Adsorption characteristics of methylene blue on poplar leaf in batch mode: Equilibrium, kinetics and thermodynamics

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(Received 22 March 2011 • accepted 13 August 2011)

Abstract—Adsorption characteristics of methylene blue (MB) from aqueous solution on natural poplar leaf were investigated. Batch experiments were carried out to study the effects of initial pH, contact time, adsorbent dosage, and initial MB concentration, salt concentration (Ca\(^{2+}\) and Na\(^{+}\)) as well as temperature on MB adsorption. The optimum condition for adsorption was found at pH 6-9 and adsorbent dosage of 2 g L\(^{-1}\). The equilibrium time was 240 min. The salt concentration had a negative effect on MB removal. The equilibrium data were analyzed with Langmuir, Freundlich and Koble-Corrigan isotherm models using nonlinear regression method. The adsorption process was more effectively described by Langmuir isotherm based on the values of the correlation coefficient \(R^2\) and chi-square statistic \(x^2\). The maximum monolayer adsorption capacity of poplar leaf from the Langmuir model was 135.35 mg g\(^{-1}\) at 293 K. The pseudo second order equation provided a better fit to experimental data in the kinetic studies. Intraparticle diffusion was involved in adsorption process, but it was not the only rate-controlling step. Thermodynamic quantities such as \(\Delta G\), \(\Delta H\) and \(\Delta S\) were calculated, indicating that the adsorption process was spontaneous and endothermic. Dye-adsorbent interactions were examined by FTIR and SEM analysis. The FTIR results suggested that there were hydroxyl and carboxyl groups on the surface of poplar leaf, which would make MB adsorption possible. The SEM images showed effective adsorption of MB molecules on the adsorbent surface.

Key words: Adsorption, Methylene Blue, Poplar Leaf, Isotherm, Kinetics, Thermodynamics

INTRODUCTION

Extensive use of synthetic dyestuffs in a number of industrial processes such as textile, paper, plastics, food, cosmetics, and leather has brought about intractable environmental problems. Even a thimbleful of dye in water is highly visible and disgusting. The presence of various dyes also causes damage to living beings in water by reducing light penetration and inhibition of photosynthesis [1]. In addition, the stability of most dye molecules under the condition of light, heat and chemicals leads to the fact that the dyeing effluents are difficult to degrade [2,3]. Economic, effective and feasible methods for comprehensive treatment of dyeing industrial effluents are therefore paid much more attention, owing to the increased environmental stress and consciousness from people.

Processing methods on dye removal are classified as coagulation, chemical oxidation, flocculation, hyper filtration, biological treatment and adsorption. Adsorption onto activated carbon has been widely used in actual effluent treatment as a highly effective process. However, the application of this material is limited due to high cost and the difficulty in regeneration [4,5]. Therefore, studies on dye removal have been focusing on searching for abundant and low-cost adsorbents. For instance, agricultural by-products such as neem sawdust [6], palm kernel fiber [7], apple pomace [1], rice husk [8,9], tree fern [10], lemon peel [11] and pineapple leaf [12] have been widely studied for dye removal.

The poplar leaf powders have been reported to have the potential as a novel adsorbent for heavy metals removal [13,14]. In this work, the biomaterial was tested for its ability to adsorb alkaline dyestuff from aqueous solution. The fallen poplar leaf could be obtained easily in campuses and city streets. Methylene blue dissolved in aqueous solution was taken as the simulated industrial effluent. Investigations were made to evaluate the potential of poplar leaf for MB removal in batch system. The respective thermodynamic and kinetic studies were also carried out, and the isotherm constants for the Langmuir, Freundlich and Koble-Corrigan models were calculated by nonlinear regression analysis.

MATERIALS AND METHODS

1. Preparation of Adsorbent and MB Solution

The fallen poplar leaves were collected from Zhengzhou University in autumn. Then the materials were continuously washed with distilled water to remove the surface dirty particles. The washed leaves were dried at 80 °C in an oven for several hours until constant weight and crushed to particle sizes in the range of 20-40 mesh with a grinder (JFSD-100, China).

