

Upgrading of Bio-oil: Removal of the Fermentation Inhibitor (Furfural) from the Model Compounds of Bio-oil Using Pyrolytic Char

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ABSTRACT: To effectively transform sugar-enriched bio-oil to fuel ethanol, it is important to develop a cost-effective approach to the removal of the fermentation inhibitors. In this study, pyrolytic char from biomass pyrolysis was utilized to remove the representative fermentation inhibitor (furfural) in order to develop a new method to upgrade the bio-oil, which can then be used to produce bioethanol. As the bio-oil compound is complex, the method was initially explored using model compounds. The properties of the pyrolytic char (bamboo charcoal) were first analyzed and the effects of various experimental parameters on the adsorptive removal of furfural were evaluated. Results showed that temperature has little effect on the adsorption of furfural. Because of the π - π interaction between the adsorbent and adsorbate, the bamboo charcoal tends to adsorb furfural despite the presence of sugar. The kinetic mechanism of furfural onto the pyrolytic char was proposed. The intraparticle diffusion model revealed that the pore diffusion (from macropore to micropore) is the main rate-controlling step in the adsorption process of furfural. Results confirmed that pyrolytic char is an effective and promising adsorbent for the removal of furfural from bio-oil with minimal loss of sugars.

1. INTRODUCTION

The utilization of biomass-derived fuels can significantly address the concerns of depleting fossil fuel reserves and greenhouse gas emissions.¹ Fermentable sugars produced from lignocellulosic biomass show remarkable potential as a cost-effective and renewable feedstock for the production of bioethanol, which will promote the large-scale commercial utilization of lignocellulosic materials.^{1,2} To obtain fermentable sugars from lignocellulosic material, three main technologies are currently employed: acid hydrolysis, enzymatic hydrolysis, and a pyrolysis process.³ Recent advances in the pyrolysis process of lignocellulosics may offer a new alternative for biomass pretreatment and saccharification.⁴ By adjusting the reaction conditions of pyrolysis, the sugars, such as levoglucosan and D-glucopyranose, can be easily formed.⁵ The sugar-enriched bio-oil might be a promising alternative to be used as a fermentative carbon or energy source in the fermentation industry.^{6,7} However, furfural, which is a typical fermentation inhibitor, will be simultaneously generated in the hydrolysis or pyrolysis process, which will restrict the growth of micro-organisms.⁸ The content of furfural in bio-oil formed in the pyrolysis process can even be up to 10 wt %.⁹

Various methods have been taken to remove furfural and other fermentation inhibitors from the hydrolyzates or bio-oil, including overliming,^{10,11} ion exchange,¹² treatment with enzymes,⁸ treatment with micro-organisms,^{8,13} treatment with polymeric sorbents,¹⁴ and adsorption on activated carbon.^{15,16} Among them, adsorption is proven to be a reliable technology, and it can effectively remove inhibitors and transform bio-oil into product whose fermentation performance is similar to that of an inhibitor-free model substrate.¹⁷ However, the polymeric sorbent or activated carbon is expensive, since it is very difficult to regenerate the powdered activated carbon, and each thermal

reactivation cycle of the granular sorbent will generally cause a 10% loss.¹⁷

The pyrolytic char is a byproduct from biomass pyrolysis process, which has received less attention in the field of biofuel research than bio-oil or gas. The pyrolytic char is a low-cost and renewable carbon material with porous structures that is a potential adsorbent, and it has been used in adsorption applications for heavy metals, Methylene Blue, copper, etc.^{18–22} However, to our best knowledge, there is no report related to the removal of the fermentation inhibitor by using the pyrolytic char.

Therefore, the objective of the present work is to evaluate the possibility of using the pyrolytic char as the adsorbent to remove furfural in bio-oil. Because of the complexity of pyrolytic bio-oil, the bio-oil model compounds are used to investigate the adsorption of furfural. Bamboo chips, which are a typical forestry waste in China, are used as raw material to produce pyrolytic char. As reported, bamboo resource is very abundant in China. The annual production of bamboo charcoal is ~40 000 tons, with a price of only 1/3 to 1/5 of the activated carbon in China.^{23,24} The cost-effective pyrolytic char is first characterized to relate the composition and surface properties of the char to its adsorptive affinities. The effects of various experimental parameters on the removal of furfural from the model compounds of bio-oil are then evaluated extensively. The kinetic and adsorption mechanisms of furfural onto the pyrolytic char are also discussed.

