

Equilibrium and kinetic studies of sorption of 2,4-dichlorophenol onto 2 mixtures: bamboo biochar plus calcium sulphate (BC) and hydroxyapatite plus bamboo biochar plus calcium sulphate (HBC), in a fluidized bed circulation column

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Sorption studies were carried out to investigate removal of 2,4-dichlorophenol (2,4-DCP) from aqueous solution in a fluidized bed by two types of adsorbent mixtures: BC (Bamboo char plus Calcium sulphate), and HBC (Hydroxyapatite plus Bamboo char plus Calcium sulphate); both manufactured in ball shape. The main material bamboo char was characterized by FTIR, DTA and SEM. The adsorption experiments were conducted in a fluidized bed circulation column. Adsorption, isotherms and kinetic studies were established under 180 min operating process time, at different initial 2,4-DCP solution concentrations ranging from 5–10 mg/L, and at different flow rates ranging from 0.25–0.75 L/min. The data obtained fitted well for both the Langmuir and Freundlich isotherm models; indicating favorable condition of monolayer adsorption. The kinetics of both adsorbents complies with the pseudo second-order kinetic model. BC was proven a new effective composite and low cost adsorbent which can be applied in the field of wastewater treatment, and it can also play an important role in industry water treatment.

Keywords: 2,4-dichlorophenol, bamboo biochar, hydroxyapatite, calcium sulphate, adsorption.

INTRODUCTION

Phenolic compounds pose a major worldwide environmental health problem concerning industries handling phenol and metal process. Chlorophenol is a group of chemical, of which chlorines (between one and five) have been added to phenol¹. Main pollution source containing chlorophenols are wastewaters released from industries producing pesticides, paints, solvents, pharmaceuticals, plastics, wood, paper and pulps, as well as water disinfecting process². In addition, phenolic derivatives are largely used as intermediates in productions of plastics, colors, pesticides, insecticides, etc.³. However, phenol containing water-when chlorinated during disinfection of water-results in formation of chlorophenol⁴.

Chlorophenols and related compounds are toxic to humans and aquatic lives, which are carcinogenic, mutagenic, and resistant to biodegradation⁵. Phenols are considered as priority (persistence bioaccumulation and toxicity (PBT)) pollutants since they are harmful to organisms at low concentrations and many of them have been classified as hazardous pollutants because of their potential to harm human health. The United States Environmental Protection Agency (USEPA) and the European Union (EU) have designated phenols as priority pollutants⁶. Thus, removal of phenol from drinking water is of great importance, and has been receiving particular concerns in the last few decades⁷.

Treatment technologies, depending on the load of phenol compound in wastewater, are either physicochemical or biological⁸. Some conventional methods used to remove phenol from aqueous solutions are: adsorption; precipitation and coagulation; sedimentation; filtration; membrane separation; chemical oxidation; ion exchange, and reverse osmosis⁹.

Phenol can be removed effectively through adsorption process using a variety of adsorbents¹⁰, but use of bamboo

biochar is seldom mentioned. Various functional groups on bamboo biochar surface contribute to a unique and specific uptake for different molecules species¹¹. Furthermore, it is well known that nano-size adsorbents, including hydroxyapatite, possess excellent surface properties, such as large accessible internal and external surface and have large surface area¹², bamboo biochar is a nano-size adsorbent. Bamboo biochar is a very fine adsorbent. It is obtained from burning of bamboo. The char is then ground into very fine powders; the pore sizes are approx. 2–50 nm¹³.

A new composite material made from bamboo biochar plus calcium sulphate (BC), can be used as an adsorbent in that calcium sulphate plays a role on its hydrophilic property¹⁴. Hydroxyapatite, by itself or together with calcium sulphate – better known for their combined properties in the medical profession, particularly in bone surgery and bone treatment¹⁵, has reportedly been used more in the removal of heavy metals¹⁶, but less so in the removal of phenols¹⁷. As far as we know no literature has reported on the use of HBC in the removal of phenols either.

Fluidized-bed reactors have received considerable attention and wide utilization in wastewater treatment due to several advantages¹⁸. First, this type of reactor renders a more intensive contact between liquid and solid phase causing high mass transfer, a high reaction rate, and small external mass transfer resistance between solid and liquid phase. Second, it could eliminate operating problems such as bed clogging and high pressure drop, which occur in packed-bed systems operations. Third, it is a high efficient, simple, stable and economical operation compared to other reactor configurations¹⁸.

The objective of this study was to investigate the adsorption of 2,4-dichlorophenol (2,4-DCP) in aqueous solution (wastewater) onto two types of ball-shape adsorbents: BC and HBC, in a laboratory-scale fluidized-bed

circulation column. Adsorption isotherms, Langmuir and Freundlich were investigated. Moreover, adsorption kinetics pseudo-first and pseudo-second order were calculated for comparison.