Methylene Blue widely used in synthetic fiber and paper industries was obtained from Zhengzhou Chemical Corporation in China. Its chemical structure is shown in Fig. 1. The molecular weight of methylene blue is 373.9 g mol\(^{-1}\). The stock solution of MB was prepared by dissolving MB (0.2 g) into distilled water (1 L). Then the stock solution was diluted to working concentrations ranging from 20 to 200 mg L\(^{-1}\).
2. Methods

Both poplar leaf and MB solution (20 mL) at the desired concentration were placed in a 50 mL conical flask. Then the conical flask was agitated at 100 rpm min$^{-1}$ in a water bath shaker at the needed temperature to attain equilibrium. The solution and solid phase were separated by filtration with syringe filter. The filtrate was analyzed using UV-vis Spectrophotometer (WFZ UV-2102PC) for MB concentration. Percent removal efficiency ($\%R$) and the amount of MB adsorbed on per unit mass of poplar leaf ($q$) were determined respectively as follows:

$$\%R = \frac{C_0 - C_f}{C_0} \times 100$$  \hspace{1cm} (1)

$$q = \frac{(C_0 - C_f) \times V}{m}$$  \hspace{1cm} (2)

Where $C_0$ and $C_f$ (mg L$^{-1}$) are the initial MB concentration and final MB concentration after adsorption, $V$ (L) the volume of MB solution, and $m$ (g) is the total mass of poplar leaf.

Influences of contact time, initial pH, adsorbent dosage, dye concentration, salt concentration and temperature were investigated as described above.

3. Characterization of Poplar Leaf

The presence of different functional groups present in poplar leaf was characterized with a FTIR spectrophotometer (PE-1710, USA). The poplar leaf of 0.02 g and the KBr powders were mixed adequately, and then the mixture was pressed to a flake. The FTIR spectrum was recorded by scanning of the spectrophotometer. The spectral range changed from 4,000 to 400 cm$^{-1}$. Scanning electron micrographs of poplar leaf were obtained by scanning electron microscopy (JEOL 6335F-SEM, Japan). Before analysis, the samples were coated with a thin layer of gold under an argon atmosphere. An element analyzer (EA1112, USA) was used to determine the major elements of poplar leaf. The point of zero charge (pH$_{PZC}$) of poplar leaf was measured at different pH values (2-11) at a constant electrolyte concentration of 0.01 mol L$^{-1}$ by means of a pH-meter (pHS-3C, China). Then initial and final pH after an equilibrium time of 240 min was also measured.
RESULTS AND DISCUSSION

1. Property of Adsorbent

The FTIR analysis confirmed functional groups on the surface of poplar leaf. The infrared spectrum of poplar leaf before adsorption is presented in Fig. 2(a). The band at 3,419 cm$^{-1}$ is associated with O-H stretching vibration. The strong peak at around 1,626 cm$^{-1}$ is caused by C=O stretching band of carboxyl groups. A 1,432 cm$^{-1}$ band is due to C-O stretching from carboxyl groups. The infrared spectrum of poplar leaf after adsorption is shown in Fig. 2(b). The band of O-H stretching vibration is slightly shifted from 3,419 to 3,415 cm$^{-1}$. The peaks of C=O stretching band and C-O stretching from carboxyl groups are also shifted to 1,602 cm$^{-1}$ and 1,491 cm$^{-1}$, respectively.

FTIR spectrum indicated that there are large numbers of hydroxyl and carboxyl groups on the surface of poplar leaf, which possibly react with dye molecules in aqueous solution. The surface of poplar leaf is negatively charged at proper pH due to deprotonation of acid groups such as carboxyl and hydroxyl groups. These groups may be the major adsorption sites for cationic dye.

The scanning electron micrograph of original poplar leaf (Fig. 3(a)) at a magnification of 2,000 times represented highly heterogeneous surface with porous structure. The rough and porous surface contributed to an increase in surface area of poplar leaf [15]. The SEM image of poplar leaf after MB adsorption (Fig. 3(b)) shows significant differences from Fig. 3(a), indicating an effective adsorption of MB molecules onto poplar leaf [16]. The results of element analysis of poplar leaf were found to be C 43.79%, H 6.25%, N 1.54%, S 0.22%.

The pH$_{PZC}$ is a concept related to the phenomenon of adsorption that describes the condition when the electrical charge density on the adsorbent surface is zero. The pH$_{PZC}$ of poplar leaf was obtained from the plot of $\Delta$pH (the difference between initial pH and final pH at equilibrium) versus initial pH. The results shown in Fig. 4 indicate that the pH$_{PZC}$ of poplar leaf was around 5.6. The adsorbent surface was positively charged at pH<pH$_{PZC}$, and the adsor-
bent presented a negative surface charge at pH > pH_{PZC}.