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2. MATERIALS AND METHODS

2.1. Chemicals and Materials. The pyrolytic char in this study was prepared from bamboo chips pyrolyzed in a bench-scale fluidized bed reactor at the temperature of 823 ± 20 K. The details of experimental setup and the preparation method can be found in the literature.²⁵ The solid residue (named bamboo charcoal) with a particle size of 0.25–0.83 mm was collected and kept in a desiccator for later use. The model compounds of bio-oil were prepared by dissolving accurate amounts of furfural in the deionized water to simulate the typical inhibitor concentrations ($C_i = 5\text{--}20$ g/L) in bio-oil. The glucose was selected as the model for sugars in bio-oil and the concentration of glucose (C_g) was 10 g/L. All the reagents used in this study were analytical grade.

2.2. Char Characterization. The pore structure of the bamboo charcoal was studied using liquid nitrogen adsorption at 77 K in an ASAP 2020 automatic apparatus (Micromeritics, USA). Nitrogen adsorption isotherms were measured over a relative pressure (P/P_0) ranging from $\sim 10^{-5}$ to 0.995. The surface area, pore volume, and average pore size of the bamboo charcoal were determined using the Brunauer–Emmett–Teller (BET) method.²⁶ The pore size distribution was obtained with the Barrett–Joyner–Halenda (BJH) method.²⁷ The carbon, hydrogen, and nitrogen (CHN) contents in the bamboo charcoal were measured using an EL-2 CHN elemental analyzer (Vario, Germany), and the oxygen content was obtained by difference. The organic functional group was determined in the range of 400–4000 cm^{-1} , using a potassium bromide pelletization method (carbon loading of ca. 1.0 wt.%) on a VERTEX 70 spectrophotometer (Bruker, Germany).

2.3. Adsorption Experiment. In each adsorption experiment, a certain amount of the bamboo charcoal was added into a conical flask (250 mL) with 100 mL furfural solution of known initial concentration sealed with a rubber stopper. The flasks were agitated in a temperature-controlled orbital shaker at a constant speed of 100 rpm at 298 K. The samples were withdrawn at appropriate time intervals, filtered, and then analyzed for the residual furfural concentration using a Lambda 35 UV-spectrophotometer (Perkin–Elmer, USA) at 277 nm. All experiments were carried out at the natural pH of the solutions (pH 5.0–5.6, depending on the furfural concentrations).

To determine the optimal dose of the bamboo charcoal, different amounts of bamboo charcoal was immersed in a 100-mL furfural solution for 24 h. The effects of the temperature on the adsorption characteristics were investigated at 298, 308, 318, 328, and 338 K. The kinetics of adsorption was determined by analyzing the adsorptive uptake of the furfural from the furfural solution of different initial concentrations at different time intervals. To investigate the adsorption in sugar solutions, a known amount of glucose was also dissolved in the furfural solution in order to evaluate the competitive adsorption between furfural and glucose. The glucose concentration was determined using an eB-G16 Glucose-Analyzer (Yima, China). All experiments were performed in triplicate. Calibration curves of different compounds were established before each sample run and the blank experiment was also implemented.

2.4. Calculation of Removal Efficiency and Adsorption Capacity. The removal efficiency (E), the amount of adsorbate adsorbed per unit mass of adsorbent at time t (q_t , mg/g) and the amount of adsorbate adsorbed at equilibrium (q_e , mg/g), were calculated using the following equations:

$$E (\%) = \left(\frac{C_0 - C_t}{C_0} \right) \times 100 \quad (1)$$

$$q_t = \frac{V(C_0 - C_t)}{w} \quad (2)$$

$$q_e = \frac{V(C_0 - C_e)}{w} \quad (3)$$

where C_0 and C_e are the initial and the equilibrium concentration of adsorbates (g/L), respectively; C_t is the instant concentration of

adsorbates (g/L) at time t ; V is the volume of the solution (mL); and w is the mass of the bamboo charcoal (g) in this study.

3. RESULTS AND DISCUSSION

3.1. Physicochemical Properties of Pyrolytic Char.

3.1.1. Pore Property. The adsorption and desorption isotherms of N_2 at 77 K for the bamboo charcoal are plotted in Figure 1.