MATERIAL AND EXPERIMENTAL METHODS

Adsorbent properties and preparation

Bamboo biochar (BB), bamboo, obtained locally near our laboratory, was cleaned, chopped into 10 mm x 10 mm pieces, and dried. One hundred grams of the sample was put onto a sieve tray and put into a stainless steel reactor 450 mm long, 110 mm in diameter. The reactor was then flushed with nitrogen gas at a pressure of 5 kPa to remove air. It was then put inside a furnace. Pyrolysis process then started; temperature inside the furnace was raised at an average rate of 20°C/min until it reached 500°C, then maintained for 4 hours. After the system was allowed to cool overnight, bamboo biochar was collected. The BB, was then ground into very fine powder to be used in this study as the main material. Hydroxyapatite (HAP), and 2,4-DCP were purchased from Sigma-Aldrich Co. LLC, while Calcium sulphate (CS) was from Aldrich Chemicals. BB was mixed with CS to form an adsorbent composite BC, and with HAP and CS to form another adsorbent composite HBC. The weight ratio of BB:CS is 0.62:0.38, and that of BB:HAP:CS is 0.46:0.27:0.27. A glue, prepared from polyvinyl alcohol (PVA) having a molecular weight MW of 22,000, was added to the mixtures to manufacture ball-shape adsorbents. Table 1 details some characteristics of BC and HBC. The concentration of residual phenol was determined using a double beam UV-Vis spectrophotometer (Shimadzu UV-1601 Spectrophotometer, Japan) at wave length 765 nm. Fourier transforms infrared spectroscopies (FTIR) (Bomem, MB 100) were carried out to identify the functional groups of the biochar. DTA for thermal stability of BB was analyzed. Scanning electron microscopy (SEM) was conducted with a Hitachi JSM-6700F SEM to observe the surface microstructures of the fresh Bamboo biochar.

Adsorbate properties and preparation

A stock solution of 2,4-DCP was obtained by dissolving it in double distilled water. Desired solutions of phenol were prepared using appropriate subsequent dilutions of the stock solution. The range of concentration of the phenol prepared from the standard solution varied between 5–10 mg/L as 2,4-DCP. The pH of the solutions was adjusted to 6.5 by 0.1 N NaOH and 0.1 N HCl solutions.

Experimental method

The study of 2,4-DCP adsorption was carried out in laboratory scale; a circulation fluidized bed reactor was

used to improve mixing and homogeneity. The experimental system consisted of a reactor column, a water reservoir and a peristaltic pump as shown in Figure 1. The reactor's outside diameter is 50 mm and its height is 240 mm. This reactor of the fluidized-bed column, having an effective volume of 470 ml, was made from transparent acrylic material. A mesh screen was fit at the top of the fluidized circulation column in order to capture the solid coming out of the column. A conical distributor was placed at the bottom to ensure proper distribution of fluid. Aqueous solutions of phenol were continuously fed with an upward flow at different flow rates, from 250 to 750 ml/min. The liquid effluent stream was recycled to the hold-up tank. Three liters of the phenolic aqueous solution was treated with adsorbent of 3 g for each adsorbent. Adsorptions of the 2,4-DCP onto adsorbent BC and adsorbent HBC were compared. Aqueous solution of 2,4-DCP flowed through the adsorbents in the fluidized bed column and recycles back to the hold-up tank. Samples, approx. 10 ml each, were taken from this closed-loop stream just before the effluent reaches the hold-up tank. Sampling starts at very close to time zero, and thereafter every 15 min. Each test lasts 3 h or 180 min, and thus there are 13 samples taken in each experiment. The suspensions samples in all studies were filtered through 0.45 μm syringe membrane filters. All the experiments were conducted in triplicates for statistical analysis.

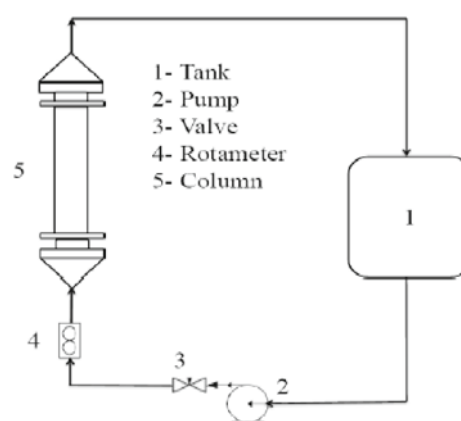


Figure 1. Process diagram

RESULTS AND DISCUSSION

Fourier Transform Infrared (FTIR) analysis

The progress for the pyrolysis process of BB was tracked and investigated by FTIR analysis which is a wavenumber technique. Sample discs were prepared by mixing oven-dried (at 105°C) BB samples with spectroscopy-grade KBr in an agate mortar. Infrared spectra of wavenumbers (4000–400 cm⁻¹) were recorded using a Nicolet IR100

Table 1. Outstanding Characteristics of Biochar plus Calcium sulphate (BC) and Hydroxyapatite plus BC (HBC)

Characteristics	BC	HBC
Dry specific weight	0.771±0.001	0.89±0.001
TOC, [g/kg]	409.92	301.21
Ash content, [%]	34.23±0.16	48.35±0.13
Total-N, [% w/w]	0.300±0.012	0.224±0.004
Tot-P, [%]	0.04±0.00	2.09±0.00
pH	7.47±0.03	7.18±0.04

FTIR spectrometer that was equipped with a TGS/PE detector and a silicon beam splitter with 1 cm^{-1} resolution. Figure 2 shows the FTIR spectrum containing tracks of wavenumbers related to many functional groups of the BB. Biochar produced at 500°C clearly revealed changes of functional groups on the surface. With increasing pyrolysis temperature, bands assigned to O–H should have wavenumber close to (3400 cm^{-1}). For the BB sample the O–H band of hydroxyl group was found at (3461 cm^{-1}), and the peak at (2830 cm^{-1}) is assigned to C–H of aldehydes. Aliphatic was lowered markedly by C–H at wavenumbers ($2921.21\text{--}2855\text{ cm}^{-1}$), indicating decreases of labile aliphatic compounds in the biochar with rising pyrolysis temperature and a possible occurrence of demethoxylation, demethylation, and dehydration of lignin.