2. Effect of Contact Time

Experiments were performed to investigate the effect of contact time (10 to 300 min) for MB (C_0=100 mg L^{-1}) removal from aqueous solution at 293 K. In Fig. 5, MB adsorption represents a two-step kinetic process. The rate of MB adsorption on poplar leaf was rapid in the beginning, but it gradually reduced with time until the system reached equilibrium. It was evident that the amount of MB adsorbed per unit mass of poplar leaf increased quickly in the first stage. The second stage was a much slower adsorption process after 120 min. The values of q changed slowly. So within 180 min, adsorption equilibrium was nearly established. In the following batch experiments, 240 min was taken to ensure equilibrium.

3. Effect of Initial pH

Initial pH of dye solution has an effect on the property of surface charge, which plays an important role in dye removal. Fig. 6 shows the effect of solution pH (2-10) for MB removal. The solution pH was adjusted with 0.1 mol L^{-1} HCl and 0.1 mol L^{-1} NaOH. The dye adsorption on poplar leaf was significantly affected over the pH range of 2-4. It was observed that the values of %R increased from 38% to nearly 80% and the adsorption quantity increased from 20 to 40 mg g^{-1} when the value of pH increased from 2 to 4. The results, however, show the constant MB adsorption when initial solution pH varied from 5 to 10. The values of %R and adsorption quantity were approximately unchanged.

It may be explained that at low pH, active groups on the surface of poplar leaf such as carboxyl, hydroxyl groups were more protonated, and positive charges surrounded the surface of adsorbent. The phenomenon hindered the adsorption of basic dye due to competition for adsorption sites between dye cations and protons. When the initial pH increased, the active groups on the surface of adsorbent may have become negatively charged, which provided more binding sites for the positively charged dye cations due to electrostatic attraction [1,9]. The results of solution pH experiments agreed with the adsorbent surface property represented from FTIR analysis and pH_{PZC} measurement. We concluded that the higher pH (6-9) favored MB removal on poplar leaf in practice. The pH of original solution was near 7, and it was not adjusted in subsequent batch experiments. The adsorption mechanism explained that poplar leaf was favorable to remove basic dye.

4. Effect of Adsorbent Dosage

The plot of adsorption capacity and percent removal efficiency versus the adsorbent dosage at initial MB concentration of 100 mg L^{-1} is shown in Fig. 7. The percent removal efficiency increased from 54.4% to 88.3% as the adsorbent dosage increased from 0.5 to 8 g L^{-1}, while the adsorption capacity q_e decreased from 108.7 to 11.04 mg g^{-1} with an increase in adsorbent dosage. At higher adsorbent dosage, many more adsorption sites were available and adsorption surface area was increased, which contributed to an increase of MB amount adsorbed on adsorbents [7]. However, there was a very fast superficial adsorption onto the poplar leaf surface at higher adsorbent dosage, which produced a lower solute concentration in the solution than when the poplar leaf dosage was lower. Splitting effects of concentration gradient caused a decrease in q_e [17-19].

Fig. 6. Effect of initial pH for adsorption of MB on poplar leaf at 293 K (C_0=100 mg L^{-1}; V=0.01 L; adsorbent dosage=2 g L^{-1}).

Fig. 7. Effect of adsorbent dosage for the adsorption of MB on poplar leaf at 293 K (C_0=100 mg L^{-1}; V=0.01 L).

Fig. 8. Effect of salt concentration for adsorption of MB on poplar leaf at 293 K (C_0=100 mg L^{-1}; V=0.01 L; adsorbent dosage=2 g L^{-1}).
The optimum adsorbent dosage was taken as 2 g L\(^{-1}\) for this study on MB removal.

5. Effect of Salt Concentration (NaCl and CaCl\(_2\))

It is essential to investigate the effect of salt concentration (NaCl and CaCl\(_2\)) for dye removal because of the presence of salts in actual dyestuff effluents. This experiment was carried out by dissolving calculated mass of NaCl and CaCl\(_2\) into MB solution of 0.01 L. It was observed from Fig. 8 that both Na\(^+\) and Ca\(^{2+}\) had negative effects on MB removal. The adsorption capacity decreased from 42.36 to 10.36 mg g\(^{-1}\), and the percent removal efficiency decreased from 83.03\% to 21.24\% with an increase in Ca\(^{2+}\) concentration from 0 to 0.3 mol L\(^{-1}\). The values of \(q_e\) decreased from 42.36 to 17.17 mg g\(^{-1}\), and the percent removal efficiency decreased from 83.03\% to 34.68\% by increasing Na\(^+\) concentration from 0 to 0.3 mol L\(^{-1}\).

