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Removal of phenol from aqueous solution by adsorption onto activated carbon and fungal biomass

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Abstract

Removal of phenol from aqueous solution by adsorption onto activated carbon and *Aspergillus niger* biomass was investigated. The effects of pH, adsorbent dose and contact time on phenol adsorption onto activated carbon and H_2SO_4-treated *A. niger* biomass were evaluated. Optimum adsorption of phenol onto H_2SO_4-treated *A. niger* was obtained at pH 3.0 while pH had no significant effect on the adsorption of phenol onto activated carbon. The amount of phenol adsorbed per unit mass of *A. niger* biomass decreased with increase in adsorbent dose. Adsorption of phenol on activated carbon was rapid reaching equilibrium within 2 minutes. Conversely, the equilibrium time for adsorption of phenol onto H_2SO_4-treated *A. niger* biomass was 180 minutes. . The kinetic data obtained from the batch studies of phenol adsorption on *A. niger* biomass and activated carbon were better described by pseudo-second-order kinetic model with correlation coefficients of 1.000 and 0.999 for activated carbon and H_2SO_4-treated *A. niger* respectively. The second-order kinetic constant (K_2) were 1.4057 min^{-1} and 0.0122 min^{-1} for activated carbon and H_2SO_4-treated *A. niger* respectively. Freundlich adsorption isotherm fitted the experimental data better than Langmuir model. The correlation coefficients obtained with Freundlich isotherm were 0.997 and 0.999 for activated carbon and H_2SO_4-treated *A. niger* biomass respectively The maximum adsorption capacity of activated carbon is 165.941 mg phenol/g activated carbon. The result of this study showed the potential of *A. niger* adsorption to remove phenol from aqueous media

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Introduction

Wastewater generated from chemical operations such as in resin, paint, pharmaceutical, pulp and paper, pesticide, coal processing, petroleum and petrochemical industries usually contain phenol and its derivatives. Introducing phenolic compounds into the environment or degradation of these substances means the appearance of phenol and its derivatives in the environment. Phenols are considered as priority pollutants since they are toxic to humans, animals and microorganisms even at low concentrations. Due to its toxicity, phenol has been classified as priority pollutant by environmental protection agency of many countries and it has been made mandatory worldwide for industries to treat phenolic wastewater before disposal. Several methods such as adsorption and biodegradation have been employed in the removal of phenols from wastewater.

Adsorption is an effective separation process for removing phenolic impurities from industrial and domestic effluents. Traditionally, activated carbon is the most widely used adsorbent for removal of phenol and its derivatives. Several investigators have studied the adsorption of phenols on active carbon (Costa *et al*., 1988; Biniak *et al*., 1989; Abuzeid and Harrozim, 1991; Radeke, 1993; Qadeer and Rehan, 2002; Chern and Chien, 2002; Roostaei and Tezel, 2004; Kaleta, 2006) and low-cost adsorbents (Ahmaruzzaman, 2008). Although adsorption onto activated carbon is an effective means of removing pollutants from wastewater, it presents several disadvantages (Streat *et al*., 1995; Babel and Kurniawa, 2003). Regeneration of used activated carbon is expensive and results to loss of the adsorbent. Thus, research efforts have been intensified to develop alternative adsorbents to replace the costly activated carbon.

Attention has focused on various natural solid materials, which are able to remove the pollutants from the contaminated wastewater at low cost, such as activated sludge and other microbial biomass. Activated sludge is a well-known biomass used for the removal of phenolic compounds (Kennedy and Pham, 1995; Ning *et al*., 1996; Wang *et al*., 2000; Wang *et al*., 2002). In addition to activated sludge, some fungal mycelia and bacterial biomass have also been utilized to remove phenolic compounds through adsorption (Benoit *et al*., 1998; Daughney and Fein, 1998; Rao and Viraraghavan, 2002; Wang *et al*., 2002; Denizli *et al*., 2005; Wu and Yu, 2006). The interest in the potential utilization of fungal biomass as a biosorbent is increasing due to the need for economical and efficient adsorbents to remove organic contaminants from wastewater. Rao and Viraraghavan (2002) have used dead pretreated cells of *Aspergillus niger* to remove phenol from an aqueous solution, and observed that the maximum removal of phenol occurred at an initial pH of 5.1 for the biomass powder treated with sulphuric acid. Benoit *et al*. (1998) have studied the biosorption characteristics of 4-chlorophenol and 2,4-dichlorophenol on the fungal mycelium of *Emericella nidulans* and *Penicillium miczynskii*. Their results showed that a rapid adsorption on inactivated fungal cell surfaces was the main phenomenon for the more hydrophobic molecules. Denizli *et al*. (2005) investigated removal of phenol and chlorophenol from aquatic systems using dead biomass of *Pleurotus sajor caju*. The maximum adsorption of phenol and chlorophenols onto the *Pleurotus sajor caju* were 0.95 mmol/g for phenol, 1.24 mmol/g for *o*-chlorophenol, 1.47 mmol/g for *p*-chlorophenol and 1.89 mmol/g for 2,4,6-trichlorophenol. Using *Phanerochaete chrysosporium* in a similar study, adsorption capacities of 1.23, 1.49, 1.78 and 2.14 mmol/g for phenol, *o*-chlorophenol, *p*-chlorophenol and 2,4,6-trichlorophenol respectively was reported by Denizli *et al*. (2004). Other workers have also investigated the biosorption capacity of dead and live fungal biomass and they found that better removal was achieved with dead fungal biomass than with live one (Tsezos and Bell, 1989; Yesilda *et al*., 1995).