The loss of OH and aliphatic groups explain the enhanced pore formation, exceptionally for a high pyrolysis temperature; and this hypothesis was consistent with the results of increased surface area. The two functional groups, asymmetric (2921.21 cm^{-1}) and symmetric (2855 cm^{-1}) C–H bands, were associated with aliphatic functional groups. Intense bands belonging to aliphatic CH_2 become less with rising temperature; denoting lower contents of nonpolar groups.

The intensity of the band at ($1690\text{--}1591.73\text{ cm}^{-1}$) (aromatic C=C and C=O of conjugated ketones and quinones) also diminished with rising temperature. The peak at (1513.55 cm^{-1}) represents the C=C ring of lignin, while the bands at (1434.91 cm^{-1}) aromatic C=C and (885 cm^{-1}) out-of-plane deformation by aromatic C–H groups might be caused by carbonates. Several outstanding peaks at ($1248.6\text{--}1000\text{ cm}^{-1}$) were assigned to C–O and C–C, and these peaks lessen markedly, probably due to losses of polysaccharides during pyrolysis. Moreover, the sharp band at (1372 cm^{-1}) confirmed the existence of a C–O bond on BB, reinforcing the interaction with the carboxyl groups.

Differential thermal analysis (DTA)

Thermal stability of the BB was investigated by DTA analysis. The BB sample generally showed three main peaks for weight loss in the temperature due to range $25\text{--}800^\circ\text{C}$ in Figure 3. The first strong peak among the three peaks, at $75\text{--}96.17^\circ\text{C}$, is assigned to the evaporation procedure of adsorbed water molecules. The second weak peak in the range $280\text{--}294^\circ\text{C}$ indicates dissociation of the surfaces. And the third broad peak, appearing in the range $402\text{--}570^\circ\text{C}$, could originate from the further carbonization process of the BB. Above this range, a new peak is found at 814°C .

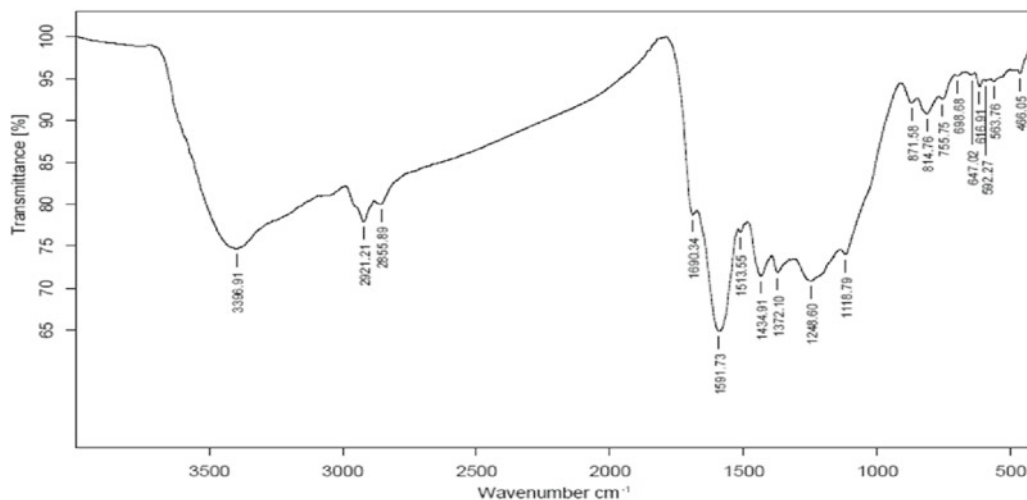


Figure 2. Characteristics of BB from FTIR analysis

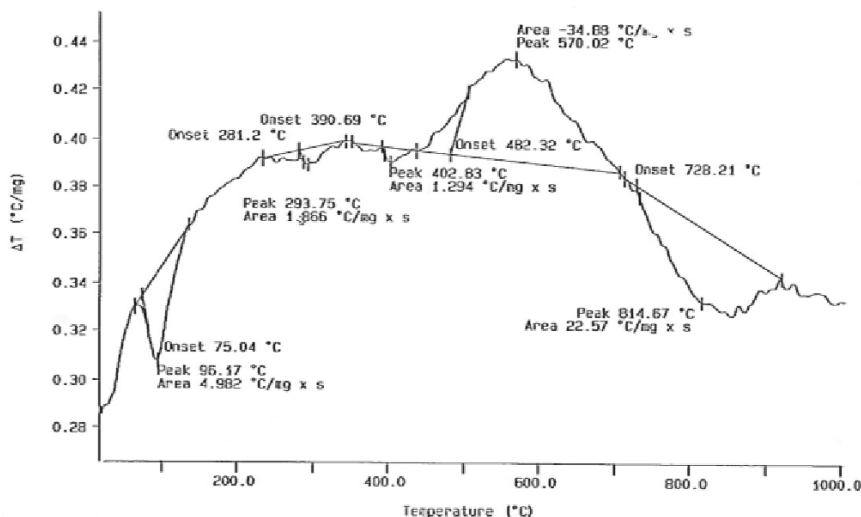


Figure 3. Characteristics of BB from DTA analysis

Scanning electron microscope images (SEM)