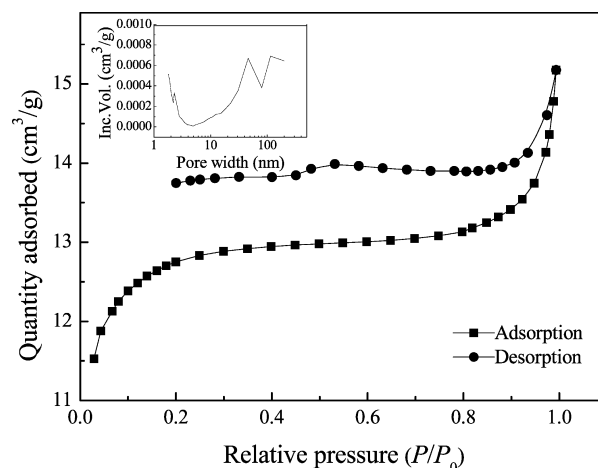


Figure 1. N_2 adsorption and desorption isotherms at 77 K for the bamboo charcoal.

The shape of the isotherm suggests that the isotherm of the bamboo charcoal is of Type II, according to IUPAC classifications.²⁸ The adsorption capacity of the bamboo charcoal increased sharply at low relative pressures, and then increased slightly with the increase of the relative pressure ranging from 0.2 to 0.8. Afterward, the adsorption capacity of the bamboo charcoal increased rapidly again. The shape of the isotherm also revealed that the bamboo charcoal mainly includes micropores along with a certain amount of macropores.

The pore size distribution of the bamboo charcoal investigated with the BJH method is shown in Figure 1 (inset). It can be observed that the main peaks of the bamboo charcoal appeared when the pore size is less than 2 nm or larger than 45 nm. The BET surface area of bamboo charcoal was 42.8 m^2/g , and the average pore diameter was 2.04 nm. The analysis of the BJH adsorption pore distribution of the bamboo charcoal showed that the micropores and the macropores accounted for $\sim 81\%$ and $\sim 16\%$ of the total pore area, respectively, while the mesopores accounted for only $\sim 3\%$. In other words, the bamboo charcoal mainly consists of micropores along with some macropores, but few mesopores.

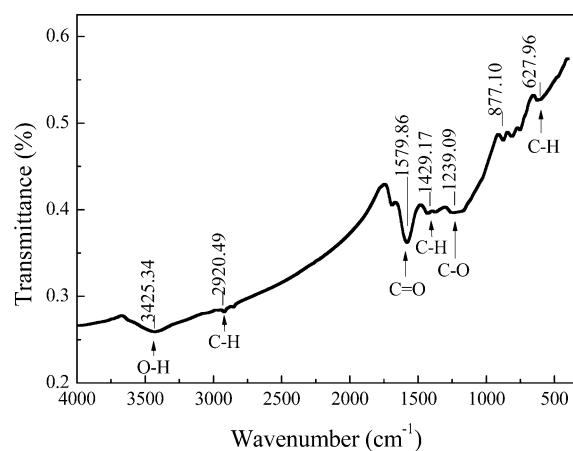
3.1.2. Chemical Composition of Pyrolytic Char. **3.1.2.1. Elemental Analysis.** Table 1 shows the C, H and O contents of the bamboo charcoal compared with some samples from literature.²⁹ The production of the bamboo charcoal through fluidized bed pyrolysis is a typical carbonization process. In general, with the increase of pyrolytic temperature, the carbon content increases, whereas the oxygen and hydrogen contents decrease, indicating an increasing carbonization degree of chars.²⁹ Considering that H is primarily associated with plant organic matter, the degree of carbonization can be described by the molar H:C ratio.³⁰ The H:C ratio for the bamboo charcoal is 0.55, which is the same as that of WC-573 (wheat char obtained from pyrolysis of wheat at 573 K, Table 1). Compared

