

# Adsorption Characteristics of 2, 4-DNP on Bamboo-Based Activated Carbon

Tae Young Kim, Song Yong Cho, and Jin Hwan Kim

**Abstract**—A bamboo-based activated carbon with large surface area was successfully prepared by KOH activation, and used to remove 2,4-Dinitrophenol from aqueous solution. The surface area and pore volume of bamboo-based activated carbon were 1092 m<sup>2</sup>/g and 0.259 cc/g. Adsorption equilibrium of 2,4-dinitrophenol on bamboo-based activated carbon could be represented by the Sips equation. Equilibrium capacity increased with decreasing initial pH and temperature. The internal diffusion coefficients were determined by comparing the experimental concentration decay curves with those predicted from surface diffusion model and pore diffusion model.

**Index Terms** - Adsorption, Bamboo, 2,4-Dinitrophenol, Kinetic

## I. INTRODUCTION

Alkyl dinitrophenols are widely acknowledged to be a group of toxic refractory chemicals, which can be detrimental to human health and the environment. 2,4-Dinitrophenol (2,4-DNP) is a typical example of this class of toxic compounds. DNP is widely used in petrochemical industry as polymerization inhibitor for vinyl aromatics and in agriculture as a pesticide [1]. Nitrophenols pose potential risks to both human health and ecosystem since they are toxic to plants, fish and many other organisms and can accumulate in the food chain [2].

Various treatment techniques have been employed to treat the wastewater, including precipitation, adsorption, ion exchange, and reverse osmosis [3]. Among them, adsorption onto solid adsorbents has great environmental significance, since it can effectively remove pollutants from both aqueous and gaseous streams. In wastewater treatment, activated carbon is a powerful adsorbent because it has a large surface area and pore volume, which remove liquid-phase contaminants, including organic compounds, heavy metal ions and coloring matters [4].

Bamboo is a tropical plant and is common in Southern Asia such as Korea, China, Thailand, and Vietnam [5]. Bamboo can be used as a raw material for the production of a range of carbon chars and activated carbons due to its high carbon content. The bamboo cane can be carbonized/charred in a furnace at high temperature in the absence of oxygen to produce carbon chars.

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Bamboo-based activated carbons can be expected to find uses as a potential commercially available activated carbon for the treatment of gaseous pollutants in industrial effluents and liquid pollutants in drinking water filtration applications. In this study, the bamboo-based activated carbon was prepared by KOH activation for removal of 2,4-DNP and then the adsorption experiments including adsorption isotherms, kinetics, and effect of solution pH and temperature were conducted to investigate its adsorption behavior.

## II. MATERIALS AND METHODS

The bamboo was obtained in Damyang (Korea), and cut into the particle size in the range of 2-3mm. 2,4-DNP was purchased from Kanto Chemical Co., INC. (Japan). The buffer solution used for adjusting the pH of the aqueous solutions contained sodium hydroxide (Sigma, USA) and acetic acid (Yakuri Co., Japan). All solutions were prepared with deionized water. All reagents used were of analytical grade.

In the activation process, the bamboo chips were impregnated by 60wt% KOH solution for 24 h and then dried at 105°C for 24 h. The obtained material was placed in a furnace, followed by heating to the carbonization temperature 450°C at an increasing rate of 5°C/min and maintaining at the temperature for 0.5 h under N<sub>2</sub> flow protection. Activation temperature 750°C, and maintaining at the temperature for 1 h. The obtained bamboo-based activated carbon was washed with deionized water until the pH of neutral. Finally, the bamboo-based activated carbon was dried in an oven at 105°C for 12 h.