SEM result on BB characteristics showed its morphology and elemental composition. There were large internal surface and porous structures at different Figure 4(a), and Figure 4(b). Figure 4(c), at x500 magnification, showed an average porous opening of $38.67 \mu\text{m}$. Elemental percent compositions of the BB were evaluated by SEM mapping technique; results as shown in Table 2.

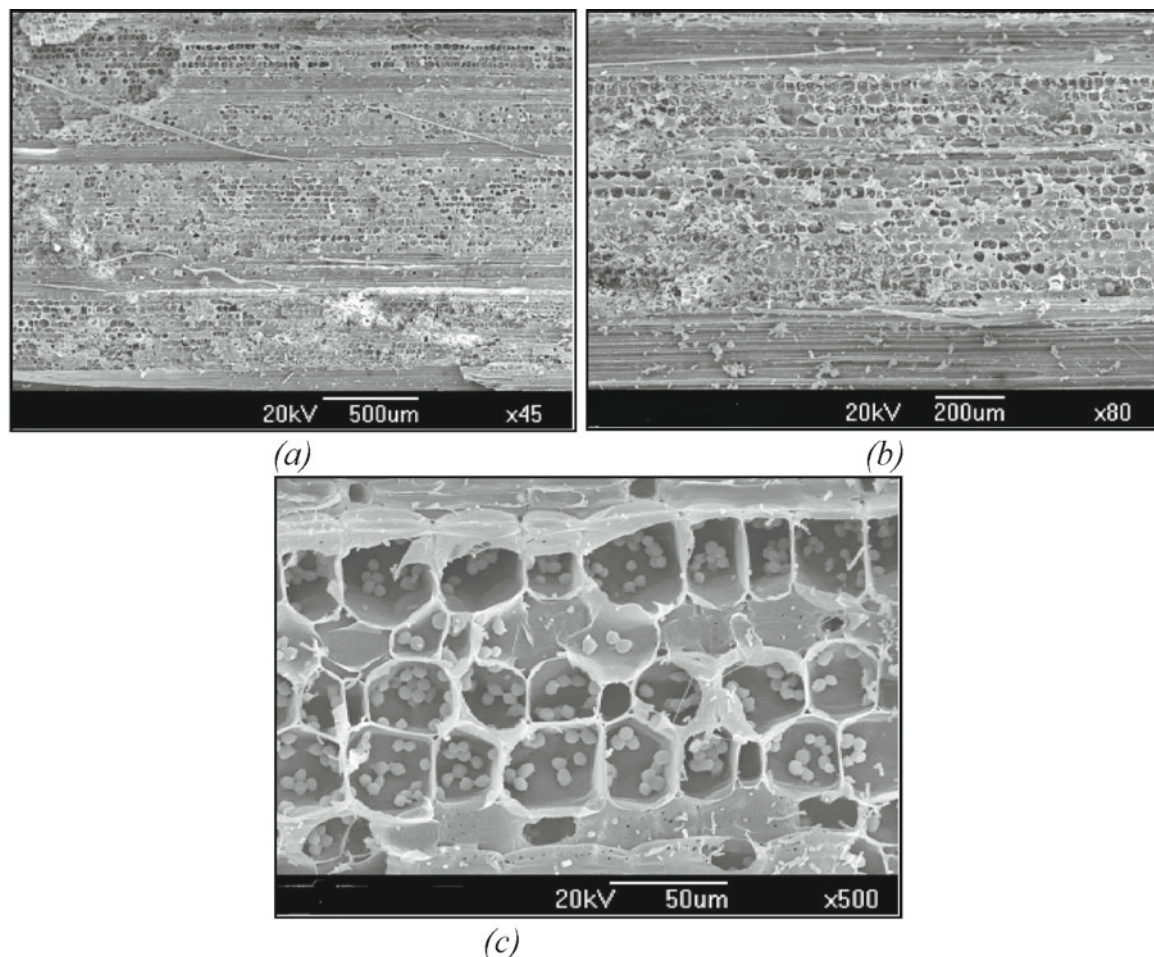


Figure 4. SEM of the bamboo biochar

Table 2. Elemental percent compositions of the BB were evaluated by SEM

Elements	Amounts %
C	59
S	1.55
K	30.5
Cl	9.4

Effect of initial pH solution on 2,4-DCP adsorption

Adsorbent behaviour of BC and HBC on the adsorption of 2,4-DCP were studied from adjustment effect of the initial pH between 3 to 10 at room temperature of 28°C while the initial concentration of 2,4-DCP solution of 10 mg/L was constantly maintained for both adsorbents. As shown in Figure 5, the removal rates of the 2,4-DCP were lower on both ends of the pH region. Different behavior trends were observed for the two different adsorbents. For HBC adsorbent, the maximum 2,4-DCP percent removal of 60% was at pH 6, and its rates declined to 45–50% on either side. For BC adsorbent, the maximum removal percent of nearly 40% was at pH 8, but was rather stable between pH

6–10, though with a sharp drop at pH 4. The drop in adsorption was sharper for HBC in the alkaline region while the drop was a little sharper for BC in the acidic region. Chlorophenols are weakly acidic, and pH has a significant effect on the degree of ionization of 2,4-DCP and the adsorbent surface properties¹⁹.

