction in the adsorption system is in accordance with the parameter value $B_T > 8$ J/mol in the Temkin model. The Dubinin-Radushkevich model also confirmed the physical interaction because the parameter value $E < 8$ kJ/mol.

5.1. Prediction Model for CPS Adsorbent

The adsorption system uses CPS adsorbent following the Langmuir and Jovanovic model which assumes monolayer adsorption. The CPS adsorption system is also compatible with the Harkin-Jura model which assumes multilayer adsorption. Adsorption system using CPS shows weak physical interaction (adsorbent-adsorbate interaction) and chemical interaction (adsorbate-adsorbate interaction). Prediction model for CPS adsorbent is illustrated in Figure 12.
5.2. Prediction Model for CRH Adsorbent

The adsorption system uses CRH adsorbent following the Langmuir and Jovanovic model which assumes monolayer adsorption with weak interaction between adsorbate-adsorbent (physical interaction) since the $K_L$ has small values based on Langmuir. Prediction model for CPS adsorbent is illustrated in Figure 13.

![Figure 13. Prediction model for system adsorption using CRH adsorbent](image)

5.3. Prediction Model for SRH and WO$_3$ Adsorbents

The adsorption system uses SRH and WO$_3$ adsorbents following monolayer and multilayer adsorption with weak chemical interaction (adsorbate-adsorbate interaction) and physical interaction (adsorbate-adsorbent interaction) since the $K_L$ and $A_T$ have small values based on Langmuir and Temkin parameter respectively. The multilayer adsorption process results from the presence of a heterogeneous structure in the adsorbent which is assumed by the Temkin, Dubinin-Radushkevich, Harkin-Jura, and Halsey isotherm where filling pores occur (Dada et al., 2012). Prediction model for CPS adsorbent is illustrated in Figure 14.

![Figure 14. Prediction model for system adsorption using SRH and WO$_3$ adsorbents](image)

5. CONCLUSION

This study demonstrates a simple way of understanding the calculation of the results of the adsorption data analysis by matching and reviewing the adsorption data in several adsorption isotherm models and demonstrating its application for the adsorption system of various adsorbents. The criteria for selecting a suitable and optimal adsorption isotherm model for the adsorption process have also been discussed in this study. Based on our study, the adsorption system with carbon obtained from peanut shells and carbon obtained from rice husks followed the Jovanovic isotherm. Adsorption system with silica adsorbent extracted from rice husk and WO$_3$ following Langmuir, Freundlich, Temkin, Dubinin-Radushkevich, Halsey, Jovanovic isotherms.

6. AUTHORS’ NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

7. REFERENCES

Afonso, R., Gales, L., and Mendes, A. (2016). Kinetic derivation of common isotherm equations

DOI: https://doi.org/10.17509/ijost.v6i1.32354
p- ISSN 2528-1410 e- ISSN 2527-8045
for surface and micropore adsorption. *Adsorption*, 22(7), 963-971.

Afroze, S., and Sen, T. K. (2018). A review on heavy metal ions and dye adsorption from water by agricultural solid waste adsorbents. *Water, Air, & Soil Pollution*, 229(7), 1-50.

Al-Ghouti, M. A., and Da’ana, D. A. (2020). Guidelines for the use and interpretation of adsorption isotherm models: A review. *Journal of Hazardous Materials*, 393, 122383.

Anshar, A. M., Taba, P., and Raya, I. (2016). Kinetic and Thermodynamics Studies the Adsorption of Phenol on Activated Carbon from Rice Husk Activated by ZnCl₂. *Indonesian Journal of Science and Technology*, 1(1), 47-60.

Ayawei, N., Ebelegi, A. N., and Wankasi, D. (2017). Modelling and interpretation of adsorption isotherms. *Journal of chemistry*, 2017.

Barakat, M. A. (2011). New trends in removing heavy metals from industrial wastewater. *Arabian journal of Chemistry*, 4(4), 361-377.