Table 1. Elemental Compositions of Bamboo Charcoal in This Work and Wheat Char (WC) and Activated Carbon from Ref 29

sample	pyrolysis temp (K)	Elemental Composition (wt %)				H:C molar ratio	O:C molar ratio
		C	O	H	others		
bamboo charcoal	823	63.5	32.6	2.9	1.0	0.55	0.38
WC-573	573	69.2	26.6	3.2	1.0	0.55	0.29
WC-773	773	83.4	10.1	2.5	4.0	0.36	0.09
WC-973	973	88.0	6.0	1.1	4.9	0.15	0.05
activated carbon		87.6	7.0	0.9	4.5	0.12	0.06

with WC-973 (wheat char obtained at 973 K, Table 1) with an H:C ratio of 0.15, and activated carbon with an H:C ratio of 0.12, the bamboo charcoal is not fully carbonized due to the short residence time in fluidized bed reactor. On the other hand, the much higher H:C ratio of the bamboo charcoal suggests that it contains a large amount of organic residue. Table 1 also shows that the O:C ratio of the bamboo charcoal is 0.38 and that of WC-573 is 0.29, which indicates that these two samples are similar in composition, even though the bamboo chips underwent a higher carbonization temperature. Since the molar O:C ratio can be used to approximate the surface hydrophilicity,²⁹ the bamboo charcoal is more hydrophilic than WC-573, suggesting that it has much higher polar-group contents. However, the high hydrophilicity of the bamboo charcoal may cause a conflict between the water and adsorbates in solutions.

3.1.2.2. Fourier Transform Infrared Spectroscopy (FT-IR) Analysis. Figure 2 shows the infrared spectra of the bamboo

**Figure 2.** Fourier transform infrared (FT-IR) spectra of the bamboo charcoal.

charcoal. The broad bands observed in the spectra are expected due to the functional groups, which can be found in a wide range of different electronic environments. In the region of 3600–3100 cm^{-1} , a strong peak located at 3425 cm^{-1} can be assigned to O–H stretching vibrations. The peak at 2920 cm^{-1} is due to the presence of aliphatic CH, CH_2 , and CH_3 groups.³¹ Three prominent peaks are also observed in the region between 2000 cm^{-1} and 1000 cm^{-1} , which can be attributed to the C=O stretching vibrations, because of the presence of carbonyl and carboxyl groups.³² For example, the peak at 1580 cm^{-1} may

be attributed to the presence of the ionoradical structures C=O. These functional groups will form the adsorption active sites for furfural removal.

3.2. Adsorption Characteristics of Bio-oil Model Compounds.

3.2.1. Effect of Adsorbent Dosage. Bamboo charcoal (~0.2–20 g) was added into a 100-mL solution with an initial furfural concentration of 10 g/L, which corresponds to a bamboo charcoal dosage of 2–200 g/L, respectively. The furfural removal efficiencies of bamboo charcoal are plotted in Figure 3a. As shown in Figure 3a, the furfural removal efficiency increased rapidly with the increase of bamboo charcoal amount when it was lower than 75 g/L. The removal efficiency then increased slowly with the further increase of the bamboo charcoal dosage. This is probably because a greater surface area and more absorption sites would be available when the amount of the adsorbent increased to a certain level (<75 g/L in this study), whereas the concentration gradient would decrease when the amount of absorbant further increased. When the adsorbent dosage was 200 g/L, the removal efficiency could be over 95%, showing a high adsorption of furfural by the bamboo charcoal. Even though higher dosage resulted in higher removal efficiency of furfural, considering cost effectiveness, the adsorbent dosage of 75 g/L was selected as the optimal amount and was used in the following study.

3.2.2. Effect of Temperature. The effect of temperature on the adsorption of furfural is shown in Figure 3b. As can be seen, the adsorption of furfural increased with the temperature increasing from 298 K (57%) and reached the maximum at 328 K (61%), then decreased when the temperature increased further. This is probably because the molecular movement of furfural molecules increases as the temperature increases, and the furfural molecules then begin to escape from the adsorption sites, making the desorption dominant. Under this experimental condition, 328 K is the optimal temperature for the removal of the furfural molecule. However, the removal efficiency was increased by only 4% with the increase of temperature for 30 K. Thus, the effect of temperature on furfural removal is not very significant. Taking into account of the operating cost, 298 K was still used for the following furfural adsorption experiments.

3.2.3. Effect of Initial Concentration and Contact Time.

Figure 3c presents the effects of the initial concentration of furfural (5–20 g/L) and contact time on the relative concentration of furfural and adsorption capacity of the bamboo charcoal. The results showed that the adsorption was rapid for the first 6 h, probably because the vacant adsorption sites were abundant and the driving force was high during the first stage. Afterward, the adsorption rate decreased gradually. The adsorption process attained equilibrium in 24 h. Furthermore, the amount of furfural adsorbed per unit mass of the bamboo charcoal increased with the increase of initial concentration, although the furfural removal percentage decreased with the increase of the initial concentration. For instance, when the initial concentration of the furfural solution increased from 5 g/L to 20 g/L, the adsorption capacity of bamboo charcoal at 24 h increased from ~57 mg/g to ~98 mg/g; however, the furfural removal efficiency was reduced.