The surface charge of the BC and HBC, were negative in the pH-range between 3–10, see Figure 5. The ionic

fraction of chlorophenol ions increases with increasing pH, and chlorophenol could be expected to become negatively charged as pH increases¹⁹, with a constant pKa value of 7.89 for the 2,4-DCP solution²⁰. Non-dissociated form activated by the OH^- and Cl^- dominates

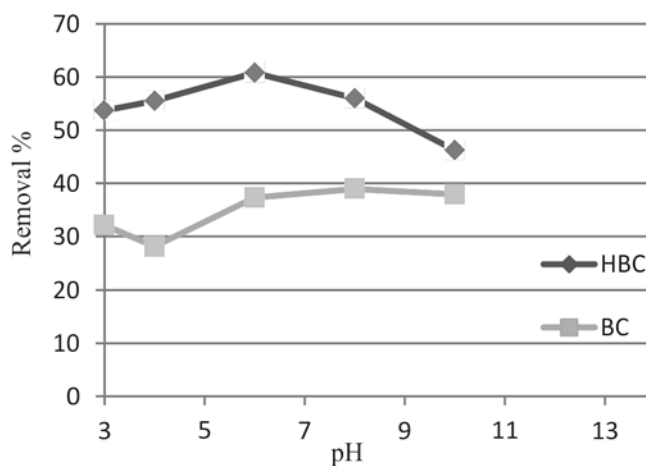


Figure 5. Percentage of removal vs. initial pH solution of 2,4-DCP adsorption

the overall sorption of chlorinated phenols on organic sorbents². The slow and low removal percent of 2,4-DCP at highest pH could have been resulted from competition between the OH⁻ ions and the ionic species of 2,4-DCP, hence reducing the 2,4-DCP removal¹.

Effect of contact time of fluidization

The dependency on time on the efficiency of the removal 2,4-DCP was studied at time intervals up to 180 min at room temperature. At the initial stage the adsorbents have more available pore space on the surface and hence were ready for adsorption. Adsorption gradually increases depending on the accumulation of phenol on the adsorbents surface during this time. As a result, the remaining vacant surface sites are difficult to be occupied due to formation of similarly charged particles which exert repulsive forces between the phenol molecules on the solid surface and in the bulk phase²¹. Besides, phenol molecules are very small in size and can easily diffuse into internal pores until they become saturated; which will reduce the driving force for mass transfer between the bulk liquid phase and the solid phase over time¹¹. Figure 6 depicts the effect of time on the percentage removal and the result was that the equilibrium time for either adsorbent was reached at approx. 180 min; the authors had conducted up to 6 hrs and found no significant increase in percentage removal. However, adsorption of 2,4-DCP employing either BC or HBC increased slowly to equilibrium, particularly the BC. At equilibrium, the removal percent were approx. 68% for HBC, and 53% for BC.

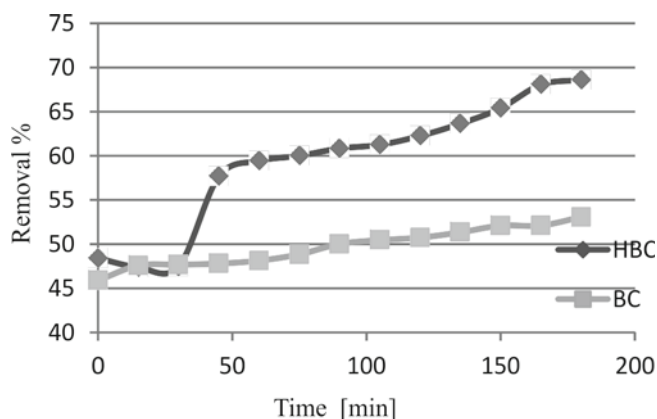


Figure 6. Percentage of removal 2, 4-DCP vs. contact time of circulation fluidization

Effect of flow rate of 2,4-DCP solution

The effect of different flow rate was investigated for adsorption of 2,4-DCP from aqueous solution employing the two adsorbents. Experiments were carried out at room temperature with flow rate in range of 250–750 ml/min while other variables were kept constant (solute pH of 6.5, 3 g of adsorbent, 7.5 mg/L of the 2,4-DCP initial concentration). From Figure 7, the percentage removal of the 2,4-DCP solution using BC adsorbent declined with increasing flow rate of the solution, whereas for HBC it was the opposite. The behavior for the BC can be explained by insufficient residence time of the solute in the column; the residence time decreased with increasing flow rate, leading to insufficient time for diffusion of the solution into the pores of the BC adsorbent and thus limiting the number of available active