Crini, G., and Badot, P. M. (2008). Application of chitosan, a natural aminopolysaccharide, for dye removal from aqueous solutions by adsorption processes using batch studies: a review of recent literature. *Progress in Polymer Science*, 33(4), 399-447.

Dąbrowski, A. (2001). Adsorption—from theory to practice. *Advances in Colloid and Interface Science*, 93(1-3), 135-224.

Dada, A. O., Olalekan, A. P., Olatunya, A. M., and Dada, O. J. I. J. C. (2012). Langmuir, Freundlich, Temkin and Dubinin–Radushkevich isotherms studies of equilibrium sorption of Zn2+ unto phosphoric acid modified rice husk. *IOSR Journal of Applied Chemistry*, 3(1), 38-45.

Fiandini, M., Ragadhita, R., Nandiyanto, A. B. D., and Nugraha, W. C. (2020). Adsorption characteristics of submicron porous carbon particles prepared from rice husk. *J. Eng. Sci. Technol*, 15, 022-031.

Foo, K. Y., and Hameed, B. H. (2009). Utilization of biodiesel waste as a renewable resource for activated carbon: application to environmental problems. *Renewable and Sustainable Energy Reviews*, 13(9), 2495-2504.

Ghani, S. A. A. (2015). Trace metals in seawater, sediments and some fish species from Marsa Matrouh Beaches in north-western Mediterranean coast, Egypt. *The Egyptian Journal of Aquatic Research*, 41(2), 145-154.

Guddati, S., Kiran, A. S. K., Leavy, M., and Ramakrishna, S. (2019). Recent advancements in additive manufacturing technologies for porous material applications. *The International Journal of Advanced Manufacturing Technology*, 105(1), 193-215.

Gupta, V. K. (2009). Application of low-cost adsorbents for dye removal—a review. *Journal of Environmental Management*, 90(8), 2313-2342.

Hegazi, H. A. (2013). Removal of heavy metals from wastewater using agricultural and industrial wastes as adsorbents. *HBRC Journal*, 9(3), 276-282.

Hamdaoui, O., and Naffrechoux, E. (2007). Modeling of adsorption isotherms of phenol and chlorophenols onto granular activated carbon: Part I. Two-parameter models and
equations allowing determination of thermodynamic parameters. *Journal of Hazardous Materials*, 147(1-2), 381-394.

Holkar, C. R., Jadhav, A. J., Pinjari, D. V., Mahamuni, N. M., and Pandit, A. B. (2016). A critical review on textile wastewater treatments: possible approaches. *Journal of Environmental Management*, 182, 351-366.

Kadja, G., and Ilmi, M. M. (2019). Indonesia natural mineral for heavy metal adsorption: A review. *Journal of Environmental Science and Sustainable Development*, 2(2), 3.

Kong, L., and Adidharma, H. (2019). A new adsorption model based on generalized van der Waals partition function for the description of all types of adsorption isotherms. *Chemical Engineering Journal*, 375, 122112.

Langmuir, I. (1918). The adsorption of gases on plane surfaces of glass, mica and platinum. *Journal of the American Chemical Society*, 40(9), 1361-1403.

Liu, S. (2015). Cooperative adsorption on solid surfaces. *Journal of Colloid and Interface Science*, 450, 224-238.

Maryanti, R., Nandiyanto, A. B. D., Manullang, T. I. B., & Hufad, A. (2020). Adsorption of Dye on Carbon Microparticles: Physicochemical Properties during Adsorption, Adsorption Isotherm and Education for Students with Special Needs. *Sains Malaysiana*, 49(12), 2949-2960.

Naggar, Y. A., Naiem, E., Mona, M., Giesy, J. P., and Seif, A. (2014). Metals in agricultural soils and plants in Egypt. *Toxicological & Environmental Chemistry*, 96(5), 730-742.

Nandiyanto, A. B. D., Girsang, G. C. S., Maryanti, R., Ragadhita, R., Anggraeni, S., Fauzi, F. M., and Al-Obaidi, A. S. M. (2020a). Isotherm adsorption characteristics of carbon microparticles prepared from pineapple peel waste. *Communications in Science and Technology*, 5(1), 31-39.