Single species equilibrium adsorption data were obtained by measuring the adsorbate concentration in an aqueous solution of the 2,4-DNP, 0.45mol/m<sup>3</sup>. The solution was kept in a shaking batch for 24 h after introducing a given amount of adsorbent. Batch adsorption experiments were conducted in a Carberry-type batch adsorber. All the experiments were carried out at approximately 400 rpm, since the film mass transfer coefficient,  $k_f$ , is practically constant at this condition. Concentrations of 2,4-DNP in the solution was determined using UV spectrophotometer (Shimadzu 1601) at 325 nm. The amount of 2,4-DNP adsorbed on the bamboo-based activated carbon at equilibrium was calculated from the following mass balance equation.

$$q = (C_i - C_e) \frac{V}{W} \quad (1)$$

Here  $q$  is the equilibrium amount adsorbed on the adsorbent (mol/kg),  $C_i$  is the initial concentration of bulk fluid (mol/m<sup>3</sup>),  $C_e$  is the equilibrium concentration of the solution (mol/m<sup>3</sup>),  $V$  is the volume of solution (m<sup>3</sup>), and  $W$  is the weight of adsorbent (kg).

### III. RESULTS AND DISCUSSION

The heat of carbonization of bamboo must be determined in order to perform a calculation of the material and energy balances for the bamboo carbonization process. The heat of carbonization can be found by using a differential thermal analysis (DTA). Fig. 1 is a differential thermogram obtained by heating the bamboo in a flowing stream of nitrogen, similar to the bamboo carbonization process, it was found that the bamboo carbonization process starts at around 240 °C and obtains a minima termed peak (350 °C) in which accounts for more than 64% weight loss of bamboo during the process.

Fig. 2 shows the SEM image of the bamboo-based activated carbon. The highly reticular, three-dimensional porous matrix of the bamboo-based activated carbon can clearly be seen in this figure. Some pores more than 20µ m can be observed in the bamboo-based activated carbon.

The specific surface area of the bamboo-based activated carbon measured from N<sub>2</sub> adsorption/desorption isotherm at 77 K. Fig. 3 shows pore size distribution of the bamboo-based activated carbon by BJH plot. The pore sizes of the activated carbon prepared with 60wt% KOH were mainly less than 10 nm. The specific surface area and average pore diameter of the bamboo-based activated carbon were 1092 m<sup>2</sup>/g and 9.447Å, respectively. According to the International Union of Pure and Applied Chemistry (IUPAC) classifications, pores can be divided in broad terms according to their diameter (d) into macropores (d > 50 nm), mesopores (2 < d < 50 nm) and micropores (d < 2 nm). Based on the results, it can be concluded that the pores of the bamboo-based activated carbon fell into the category of micropores. The physical properties of bamboo-based activated carbon listed in Table I.

Adsorption isotherms describe how adsorbates interact with adsorbents; hence, are critical in optimising the use of adsorbents. Therefore, the correlation of the equilibrium data by either theoretical or empirical equations is essential in the practical design and operation of adsorption systems. In order to optimise the design of an adsorption system for the removal of herbicides from aqueous solution, it is important to

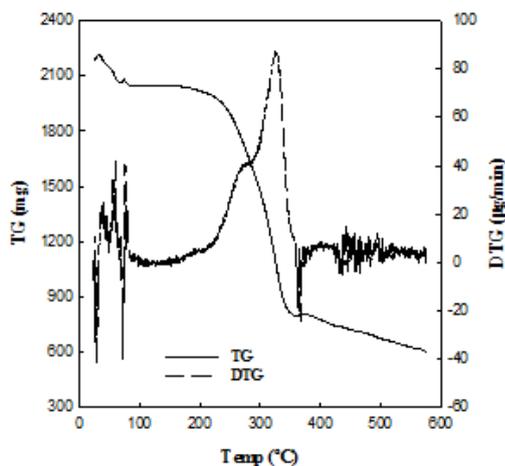


Fig. 1. Thermogram For Carbonization Of Bamboo.

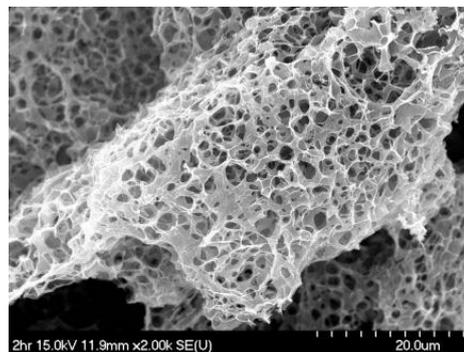


Fig. 2 SEM Photography Of Bamboo-Based Activated Carbon (X 2,000).