3.2.4. Adsorption in Sugar Solutions. Figure 3d shows the adsorption of furfural when glucose was present in solutions. The results suggested that the adsorption of furfural was not obviously affected by the presence of glucose. The adsorption of glucose onto bamboo charcoal was very low, which was <5%, probably because the molecular diameter of glucose (0.8 nm)³³ is larger than that of furfural (0.57 nm),³⁴ and the chemical

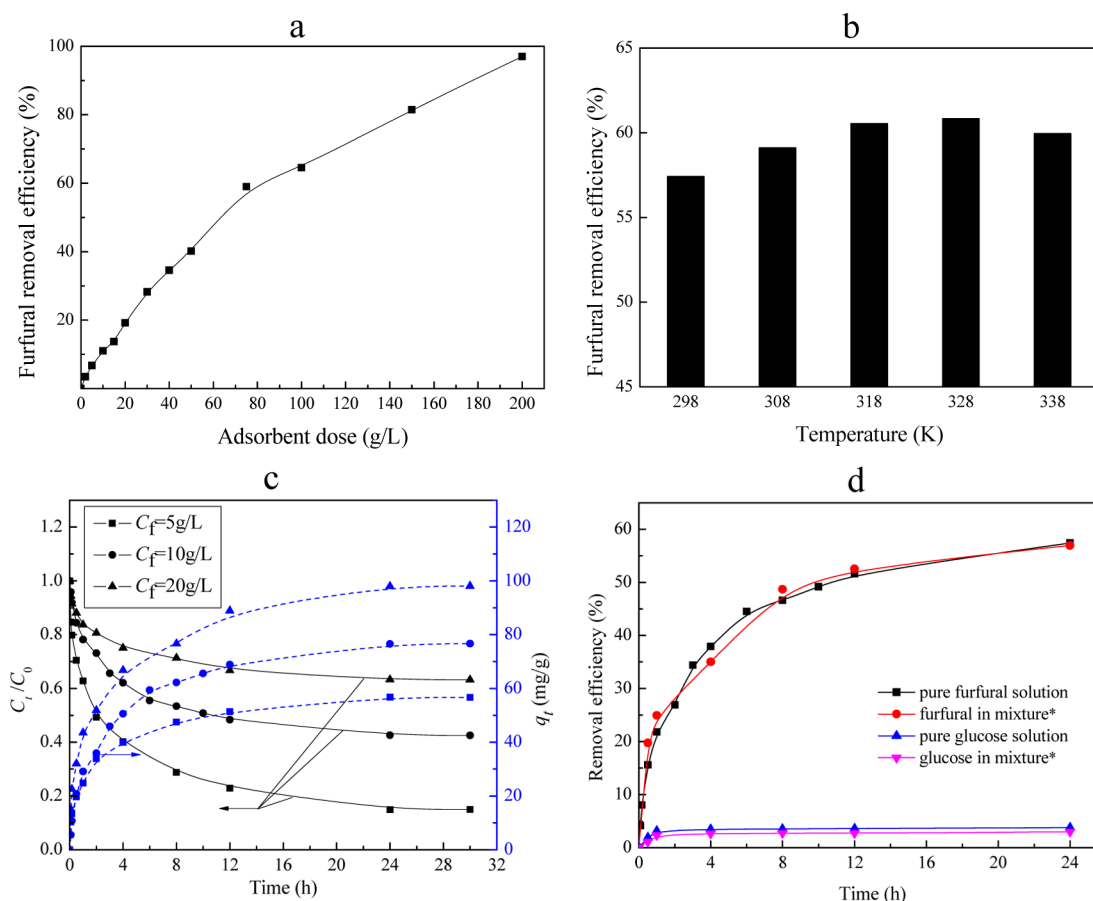


Figure 3. Furfural adsorption characteristics onto bamboo charcoal: (a) the furfural removal efficiency as a function of adsorbent dose ($T = 298$ K, $t = 24$ h, $C_i = 10$ g/L); (b) effect of temperature on the removal efficiency of furfural ($m = 75$ g/L, $t = 24$ h, $C_i = 10$ g/L); (c) effect of the initial concentration and contact time on the adsorption of furfural ($T = 298$ K, $m = 75$ g/L); and (d) furfural adsorption in sugar solutions (in the legend in panel (d), the asterisk (*) indicates that the mixture is a combination of 10 g/L furfural and 10 g/L glucose solutions). (Conditions: $T = 298$ K, $m = 75$ g/L, $C_i = 10$ g/L, $C_g = 10$ g/L.)