The possible reason for the negative effect was that Na\(^+\) and Ca\(^{2+}\) competed with dye cations for active sites on the surface of adsorbent. As Ca\(^{2+}\) had more contribution to ionic strength and more positive charge than Na\(^+\), the effect of Ca\(^{2+}\) on adsorption was stronger than Na\(^+\) in the same mole concentration [20,21].

6. Effect of Temperature and Initial MB Concentration

Removal of MB by poplar leaf was performed by varying dye concentration from 20 to 200 mg L\(^{-1}\) at temperature 293, 303 and 313 K, respectively. Fig. 9 shows that adsorption capacity on per unit weight of adsorbent increased from 8.43 to 69.43 mg g\(^{-1}\) at 293 K, from 8.51 to 70.49 mg g\(^{-1}\) at 303 K, and from 8.62 to 71.4 mg g\(^{-1}\) at 313 K by increasing MB concentration. At the same temperature, the increased initial MB concentration resulted in a higher driving force for mass transfer due to the fact that active sites on poplar leaf were surrounded by more MB cations when initial MB concentration was high [22]. Hence, a higher initial MB concentration favored the adsorption process.

Adsorption of MB on poplar leaf was enhanced by increasing the temperature from 293 to 313 K at different initial dye concentrations. According to Fig. 9, there was a slight increase in equilibrium adsorption capacity at the same dye concentration when temper-
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The equilibrium adsorption isotherm is most important in investigating adsorption mechanism. Surface property, adsorption affinity of adsorbent and the maximum adsorption capacity can be obtained from the adsorption isotherm and correlative constants. In this study, experimental adsorption equilibrium data obtained at 293, 303 and 313 K were fitted by nonlinear regression method with Langmuir and Freundlich models. The fitted curves with the two well-known isotherm models are shown in Fig. 10.

Langmuir isotherm equation is described as:

\[ q_e = \frac{q_m a_L C_e}{1 + a_L C_e} \]  

(5)

where \( a_L \) is Langmuir equilibrium constant related to binding energy of adsorption, and \( q_m \) is the maximum monolayer adsorption capacity based on hypothesis of homogeneous surface for adsorption. The calculated values of \( a_L, q_m \), nonlinear chi-square statistic \( \chi^2 \) and nonlinear regression coefficient \( R^2 \) at different temperature are given in Table 3. The uncertainties of some parameters are also presented in Table 3. It was seen that the maximum monolayer capacity of poplar leaf is determined as 135.35, 142.77 and 147.42 mg g\(^{-1}\) for 293, 303 and 313 K. The values of \( q_m \) increased slightly on increasing the temperature, while equilibrium constant \( a_L \) decreased as temperature increased. Nonlinear regression coefficients \( R^2 \) were all above 0.985.

Chi-square analysis was also used as an evaluating indicator for Langmuir model, which indicated that the Langmuir model fits were quite well for experimental data.

A comparison of adsorption capacity \( q_m \) of methylene blue on various biosorbents is listed in Table 4. It was evident from the published literature that poplar leaf has a lower adsorption capacity on MB compared with Brazilian pine-fruit shell and lotus leaf, and a higher adsorption capacity compared to peanut husk and phoenix leaf. In addition, poplar leaves are abundant and cheap. There is a huge potential to use poplar leaf for the adsorption of MB molecules from industrial effluents.

Freundlich isotherm equation is defined as follows:

\[ q_e = K_F C_e^{1/n} \]  

(6)

where \( K_F \) and \( 1/n \) are Freundlich constants. \( K_F \) is related to the adsorption capacity of the adsorbent, and \( 1/n \) is related to the heterogeneity of the surface. The uncertainties of some parameters are also presented in Table 4. It was seen that the maximum monolayer capacity of poplar leaf is determined as 0.185, 1.098, and 1.045 mg g\(^{-1}\) for 293, 303 and 313 K, respectively. The values of \( q_e \) increased slightly on increasing the temperature, while equilibrium constant \( K_F \) decreased as temperature increased. Nonlinear regression coefficients \( R^2 \) were all above 0.985.