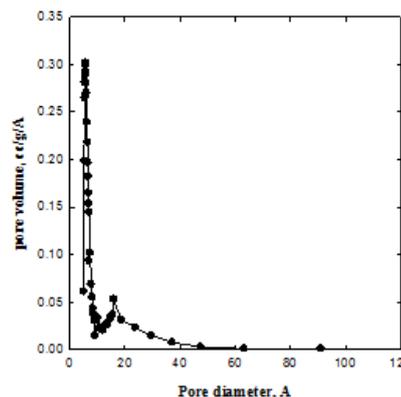


Fig. 3. Pore Size Distribution Of Bamboo- Based Activated Carbon

| Properties                             | Value |
|--|-------|
| BET surface area [m <sup>2</sup> /g]   | 1092  |
| Average pore diameter [Å]              | 9.447 |
| Total pore volume [cm <sup>3</sup> /g] | 0.259 |

By BJH Plot.

TABLE I

PHYSICAL PROPERTIES OF BAMBOO-BASED ACTIVATE CARBON.

establish the most appropriate correlation for the equilibrium curves. In this work, the Langmuir, Freundlich and Sips isotherm models were fitted to describe the adsorption equilibrium. These isotherm equations are shown below:

$$\text{Langmuir isotherm, } q = \frac{q_m b c_e}{1 + b c_e} \quad (2)$$

where  $c_e$  is the supernatant concentration at equilibrium (mol/m<sup>3</sup>),  $b$  is the Langmuir affinity constant (m<sup>3</sup>/mol) and  $q_m$  is the maximum adsorption capacity of the material (mol/kg) assuming a monolayer of adsorbate was taken up by the adsorbent.

$$\text{Freundlich isotherm, } q = k c_e^{1/n} \quad (3)$$

where  $k$  is the Freundlich constant related with adsorption capacity (mol/kg)(mol/m<sup>3</sup>)<sup>-1/n</sup> and  $n$  is the Freundlich exponent (dimensionless).

$$\text{Sips isotherm, } q = \frac{q_m b C_e^{1/n}}{1 + b C_e^{1/n}} \quad (4)$$

where  $b$  is the Sips constant related to the affinity constant (mol/m<sup>3</sup>)<sup>-1/n</sup> and  $q_m$  is the Sips maximum adsorption capacity (mol/kg).

To identify the parameters for each adsorption isotherm, the linear least square method and pattern search algorithm were used. The value of the mean percentage error has been

used as a criterion for testing the fit of the correlations. The mean percent deviation between the experimental and predicted values was obtained using Eq. 5.

$$\text{error}(\%) = \frac{100}{N} \sum_{k=1}^N \left[ \frac{|q_{\text{exp},k} - q_{\text{cal},k}|}{q_{\text{exp},k}} \right] \quad (5)$$

where,  $q_{\text{model},k}$  is each value of  $q$  predicted by the fitted model and  $q_{\text{experimental},k}$  each value of  $q$  measured experimentally.

Fig. 4 shows the experimental equilibrium adsorption isotherms obtained at different initial pHs for the adsorption of 2,4-DNP on bamboo-based activated carbon. As shown in this figure, the adsorption amounts of 2,4-DNP decreased with increasing initial pH of the solution for the pH range of 3.5-10. In general, the influence of pH is attributed to the electrostatic interaction between the adsorbent surface and the adsorbate molecule or ion. Table II gives the adsorption equilibrium constants of 2,4-DNP at different initial pH on bamboo-based activated carbon. Based on the error, the Sips model is the best isotherm model for the adsorbent at all the three pHs studied. The Sips model showed (Fig. 4) the lowest error values, which means that the  $q$  fit by the isotherm model was close to the  $q$  measured experimentally.