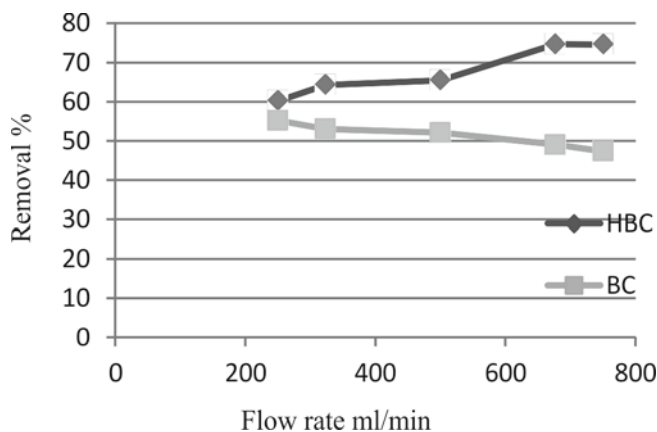


Figure 7. Percentage of removal vs. flow rate of 2,4-DCP solution

sites for adsorption, reducing the adsorbed amount of the aqueous solution since much solute left the column before equilibrium occurs²². In case of adsorbent HBC, the removal capacity increased imperceptibly below flow rate of 500 ml/min, except at 250 to 300 ml/min. Beyond flow rate of 500 ml/min the removal capacity rose rapidly to another plateau; the reason is that at higher flow rate, the rate of mass transfer tends to increase.

Effect of initial concentration of 2,4-DCP solution

Studies were carried out at room temperature to investigate the effect of initial concentrations, from 5–10 mg/L of 2,4-DCP, on adsorption at fixed parameters: pH of 6.5, adsorbent weight of 3 g, flow rate of 500 ml/min. It can be noted from Figure 8 that at lower initial concentration the capacities of sorption for both BC and HBC increased with increasing initial concentration, and then rose slowly for BC or plateau off for HBC. This is due to the raising of the mass transfer driving force and thus the rate at which 2,4-DCP molecules pass from the bulk solution to the particle surface. However, when the initial concentration went beyond 9 mg/L the adsorbents behaved differently; the percentage of removal for the BC rose up a little, whereas for the HBC it dropped.

From the experiment, the highest percentage of removal for HBC was approx. 75% at 7.5 mg/L initial concentration. For adsorbent BC, the maximum percentage of removal was at 56% at 10 mg/L. The performance of adsorbent HBC is better than BC because the former has more specific surface area and more macro porous

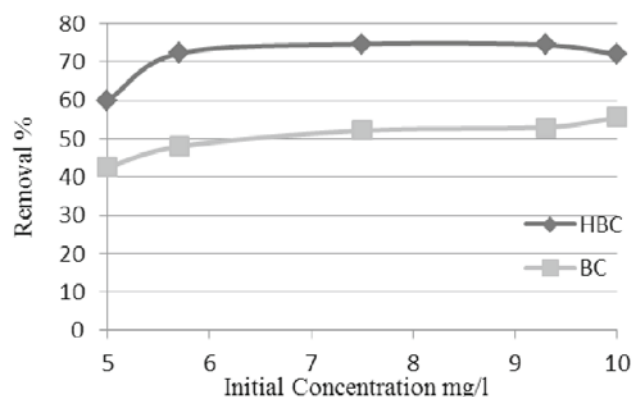


Figure 8. Percentage of removal vs. initial concentration of 2, 4-DCP solutions

structures. However, BC performance is at approx. 75% of that obtained using HBC.

Adsorption isotherms

Isotherms are very important and essential for the understanding of adsorption system mechanism, and two models, Langmuir and Freundlich, were applied in this study to investigate the performance of the BC and HBC adsorbents.

The Langmuir model is based on assumptions of adsorption homogeneity such as equal available adsorption sites, monolayer surface coverage, and no interaction between adsorbed species²³, and is described in Equation 1:

$$\frac{C_e}{q_e} = \frac{1}{b q_{\max}} + \frac{C_e}{q_{\max}} \quad (1)$$

Where q_e and q_{\max} are the observed and maximum uptake capacities in mg/g; C_e is the equilibrium concentration in mg/L; and b is the equilibrium constant in L/mg.

The plots of versus are shown in Figure 9, and the calculated results in Table 3. It can be seen from the Table that the correlation coefficients were good for both adsorbents; with HBC a little better. And hence the Langmuir isotherm model is acceptable.

Table 3. Isotherm parameters for sorption of 2,4-DCP by different adsorbent

Adsorbent	Langmuir			Freundlich		
	q_{\max}	b	R^2	K_f	n	R^2
BC	10.69	0.0350	0.9461	0.302	0.79	0.9650
HBC	16.37	0.0315	0.9699	0.410	0.80	0.9827

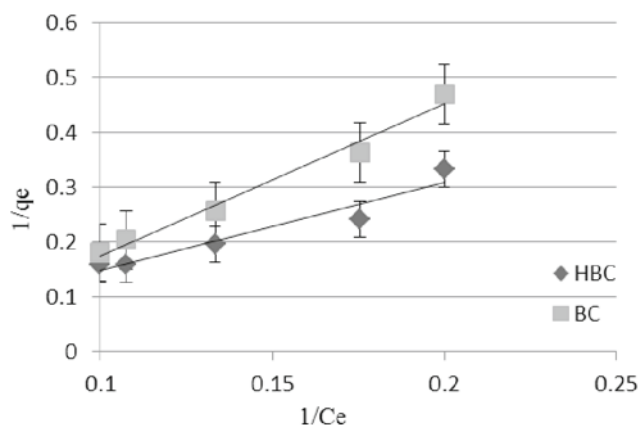


Figure 9. Linearized Langmuir isotherms ($1/q_e$) vs. $1/C_e$ for the adsorption of 2,4-DCP