Nandiyanto, A. B. D. (2020b). Isotherm adsorption of carbon microparticles prepared from pumpkin (Cucurbita maxima) seeds using two-parameter monolayer adsorption models and equations. *Moroccan Journal of Chemistry*, 8(3), 8-3.

Ragadhita, R., Nandiyanto, A. B. D., Nugraha, W. C., and Mudzakir, A. (2019). Adsorption isotherm of mesopore-free submicron silica particles from rice husk. *Journal of Engineering Science and Technology*, 14(4), 2052-2062.

Nandiyanto, A. B. D., Arinalhaq, Z. F., Rahmadianti, S., Dewi, M. W., Rizky, Y. P. C., Maulidina, A., and Yunas, J. (2020c). Curcumin Adsorption on Carbon Microparticles: Synthesis from Soursop (AnnonaMuricata L) Peel Waste, Adsorption Isotherms and Thermodynamic and Adsorption Mechanism. *International Journal of Nanoelectronics and Materials*, 13 (Special Issue Dec 2020), 173-192.

Nandiyanto, A. B. D., Maryanti, R., Fandiini, M., Ragadhita, R., Usdiyana, D., Anggraeni, S., and Al-Obaidi, A. S. M. (2020d). Synthesis of Carbon Microparticles from Red Dragon Fruit (Hylocereus undatus) Peel Waste and Their Adsorption Isotherm Characteristics. *Molekul*, 15(3), 199-209.

Nandiyanto, A. B. D., Ragadhita, R., & Yunas, J. (2020e). Adsorption Isotherm of Densed
Monoclinic Tungsten Trioxide Nanoparticles. *Sains Malaysiana*, 49(12), 2881-2890.

Nandiyanto, A. B. D., Erlangga, T. M. S., Mufidah, G., Anggraeni, S., Roil, B., & Jumril, Y. (2020f). Adsorption isotherm characteristics of calcium carbonate microparticles obtained from barred fish (Scomberomorus spp.) bone using two-parameter multilayer adsorption models. *International Journal of Nanoelectronics and Materials*, 13 (Special Issue Dec 2020), 45-58.

Nandiyanto, A. B. D., Ragadhita, R., Oktiani, R., Sukmafitri, A., and Fiandini, M. (2020g). Crystallite sizes on the photocatalytic performance of submicron WO₃ particles. Journal of Engineering Science and Technology, 15(3), 1506-1519.

Rahmani, M., and Sasani, M. (2016). Evaluation of 3A zeolite as an adsorbent for the decolorization of rhodamine B dye in contaminated waters. *Applied Chemistry*, 11(41), 83-90.

Romero-Gonzalez, J., Peralta-Videa, J. R., Rodriguez, E., Ramirez, S. L., and Gardea-Torresdey, J. L. (2005). Determination of thermodynamic parameters of Cr (VI) adsorption from aqueous solution onto Agave lechuguilla biomass. *The Journal of Chemical Thermodynamics*, 37(4), 343-347.

Saadi, R., Saadi, Z., Fazaeli, R., and Fard, N. E. (2015). Monolayer and multilayer adsorption isotherm models for sorption from aqueous media. *Korean Journal of Chemical Engineering*, 32(5), 787-799.

Sert, E. B., Turkmen, M., and Cetin, M. (2019). Heavy metal accumulation in rosemary leaves and stems exposed to traffic-related pollution near Adana-İskenderun Highway (Hatay, Turkey). *Environmental Monitoring and Assessment*, 191(9), 1-12.

Shanavas, S., Kunju, A. S., Varghese, H. T., and Panicker, C. Y. (2011). Comparison of Langmuir and Harkins-Jura adsorption isotherms for the determination of surface area of solids. *Oriental Journal of Chemistry*, 27(1), 245.

DOI: https://doi.org/10.17509/ijost.v6i1.32354
p- ISSN 2528-1410 e- ISSN 2527-8045