Fig. 5 shows the effect of temperature on adsorption capacities of the 2,4-DNP on bamboo-based activated carbon at pH 3.5. The amounts of 2,4-DNP adsorbed on bamboo-based activated carbon increased with decreasing solution temperature. This results suggested that physical adsorption is dominant for 2,4-DNP on bamboo-based activated carbon. The adsorption equilibrium constants of 2,4-DNP on bamboo-based activated carbon at different temperatures are

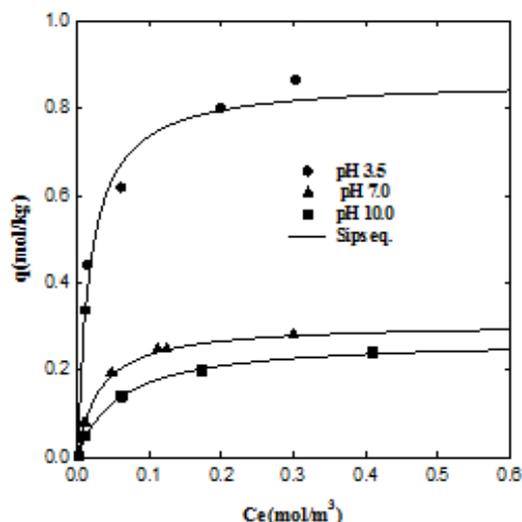


Fig. 4 Adsorption Equilibrium Isotherm Of 2,4-Dnp On Bamboo-Based Activated Carbon At Different Phs (298 K).

TABLE II  
ADSORPTION EQUILIBRIUM CONSTANTS OF 2,4-DNP ON BAMBOO-BASED ACTIVATED CARBON AT DIFFERENT INITIAL PHs (298 K).

| Isotherm type | Parameters | pH    |       |       |
|---------------|------------|-------|-------|-------|
|               |            | 3.5   | 7     | 10    |
| Langmuir      | $q_m$      | 0.891 | 0.307 | 0.272 |
|               | $b$        | 50.11 | 35.23 | 17.74 |
|               | error(%)   | 4.582 | 0.451 | 4.140 |
| Freundlich    | $k$        | 1.126 | 0.525 | 0.407 |
|               | $n$        | 4.103 | 2.619 | 2.246 |
|               | error(%)   | 7.783 | 8.751 | 7.449 |
| Sips          | $q_m$      | 0.891 | 0.306 | 0.272 |
|               | $b$        | 54.78 | 35.82 | 16.39 |
|               | $n$        | 0.987 | 0.998 | 1.035 |
|               | error(%)   | 4.303 | 0.412 | 2.925 |

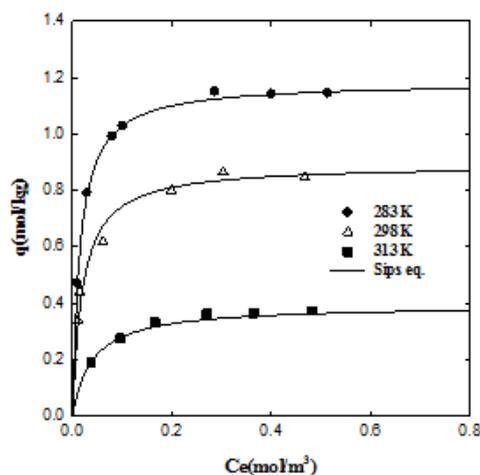


Fig. 5 Adsorption Equilibrium Isotherm Of 2,4-DNP On Bamboo-Based Activated Carbon At Different Temperature (Ph 3.5).