structures of glucose and furfural are different. The low adsorption rate may also result from the hydrophilicity of the bamboo charcoal. From Figure 3d, it can be observed that it is feasible to remove furfural from bio-oil using bamboo charcoal despite the presence of sugars. Therefore, it is promising to use pyrolytic byproduct charcoal as adsorbent for removal of the fermentation inhibitor.

3.3. Adsorption Mechanism of Bio-oil Model Compounds onto Bamboo Charcoal. Adsorptive characteristics of adsorbent for organic compounds such as furfural and glucose are generally determined by its physical and chemical interaction with the organic compounds.³⁵ Physical adsorption is characterized by studying textural parameters, among which surface area, pore volume, and pore size distribution play an important role.³⁶ According to the pore property of bamboo charcoal mentioned in section 3.1.1, given the furfural and glucose with molecular diameters of 0.57 nm (ref 34) and 0.8 nm (ref 33), respectively, both furfural and glucose can diffuse into the micropore zone of the bamboo charcoal. Simultaneously, the adsorption results presented here show that no steric hindrance exists when glucose is present. Thus, for the same adsorbent, the adsorption capability for these two adsorbates may be dependent on the chemical interaction.

The interactions responsible for chemical adsorption generally include electrostatic and dispersive interactions.³⁷ The former occurs when the adsorptive is dissociated under the

experimental conditions used. Three mechanisms have been proposed to explain the latter: the π - π interaction mechanism, the hydrogen bonding formation mechanism, and the electron donor-acceptor complex mechanism.³⁸ In the model compounds of bio-oil, since furfural or glucose exists in molecular form, electrostatic interaction is not predominant. Since carbon atoms are mostly organized as aromatic structure and furfural contains a series of benzene rings, π - π interaction may exhibit major influence on the adsorption. While for glucose, the π - π interaction with the basal planes is less important, but the hydrogen bond may serve as an important factor for glucose adsorption. Nevertheless, water can also form hydrogen bonds with the hydrophilic groups on the bamboo charcoal surface, causing the formation of clusters, which may block the passage of glucose molecules to micropores,³⁹ and a reduction in the adsorption capacity of glucose in aqueous solution. In the furfural-glucose system, since the π - π interaction plays a more important role than the hydrogen bond, the bamboo charcoal can selectively adsorb furfural from aqueous and sugar solutions.

3.4. Adsorption Kinetics. In order to fully understand the adsorption process, kinetic mechanism was studied. It helps to identify and predict the adsorption process.⁴⁰ Three sequential processes are associated with the adsorption of solute from the solution by the porous adsorbent: (a) the diffusion of the solute through the liquid film surrounding the particle (liquid film

diffusion control or external mass transfer control); (b) the diffusion of the solute through the sorbent matrix of the carbon (internal particle-diffusion control); and (c) the chemical reaction with the functional groups attached to the matrix.⁴¹ One usually offers much greater resistance than the others and thus may be considered as the rate-limiting step of the process.⁴² Two diffusion models are used here to evaluate the process in order to understand the rate-limiting step: the film diffusion model and the intraparticle diffusion model.

3.4.1. Film Diffusion Model. The Boyd film diffusion model is given by eq 4:⁴³

$$-\ln(1 - F) = k_b t \quad (4)$$

where $F = q_t/q_e$ and k_b (min^{-1}) is the rate constant of the Boyd film diffusion adsorption.