Table 3. Langmuir, Freundlich and Koble-Corrigan isotherm parameters for MB adsorption onto fallen poplar leaf at different temperatures using nonlinear regressive method

<table>
<thead>
<tr>
<th></th>
<th>293 K</th>
<th>303 K</th>
<th>313 K</th>
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<tbody>
<tr>
<td><strong>Langmuir</strong></td>
<td></td>
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<tr>
<td>( a_L ) (L mg(^{-1}))</td>
<td>0.0179±0.00216</td>
<td>0.0170±0.00252</td>
<td>0.0169±0.00342</td>
</tr>
<tr>
<td>( q_m ) (mg g(^{-1}))</td>
<td>135.35±9.620</td>
<td>142.77±12.805</td>
<td>147.42±18.348</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.995</td>
<td>0.993</td>
<td>0.988</td>
</tr>
<tr>
<td>( \chi^2 )</td>
<td>2.61</td>
<td>3.71</td>
<td>6.83</td>
</tr>
<tr>
<td><strong>Freundlich</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( K_F ) [mg g(^{-1}) (L mg(^{-1}))(^{1/n})]</td>
<td>4.883±0.784</td>
<td>4.791±0.783</td>
<td>4.827±0.898</td>
</tr>
<tr>
<td>( 1/n )</td>
<td>0.657±0.043</td>
<td>0.669±0.044</td>
<td>0.675±0.051</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.985</td>
<td>0.985</td>
<td>0.981</td>
</tr>
<tr>
<td>( \chi^2 )</td>
<td>7.95</td>
<td>8.18</td>
<td>10.72</td>
</tr>
<tr>
<td><strong>Koble-Corrigan</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( A )</td>
<td>1.915±0.653</td>
<td>2.106±0.848</td>
<td>2.237±1.216</td>
</tr>
<tr>
<td>( B )</td>
<td>0.01629±0.0033</td>
<td>0.01626±0.0035</td>
<td>0.01638±0.0045</td>
</tr>
<tr>
<td>( n )</td>
<td>1.098±0.138</td>
<td>1.0603±0.165</td>
<td>1.045±0.226</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.996</td>
<td>0.993</td>
<td>0.988</td>
</tr>
<tr>
<td>( \chi^2 )</td>
<td>2.86</td>
<td>4.35</td>
<td>8.14</td>
</tr>
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Table 4. Comparison of adsorption capacity of methylene blue with various biosorbents

<table>
<thead>
<tr>
<th>( q_m ) (mg g(^{-1}))</th>
<th>Biosorbents</th>
<th>References</th>
</tr>
</thead>
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<tr>
<td>135.4</td>
<td>Poplar leaf</td>
<td>This paper</td>
</tr>
<tr>
<td>72.1</td>
<td>Peanut husk</td>
<td>[26]</td>
</tr>
<tr>
<td>80.9</td>
<td>Phoenix leaf</td>
<td>[21]</td>
</tr>
<tr>
<td>185.2</td>
<td>Brazilian pine-fruit shell</td>
<td>[27]</td>
</tr>
<tr>
<td>221.7</td>
<td>Lotus leaf</td>
<td>[28]</td>
</tr>
</tbody>
</table>
finity and the adsorption capacity of adsorbent and \(1/n\) is related to the surface heterogeneity. The calculated \(1/n\) (0.1<\(1/n\)<1) represents an isotherm curve form which indicates powerful adsorption attraction between solid phase and liquid phase in the adsorption system [29]. The magnitude of \(R^2\) and \(x^2\) indicated the fit of the data to Freundlich equation, which meant the heterogeneous surface of poplar leaf [30]. Based on a comparison of values of \(R^2\) and \(x^2\), the adsorption isotherms were better described by the Langmuir equation.

A three-parameter isotherm equation, Koble-Corrigan, was used to analyze equilibrium data, and expressed as:

\[
q_e = \frac{ACe^n}{1 + BCe^n}
\]  
(7)

Where \(A\), \(B\), \(n\) are Koble-Corrigan parameters. The Koble-Corrigan model is a combination of Langmuir and Freundlich model. The fitted curves are shown in Fig. 11 and the values of related parameters are listed in Table 3. The values of parameter \(n\) are close to 1, which indicates that the isotherms are approaching more of the Langmuir form. The values of \(A\) increased and parameter \(B\) kept unchanged with temperature changing from 293 to 303 K. The Koble-Corrigan model was suitable for experimental data well based on values of nonlinear regression coefficient \(R^2\) (\(R^2\)>0.988) and \(x^2\) (\(x^2\)<8.14), which suggested that equilibrium data conformed to Freundlich isotherm at low dye concentration and followed Langmuir model at higher dye concentration [31].