TABLE III  
ADSORPTION EQUILIBRIUM CONSTANTS OF 2,4-DNP ON BAMBOO-BASED ACTIVATED CARBON AT DIFFERENT TEMPERATURE (PH : 3.5).

| Isotherm type | Parameters | Temperature [K] |       |       |
|---------------|------------|-----------------|-------|-------|
|               |            | 283             | 298   | 313   |
| Langmuir      | $q_m$      | 1.183           | 0.891 | 0.413 |
|               | $b$        | 65.99           | 50.11 | 22.22 |
|               | error(%)   | 1.176           | 4.582 | 1.526 |
| Freundlich    | $k$        | 1.451           | 1.126 | 0.489 |
|               | $n$        | 4.894           | 4.103 | 3.744 |
|               | error(%)   | 9.701           | 7.783 | 6.038 |
| Sips          | $q_m$      | 1.179           | 0.891 | 0.407 |
|               | $b$        | 75.26           | 54.78 | 25.19 |
|               | $n$        | 0.973           | 0.987 | 0.976 |
|               | error(%)   | 1.120           | 4.303 | 1.547 |

given in Table III. Based on the error, the Sips model is the best isotherm model for the adsorbent at all the three temperatures studied. The maximum amounts of 2,4-DNP uptake were 1.183 mol/kg at 283 K and pH 3.5. This value indicates that the bamboo-based activated carbon is good adsorbent for 2,4-DNP removal from aqueous solutions.

The thermodynamic parameters, i.e., the standard free energy ( $\Delta G^\circ$ ), enthalpy change ( $\Delta H^\circ$ ) and entropy change ( $\Delta S^\circ$ ) have been estimated to evaluate the feasibility and

exothermic nature of the adsorption process. They can be calculated by the dependence of thermodynamic equilibrium constant ( $K_s$ ) on temperatures.

$$\Delta G^\circ = -RT \ln K_s \quad (6)$$

$$\ln K_s = \frac{\Delta H^\circ}{RT} + \frac{\Delta S^\circ}{R} \quad (7)$$

The thermodynamic equilibrium constant ( $K_s$ ) for the adsorption of 2,4-DNP on bamboo-based activated carbon can be calculated using the equation [6]:

$$k_s = \frac{q_m v_1}{C_e v_2} \quad (8)$$

where  $v_1$  is the activity coefficient of the adsorbed solute, and  $v_2$  is the activity coefficient of the solute in equilibrium suspension. The ratio of activity coefficients was assumed to be uniform in the dilute range of the solutions [6]. As the concentration of the dye in the solution approached zero, the activity coefficient approached unity and Eq. (8) became

$$\lim_{C_e \rightarrow 0} \frac{q_m}{C_e} = k_s \quad (9)$$

The values of  $K_s$  are obtained by plotting  $\ln \frac{q_m}{C_e}$  versus  $C_e$

and extrapolating  $C_e$  to = 0. The calculated values of  $K_s$  and the correlation coefficients are listed in Table IV. The values of  $\Delta G^\circ$  of the 2,4-DNP/bamboo-based activated carbon adsorption systems are all positive, which indicates the spontaneous adsorption processes [7,8]. The value of  $\Delta H^\circ$  and  $\Delta S^\circ$  can be calculated from the slope and intercept of the van't Hoff plot (Eq. (7)) of  $\ln K_s$  against  $1/T$ , respectively, and the results are listed in Table IV. The positive value of  $\Delta H^\circ$  confirms the exothermic character of the adsorption of 2,4-DNP on bamboo-based activated carbon. Generally, the magnitude of standard enthalpy changes for absolute physical adsorption is less than 20 kJ/mol, while chemisorption is in the range of 80–200 kJ/mol [6]. In this study, the enthalpy implied by the temperature dependence were 3.09 kJ/mol for 2,4-DNP adsorption, suggesting that the 2,4-DNP adsorption processes should be regarded as physical adsorption.

TABLE IV  
THERMODYNAMIC PARAMETERS OF 2,4-DNP ON BAMBOO-BASED  
ACTIVATED CARBON AT DIFFERENT TEMPERATURE (PH 3.5)

| Temp. [K] | $K_s$ | $R^2$ | $\Delta G^\circ$ [kJ/mol] | $\Delta H^\circ$ [kJ/mol] | $\Delta S^\circ$ [kJ/mol K] | $R^2$ |
|-----------|-------|-------|---------------------------|---------------------------|-----------------------------|-------|
| 283       | 2.72  | 0.97  | 0.56                      |                           |                             |       |
| 298       | 3.23  | 0.95  | 0.69                      | 3.09                      | 0.13                        | 0.95  |
| 313       | 4.62  | 0.96  | 0.95                      |                           |                             |       |