The Boyd film diffusion equation was used to fit the experimental data for the adsorption of furfural onto the bamboo charcoal with $C_f = 5, 10, 20$ g/L and for glucose with the concentration of 10 g/L as a comparison. Results are shown in Figure 4. The kinetic parameters for furfural and glucose are

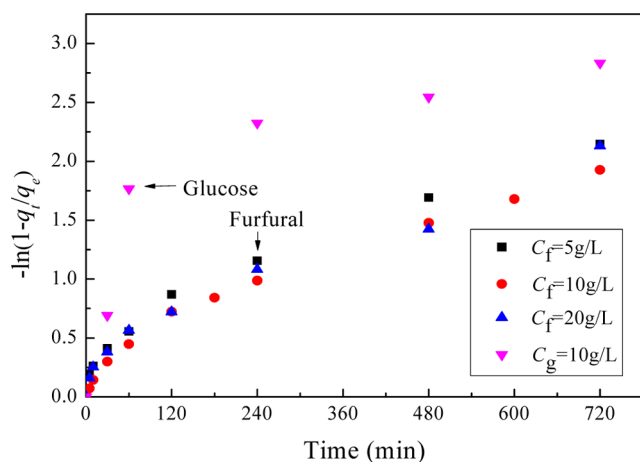


Figure 4. Boyd film diffusion model for adsorption of furfural and glucose onto bamboo charcoal.

listed in Table 2. As can be seen from Figure 4 and Table 2, the Boyd film diffusion model could not fit the adsorption data for neither furfural nor glucose. The correlation coefficient (R^2) values for both adsorbates are very low. Generally, the film diffusion tends to be the rate-controlling mechanism when a high-capacity adsorbent with a small diameter and low degree of cross-linking contacted with the slowly moving dilute solutions.⁴⁴ Obviously, the model above could not fit well with the adsorption of furfural and glucose onto bamboo charcoal under the operating condition.

3.4.2. Intraparticle Diffusion Model. The intraparticle diffusion was explored using the following equation:⁴⁵

$$q_t = k_{id} t^{1/2} + I \quad (5)$$

where k_{id} is the intraparticle diffusion rate constant, and the values of I approximate the thickness of the boundary layer or the resistance to mass transfer.

In Figure 5, the plot of q_t versus $t^{1/2}$ is presented for the adsorption of furfural and glucose. In the figure, the plots are

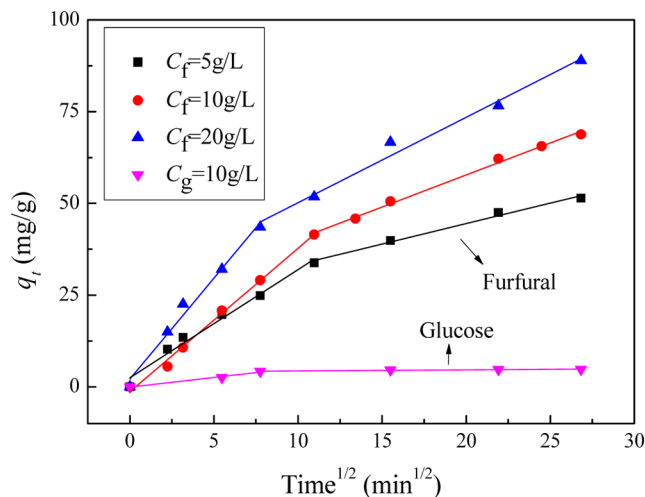


Figure 5. Intraparticle diffusion model for adsorption of furfural and glucose onto bamboo charcoal.

not linear over the entire time range, especially for furfural, suggesting that the adsorption process is influenced by more than one process. Theoretically, the plot of q_t versus $t^{1/2}$ should show at least four linear regions that represent the film diffusion, followed by pore diffusion and then adsorption equilibrium.⁴⁶ As the film diffusion is excluded as the controlling step, the presence of such distinctive features for furfural in the plots of the present work may represent the macropore and micropore diffusion, respectively.⁴² The result is consistent with the pore size distribution result of the bamboo charcoal. Based on the above analysis and the chemical structure of bamboo charcoal, the interaction mechanism can be schematized as Figure 6. For glucose, these two steps may represent the micropore diffusion and adsorption equilibrium, respectively. Comparing the intraparticle diffusion rate constants for furfural and glucose, k_{id} (furfural) > k_{id} (glucose) is always observed, suggesting that the intraparticle diffusion rate of the furfural is larger than that of glucose. Furthermore, for furfural of the same concentration, $k_{id,1}$ > $k_{id,2}$ is observed, suggesting that the intraparticle diffusion rate of the furfural into the macropores is larger than that of the micropores. Similar trends were found for the removal of furfural from aqueous solution by commercial-grade activated carbon⁴⁷ and the removal of polycyclic aromatic hydrocarbons (PAHs) by granular activated carbon.⁴² However, $I \neq 0$ suggests that the