Freundlich isotherm model describes the logarithmic relation between the energy of sorption and the increase in binding sites. The model can be applied to non-ideal sorption on heterogeneous surfaces as multilayer sorption²³. The Freundlich equation is:

$$\ln q_e = \ln k_f + \frac{1}{n} \ln C_e \quad (2)$$

Table 4. Adsorption kinetic model rate constants for 2,4-DCP removal by different adsorbents

Adsorbent	q_{eExp} mg/g _{ad}	Pseudo-first order			Pseudo-second order		
		$q_{e(cal)}$ mg/g	k_1	R^2	$q_{e(cal)}$ mg/g	k_2	R^2
BC	5.56	4.140	0.0260	0.7810	5.68	0.0190	0.9925
HBC	6.25	1.317	0.0046	0.9421	5.90	0.0311	0.9916

Where q_e is the equilibrium capacity of sorption in mg/g; C_e is the equilibrium concentration of the 2,4-DCP in mg/L; K_f is the sorption capacity coefficient; and n is a coefficient related to the sorption intensity.

The values of K_f and n were obtained from the intercept and the slope of the plots between $\ln(q_e)$ versus $\ln(C_e)$ in Figure 10 and shown in Table 3 together with other parameters from the Langmuir model.

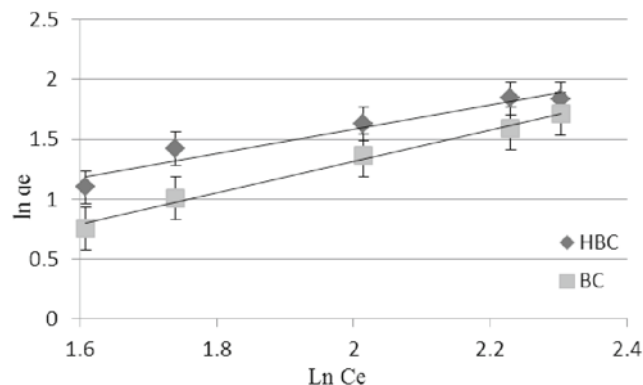


Figure 10. Linearized Freundlich isotherm $\ln(q_e)$ vs. $\ln(C_e)$ for the adsorption of 2,4-DCP

The correlation coefficients R^2 for the Freundlich isotherm model were found to be higher than those found from the Langmuir model. Both models thus gave R^2 of at least 0.9461 and are both well-fitted for the experimental results. The Freundlich model, however, yielded a better fitting for describing the adsorption of 2,4-DCP onto both adsorbents BC and HBC since the R^2 obtained were relatively higher and the computed coefficient n values were less than unity.

Adsorption kinetics

Adsorption kinetics models, pseudo-first order and pseudo-second order, were used to investigate, at room temperature, the 2,4-DCP adsorption kinetics by adsorbents BC and HBC.

The pseudo-first order equation can be explained using Lagergren equation:

$$\log(q_e - q_t) = \log(q_e) - \frac{k_1}{2.303} t \quad (3)$$

Where q_e and q_t are the amounts of 2,4-DCP, adsorbed at equilibrium and at time t in mg/g, respectively, and k_1 is the pseudo-first order rate constant in g/mg*h.

From the first order equation 3, the values of for 2,4-DCP were calculated and plotted versus time as shown in Figure 11, while the calculated data of the pseudo-first order model are shown in Table 4. If the plotted line is linear with good correlation coefficient, Lagergren equation is appropriate; and it can be clearly seen that BC did not fare well. Though with respectable R^2 , HBC does not fit well in this model either, because the q_e calculated is very different from q_e experimental.

The pseudo-second order kinetic model equation, based on equilibrium adsorption, is:

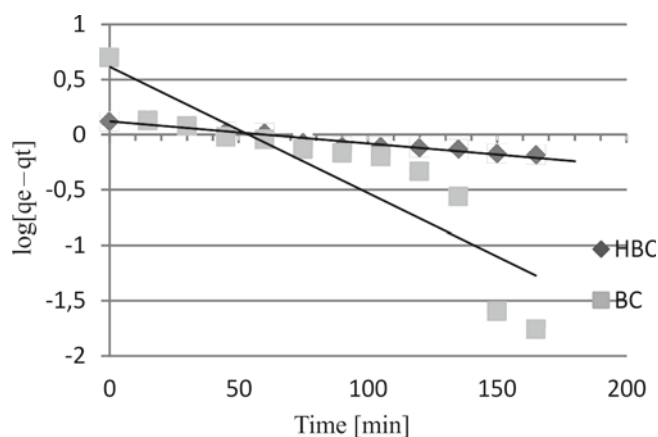


Figure 11. Results from pseudo-first order kinetic model for the removal of 2,4-DCP

$$\frac{t}{q_t} = \frac{t}{q_e} + \frac{1}{k_2 q_e^2} \quad (4)$$

Where q_e and q_t are as described in Equation 1; and k_2 is the rate constant of second-order adsorption in $\text{g}/\text{mg} \cdot \text{h}$.