To model the adsorption kinetics, one has to pay attention to two problems: (i) the pore structure of the adsorbents and (ii) the mass transfer resistance involved in the adsorption. The adsorption on a solid surface takes place in several steps, such as external diffusion, internal diffusion and actual adsorption. In general, the actual adsorption process is relatively faster than the previous two steps. Intraparticle diffusion has usually been considered as the rate-controlling step in liquid-phase adsorption. However, it is important to estimate the order of magnitude of the mass transfer coefficient. There are several correlations for estimating the

film mass transfer coefficient,  $k_f$ , in a batch system. In this work, the  $k_f$  was estimated from the initial concentration decay curve when the diffusion resistance did not prevail. The transfer rate of any species to the external surface of the adsorbent,  $N_A$ , can be expressed by:

$$N_A = k_f A_s (C - C_s) \quad (10)$$

where,  $N_A$  is the rate of mass transfer of the 2,4-DNP to the external surface of bamboo-based activated carbon (mol/s),  $k_f$  is the film mass transfer coefficient (m/sec) and  $A_s$  is the surface area of an bamboo-based activated carbon ( $m^2$ ). Rearrangement of Eq. (10) and approximation for a batch system with an adsorption time of less than 300 seconds, the following can be obtained:

$$\ln\left(\frac{C}{C_o}\right) = -k_f A_s t / V_s \quad (11)$$

$$A_s = 3M / \rho_p R_p \quad (12)$$

where,  $V_s$  is the volume of the solution ( $m^3$ ) and  $M$  is the total mass of bamboo-based activated carbon (kg), and  $\rho_p$  and  $R_p$  are the adsorbent density ( $kg/m^3$ ) and radius (m), respectively.

The external film mass transfer coefficients,  $k_f$ , can be obtained from the experimental data by plotting the value of  $\ln(C/C_o)$  vs.  $t$  at 298 K. The values of  $k_f$  for 2,4-DNP using bamboo based activated carbon are  $6.31 \times 10^{-5}$  (for pH 3.5),  $2.38 \times 10^{-5}$  (for pH 7), and  $2.03 \times 10^{-5}$  m/s (for pH 10), respectively. The coefficients of determination between measurement and calculation from the slope are 0.98, 0.97, and 0.98, respectively.

Fig. 6 shows the experimental data and model prediction for the adsorption rate of 2,4-DNP on bamboo-based activated carbon in terms of initial pH in a batch adsorber. The initial rate of adsorption of 2,4-DNP on bamboo-based activated carbon increased with decreasing initial pH. The

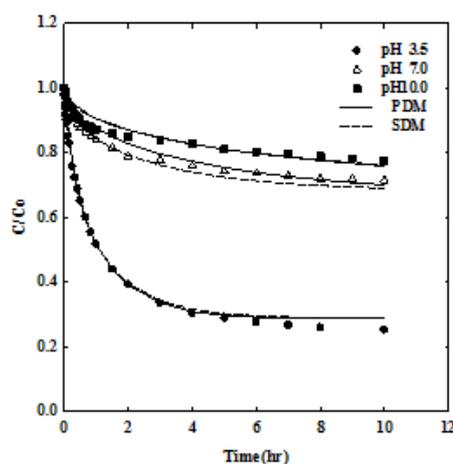


Fig. 6 Concentration Decay Curves Of 2,4-DNP On Bamboo-Based Activated Carbon At Different Initial Phs (298K).

differences in the rates of adsorption on the adsorbate were primarily attributable to the differences in the equilibrium adsorption capacities of the adsorbent (shown in Figs. 4 and 5). Also, the external film mass transfer coefficient and effective diffusion coefficients increased with decreasing initial solution pH. In this study, the pore diffusion

coefficient,  $D_p$ , and surface diffusion coefficient,  $D_s$ , were estimated using pore diffusion and surface diffusion models. The pore diffusion model predicted our experimental data well. The estimated values of  $k_f$ ,  $D_p$  and  $D_s$  for 2,4-DNP on bamboo-based activated carbon in a batch adsorber are listed in Table V.