Table 2. Kinetic Parameters for the Removal of Furfural by the Bamboo Charcoal

C_0 (g/L)	Film Diffusion Model		Intraparticle Diffusion Model					
	k_b (min^{-1})	R^2	I_1 (mg/g)	$k_{id,1}$ (mg/g $\text{min}^{1/2}$)	R^2	I_2 (mg/g)	$k_{id,2}$ (mg/g $\text{min}^{1/2}$)	R^2
5 (furfural)	3.38×10^{-3}	0.92	2.50	2.94	0.98	22.16	1.12	0.99
10 (furfural)	2.97×10^{-3}	0.95	1.33	3.91	0.99	22.84	1.75	0.99
20 (furfural)	3.17×10^{-3}	0.93	2.11	5.51	0.98	26.89	2.33	0.98
10 (glucose)	4.87×10^{-3}	0.78	-0.08	0.53	0.97	4.05	0.03	0.96

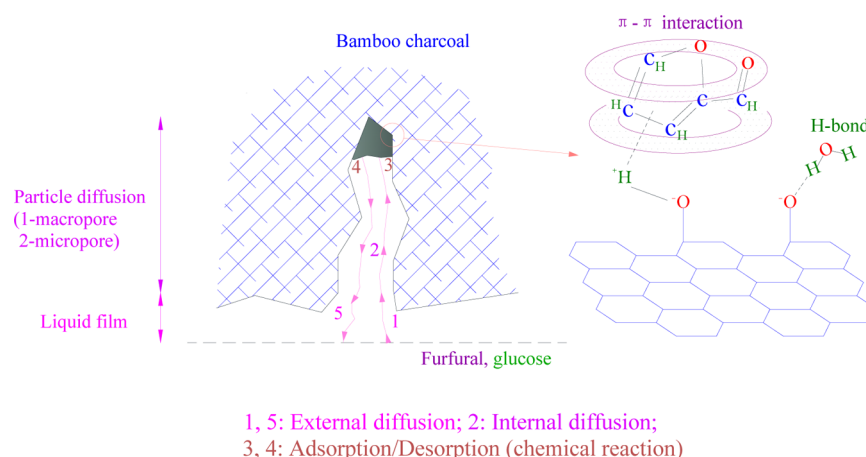


Figure 6. Adsorption mechanisms of furfural onto bamboo charcoal in model compounds of bio-oil.

pore diffusion is not the only rate-controlling step.^{47,48} Since the chemical reaction is usually assumed to be too fast to affect the overall adsorption rate, the external mass transfer cannot be ignored for both furfural and glucose.

4. CONCLUSIONS

The present preliminary study showed that the pyrolytic char (bamboo charcoal) can be used as a potential adsorbent for the removal of the fermentation inhibitor (furfural) from bio-oil. Temperature has little effect on the adsorption capacity of the adsorbents. The amount of furfural adsorbed per unit mass increased with the increase of initial concentration. The analysis of competitive adsorption behavior between the furfural and glucose molecules shows that bamboo charcoal tends to adsorb furfural rather than glucose, because of the π - π dispersion interaction. Given the hydrophilicity of the bamboo charcoal, the adsorption capacity of glucose was very low. The study of kinetic diffusion mechanism suggests that the overall adsorption rate of the furfural is controlled by the intraparticle diffusion. The furfural first diffuses through macropores, and then micropores, a scenario that is consistent with the pore size distribution result of the bamboo charcoal. It is confirmed that the pyrolytic char is an effective adsorbent for removal of furfural with minimal loss of sugars.

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Notes

The authors declare no competing financial interest.

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NOMENCLATURE

C_0 = initial concentration of adsorbate in solution, g/L

C_e = equilibrium liquid phase concentration, g/L

C_f = initial concentration of furfural in solution, g/L

C_g = initial concentration of glucose in solution, g/L

C_t = concentration of adsorbate in solution at time t , g/L

E = removal efficiency of adsorbate, %

m = mass of adsorbent per liter of solution, g/L

T = absolute temperature, K

V = volume of the solution, L

w = mass of the adsorbent, g

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