9. Adsorption Kinetics

Adsorption rate constants and intraparticle diffusion mechanism were investigated using the pseudo first-order kinetic model, pseudo second-order kinetic model and intraparticle diffusion equation by linear regression method, respectively.

The pseudo first-order kinetic model is expressed as:

\[
\log(q_e - q_t) = \log q_e - \frac{k_1 t}{2.303}
\]  
(8)

Where \(q_e\) and \(q_t\) (mg g\(^{-1}\)) are adsorption capacity on per unit dose of adsorbent at equilibrium and at time \(t\) (min), \(q_e\) the predicted values of \(q_e\) from pseudo first-order kinetic model and \(k_1\) (min\(^{-1}\)) the first-order rate constant. The plot of log\((q_e - q_t)\) versus \(t\) is linear. The rate constant \(k_1\) is calculated from the slope of the plot.

The pseudo second-order kinetic equation is

\[
\frac{1}{q_e} - \frac{1}{q_e} = \frac{1}{k_2 q_m^2} + \frac{t}{q_m^2}
\]  
(9)

Where \(k_2\) (g mg\(^{-1}\) min\(^{-1}\)) is the pseudo second-order rate constant and \(q_m\) (mg g\(^{-1}\)) is the calculated value of adsorption capacity at equilibrium according to pseudo second-order kinetic equation. The values of \(k_2\) and \(q_m\) were obtained from the plot of \(t/q_e\) against \(t\).

Fig. 12 and Fig. 13 show the fitted curves with the pseudo first- and second-order model. The pseudo second-order kinetic model shows a better fit to the whole range of contact time due to higher value of correlation coefficient \(R^2\) and lower value of standard deviation (SD) listed in Table 5. Moreover, the predicted \(q_e\) from pseudo
second-order model is more close to experimental data. The pseudo first-order model was just applicable for the beginning part of adsorption process. The conclusion expressed that the rate of adsorption process may be controlled by chemical process [32].

Intraparticle diffusion equation is described as

$$q = k t^{1/2} + C$$  \hspace{1cm} (10)

where $k$, (mg g$^{-1}$ min$^{-1/2}$) is intraparticle diffusion rate constant, and $C$ is the intercept. The plot of $q$ versus $t^{1/2}$ is used to analyze the diffusion mechanism.

The time dependence of $q$ in Fig. 14 could be represented in two straight lines which could be well fitted linearly. The multi-linearity relation suggested that the intraparticle diffusion model was dominant in MB adsorption, although the MB adsorption was affected by more than one process [33]. The $q$ in the first portion showed a drastic increase with time, which was attributed to the rapid diffusion of dyes through the solution to the external surface of adsorbent. The second portion corresponded to the final equilibration process where the intraparticle diffusion began to slow down. If the lines pass through the origin, then intraparticle diffusion is the only rate controlling step [34]. The two straight lines didn’t go through the origin, which suggested that the adsorption process was possibly controlled by some other mechanisms such as the boundary layer effect [12,34].

CONCLUSION

Natural poplar leaf was evaluated as an effective material for MB removal from aqueous solution in batch mode. Adsorptive equilibration could be achieved within 240 min. The amount of dye adsorbed on poplar leaf was influenced substantially by initial pH of dye solution and adsorbent dosage. The salt concentration (Cr$^+$ and Na$^+$) had a negative influence on the dye uptake to some extent. The increasing temperature and dye concentration was favorable for MB removal. MB adsorption on the fallen poplar leaf was found to be a spontaneous and endothermic process according to the thermodynamic study. The adsorption process was found to follow the pseudo second-order kinetics. The intraparticle diffusion model gave two linear regions, which indicated that MB adsorption followed multiple sorption rates. The Langmuir isotherm model well described MB adsorption. The maximum monolayer adsorption capacity determined with the Langmuir model was 135.35 mg g$^{-1}$ at 293 K. The dye-adsorbent interactions were confirmed by FTIR and SEM analysis, and the functional groups such as carboxyl and hydroxyl on the adsorbent surface were responsible for MB adsorption.

ACKNOWLEDGEMENTS

This study was supported by Biochemical Engineering Research Center in Zhengzhou University.

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Korean J. Chem. Eng. (Vol. 29, No. 4)