The non-dimensional Biot number, Bi, shown in Table V was estimated using the following equation.

$$Bi = \frac{k_f d_p c_o}{2D_s \rho_p q_o} \quad (13)$$

The Biot number represents the ratio of the rate of transport across the liquid layer to the rate of diffusion within the particle. For  $Bi < 1$ , external mass transport resistance is the controlling mass transfer step, while for  $Bi > 100$ , surface diffusion is the controlling mass transfer mechanism. Bi numbers between 1 and 100 indicated that both mass transfer mechanisms are important for a particular process [9]. The observed Bi number values, changing from 2.19 to 5.56 for different initial pH, i.e. 3.5 - 10, indicated external mass transport resistance and surface diffusion were the controlling mass transfer step.

TABLE V  
KINETIC PARAMETERS OF 2,4-DNP ON BAMBOO-BASED ACTIVATED CARBON IN A BATCH ADSORBER (298 K).

| pH  | $K_f \times 10^5$<br>[m/s] | $D_s \times 10^{13}$<br>[m <sup>2</sup> /s] | $D_p \times 10^9$<br>[m <sup>2</sup> /s] | Bi<br>[-] |
|-----|----------------------------|---|--|-----------|
| 3.5 | 6.31                       | 8.87  | 2.65                                     | 5.56      |
| 7   | 2.38                       | 4.23  | 0.27                                     | 2.39      |
| 10  | 2.03                       | 1.57  | 0.13                                     | 2.19      |

The study of adsorption dynamics describes the adsorbate uptake rate and; evidently, this rate controls the residence time for the uptake of an adsorbate at the solid-solution interface. In this study, the kinetics of 2,4-DNP on bamboo-based activated carbon was analyzed using pseudo-first and pseudo-second order models. The pseudo first-order rate expression of Lagergren can be expressed as [10]:

$$\log(q_{eq} - q_t) = \log q_{eq} - \frac{k_1}{2.303} t \quad (14)$$

where  $q_{eq}$  and  $q_t$  are the amounts (mol/kg) of adsorbed 2,4-DNP on bamboo-based activated carbon at equilibrium and at time  $t$ , respectively and  $k_1$  is the rate constant (1/min).

Fig. 7 shows the Lagergren pseudo-first order kinetic plot for the adsorption of 2,4-DNP on bamboo-based activated carbon, where the first-order rate constant,  $k_1$  and theoretical  $q_e$  values were calculated from the slope and intercept, respectively. The results in Table VI show that the correlation coefficients for the first-order kinetic model were close to 1.0 for all cases, and the theoretical values of  $q_e$  agreed well with the experimental data. The values of  $k_1$  increased with decreasing pH of the solution, presumably due to the enhanced mass transfer of 2,4-DNP molecules to the surface of the bamboo-based activated carbon. This observation suggested that boundary layer resistance was not the rate limiting step. Similar result was previously reported by Ryoo and Seo [11]. The sorption kinetics may be described by a pseudo-second order model. The second order kinetic model is expressed as [12]:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t \quad (15)$$

where  $k_2$  is the rate constant of pseudo second-order kinetic model (kg/mol min).

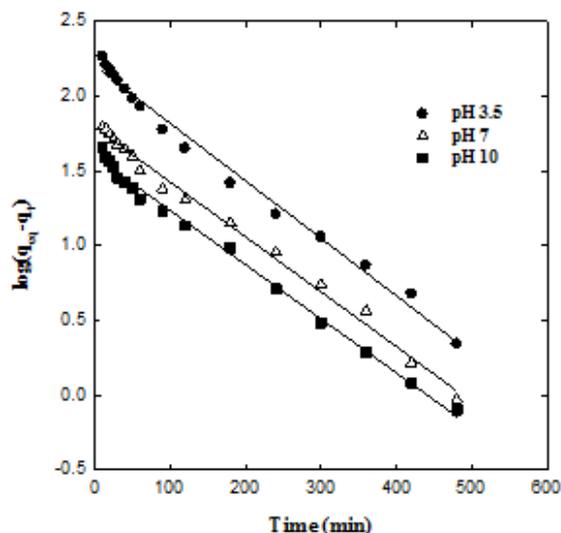


Fig. 7 Linearized Pseudo-First Order Kinetic Model In Terms Of Ph (298K).