Equation 4 was found to be easier to predict the kinetics behaviour of adsorption over the whole range; the linear plot of $\frac{t}{q_t}$ versus t , shown in Figure 12 and in Table 4 as well, was used to find the slope $\frac{1}{q_e}$, and the intercept $\frac{1}{k_2 q_e^2}$. From Table 4, agreements between calculated values of q_e and experimental values was clear; 5.68 vs. 5.56 for BC, and 5.90 and 6.25 for HBC. Moreover, both correlation coefficients derived from the second-order kinetics model were higher for those obtained from the first-order model. Thus, the second-order kinetics model is proven better than the first-order model to predict and describe the adsorption system of 2,4-DCP onto both adsorbents.

Table 5 details the effectiveness of various adsorbents for adsorption of phenolic compounds. The materials used were compared with more than ten other adsorbents. Out of 16 adsorbents, HBC ranked the 6th best in removal of contaminant, and BC the 11th best. Isotherms and kinetics investigations also support this. Hence, HBC is effective while BC fares acceptable. As for costs, HAP used in the experiment cost more than USD190 per kg, or USD190.000 per ton, while BC was

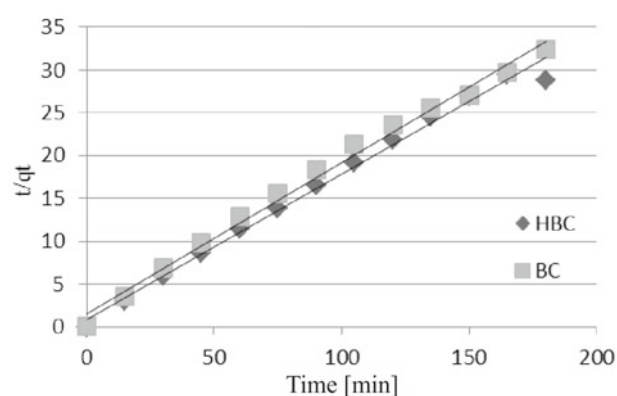


Figure 12. Results from pseudo-second order kinetic model for the removal of 2,4-DCP

reported at USD400–600 per ton in China²⁴. The use of BC and HAP to make HBC thus reduces the cost drastically than using pure HAP. However, the fact that BC performs better than quite a few others it means BC is promising to be used, particularly when its low cost is taken into consideration.

CONCLUSION

The fluidization time was found to reach max at 180 min. In the isotherms investigation it was found that all data fitted well into the Langmuir and Freundlich models, and that the Freundlich model gave a better fit than the Langmuir model. Hence, the Freundlich model is recommended to be used for any further investigations. For the adsorption kinetics, the pseudo-second order model gave a better fit. Comparison of the adsorption efficiency of BC and HBC obtained indicated that the two adsorbents have similar isotherm and kinetics behavior. The BC, however, yielded a lower quality value. Both adsorbents were compared for the removal of phenol via adsorption with many others, and HBC was found to be of good standing, while BC, though in the lower rank, fared acceptably based on its adsorbent capacity and isotherms and kinetics study. HBC and BC adsorbents are thus suitable and acceptable for the removal of 2,4-DCP from aqueous solutions at parameters it depended like the pH, the initial concentration of 2,4-DCP, the flow rate of the solution and the time of fluidization. Taken its low cost into consideration, BC could be regarded as

Table 5. Comparison of phenolic compounds adsorption capacities of different adsorbents

No	Phenolic compounds	Adsorbents	Capacity [mg/g]	Reference
1	Phenol	Activated carbon	49.72	28
2	P-Chlorophenol	Rice husk char	36.23	27
3	Phenol	Multi walled carbon nanotubes	32.23	9
4	2,4 DCP	Palm pith carbon	19.16	25
5	Phenol	Palm seed coat activated carbon	18.30	26
6	2,4-DCP	HBC (Hydroxyapatite plus BC)	16.37	This study
7	p-chlorophenol	Rice husk	14.36	27
8	3-Chlorophenol	Rice straw-based carbon	14.20	31
9	Phenol	Fly ash	13.16	8
10	2,4-DCP	Mycelial pellets of <i>P chrysosporium</i>	11.62	19
11	2,4-DCP	BC (Bamboo biochar plus Calcium sulphate)	10.69	This study
12	Phenol	Hydroxyapatite nano powders	10.33	12
13	Chlorophenol	Biofilm of <i>A. viscosus</i> supported on granular activated carbon	9.70	30
14	P-Chlorophenol	Petroleum coke	9.34	27
15	4-Chlorophenol	Anaerobic granular sludge	6.32	2
16	Phenol	Activated coal	1.48	29

a new, moderately effective adsorbent that can be applied in the field of wastewater treatment and industries.

The adsorption capacity for removal of phenol employing BC was found to be 10.69 mg/g, and that employing the HBC, 16.37 mg/g. Both were found to perform better than the metal-removal-efficient but expensive HAP. The two adsorbents, however, have to be replaced after use every time.

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