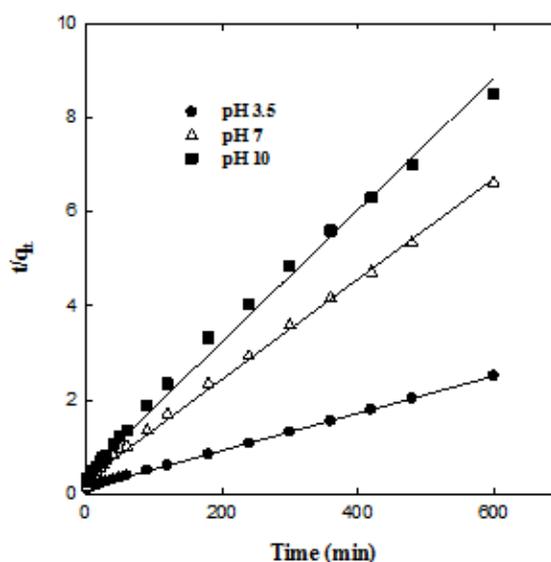


Fig. 8. Linearized Pseudo-Second Order Kinetic Model In Terms Of Ph (298 K).

The rate parameters  $k_2$  and  $q_e$  can be directly obtained from the intercept and slope of a plot of  $t/q_t$  versus  $t$ , as shown in Fig. 8. The values of  $k_2$  and  $q_e$  are shown in Table VI. Although the  $R^2$  values can be reasonably high, the calculated  $q_e$  values obtained from this kinetic model gave unreasonable values (Table VI), which were too high compared with those obtained experimentally. This suggested that the adsorption process does not follow the Lagergren expression for pseudo-second order adsorption.

TABLE VI  
KINETIC PARAMETERS FOR THE REMOVAL OF 2,4-DNP ON BAMBOO-BASED ACTIVATED CARBON.

| pH  | Pseudo-first order         |                   |       | Pseudo-second order               |                   |       | $q_{cal}$ |
|-----|----------------------------|-------------------|-------|-----------------------------------|-------------------|-------|-----------|
|     | $k_1 \times 10^3$<br>[min] | $q_e$<br>[mol/kg] | $R^2$ | $k_2 \times 10^3$<br>[kg/mol min] | $q_e$<br>[mol/kg] | $R^2$ |           |
| 3.5 | 8.85                       | 0.87              | 0.989 | 1.15                              | 1.37              | 0.999 | 0.87      |
| 7   | 8.45                       | 0.34              | 0.993 | 3.63                              | 0.51              | 0.997 | 0.31      |
| 10  | 8.34                       | 0.22              | 0.994 | 4.46                              | 0.39              | 0.995 | 0.27      |

#### IV. CONCLUSION

A bamboo-based activated carbon with large surface area was successfully prepared by KOH activation. The pore sizes of the activated carbon prepared with 60wt% KOH were mainly less than 10 nm. The specific surface area and pore volume values of the bamboo-based activated carbon were 1092 m<sup>2</sup>/g and 0.259 cc/g, respectively. The adsorption equilibrium and kinetic of 2,4-DNP on bamboo-based activated carbon were highly dependent on the initial pH and temperature. The maximum adsorption capacity of 2,4-DNP on bamboo-based activated carbon was 1.183mol/kg at pH 3.5 and 288 K. The differences in the rates of adsorption are primarily attributable to the differences in the equilibrium at the various pHs. The batch kinetic studies indicated the kinetics data tended to fit first-order kinetics.

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