In the present study, the efficiency of dead *Aspergillus niger* biomass, produced from low cost medium, to remove phenol from aqueous solution was determined and compared with commercial activated carbon.

Materials and methods

Production and pretreatment of fungal biomass

The fungus *Aspergillus niger* was isolated from soil and routinely maintained on potato dextrose agar. *A. niger* was grown in 100 ml volumes of a liquid medium in 200 ml Erlenmeyer flask. The medium contained 20 g/l dextrose and potato extract (prepared by boiling 200 g of potato in 1 litre of deionized distilled water for 10 minutes, filtering, making up the volume to 1 litre upon cooling and supplementing with 20 g of dextrose). The flasks were incubated aerobically on a rotary shaker operating at 150 rpm at room temperature (28 ± 2°C). The fungus grew into pellicles within 3 days and was harvested by filtering through Whatman No.1 filter paper. It was then washed thoroughly with deionized distilled water to remove the growth medium that adsorbed onto its surface. The biomass was autoclaved, dried in an oven at 70°C for 48 h and powdered using electric blender. Part of this biomass was pretreated by immersing in a 0.1 M solution of sulphuric acid for 1 h and washed thoroughly with deionized distilled water. The pretreated biomass was spread on glass Petri dish, dried in an oven as before and ground as previously stated. Particles passing through 300 µm sieve were used as adsorbent in batch adsorption studies. The biomass was stored in an air-tight bottle to prevent absorption of water.

Activated carbon

Commercial activated carbon (Qualikems, New Delhi, India) was used as the adsorbent. Its characteristics are shown in the Table 1.

Effect of pH on phenol adsorption

The effect of pH on the amount of phenol adsorbed by fungal biomass and activated carbon was determined over pH values ranging from 1 to 10. The pH of the solutions was adjusted to the required value with 0.1 M H_2SO_4 and NaOH solutions. In the study, 20 ml of 50 mg/l phenol solution was taken into duplicate 100 ml Erlenmeyer flasks (stoppered with plastic corks and covered with black polythene sheets to prevent loss of phenol by volatilization and photodegradation) and were agitated with 0.05 g of fungal biomass and activated carbon using rotary shaker operated at 150 rpm and room temperature (28 ± 2°C) for 2h. The samples were then filtered through Whatman No.1 filter paper. The remaining phenol was determined using 4-aminoantipyrene colorimetric method according to the procedure of Folsom *et al.* (1990).

Effect of adsorbent dose on phenol adsorption

The effect of fungal biomass on the amount of phenol removed from aqueous solution was obtained by shaking 20 ml of 50 mg/l phenol with different amount (0.02, 0.05, 0.1 and 0.2g of fungal biomass) in 100 ml flasks at optimum pH. The flasks were stoppered with plastic corks and covered with black polythene sheets to prevent loss of phenol by volatilization and photodegradation. Each sample was then shaken at constant speed of 150 rpm at room temperature for 2 h. The samples were filtered and the residual concentrations of phenol were determined as previously stated.

Determination of equilibrium time

The equilibrium time of phenol adsorption onto the adsorbents was determined by shaking 20 ml of 50 mg/l phenol solution with 0.05 g of activated carbon for up to 60 min as previously stated. Samples from separate flasks were analyzed after 2, 4, 6, 8 and 10 min and subsequently at 10 min interval. In the case of fungal biomass, 20 ml of 50 mg/l phenol solution was shaken with 0.05 g adsorbent for 3 h. Samples from separate flasks were analyzed for phenol at 30 min interval.

The kinetic data obtained from batch studies are analyzed by using pseudo-first-order (equations 1 and 2) and pseudo-second-order (equations 3 and 4) models to examine the rate of the adsorption process.

The first order equation of Lagergren is generally expressed as follows:

$$q_t = q_e\left(1 - e^{-k_1 t}\right) \qquad (1)$$

Equation 1 is linearized as:

$$Ln(q_e - q_t) = Ln\, q_e - k_1 t \qquad (2)$$

Where q_e and q_t are amounts of phenol adsorbed (mg/g) at equilibrium and at time t (min), respectively, and k_1 is the rate constant of pseudo-first-order sorption (min^{-1}).

A plot of $Ln(q_e - q_t)$ against t should give a linear relationship with the slope k_1 and intercept of $Ln\, q_e$.
The pseudo-second-order kinetic rate equation is expressed in equation 3 as follows:

$$q_t = \frac{k_2 q_e^{\,2} t}{1 + k_2 q_e t} \qquad (3)$$

Equation 3 is linearized as:

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

Where k_2 is the rate constant of pseudo-second-order sorption ($gmg^{-1}min^{-1}$).

If the second order kinetic equation is applicable, the plot of equation 4 should give a linear relationship. The q_e and k_2 can be determined from the slope and intercept of t/q_t versus t plot. The kinetic parameter values obtained from the linear plots were used as initial estimates to estimate the parameters from non-linear models.

Batch adsorption kinetics

Sorption kinetic experiments were carried out by contacting 20 ml of phenol solution of varying initial concentrations ranging from 10 to 600 mg/l with 0.05 g of activated carbon and fungal biomass in 100 ml Erlenmeyer flask at optimum pH. The samples were then shaken at constant speed of 150 rpm for 30 min (activated carbon) and 4 h (fungal biomass) under previously stated conditions. At equilibrium time, samples were filtered and the concentrations of phenol in the filtrates were determined as before. The amount of adsorption at equilibrium, q_e (mg/g) was obtained as follows:

$$q_e = \frac{(C_o - C_e)V}{1000M} \qquad (5)$$

Where C_o and C_e are the initial and equilibrium liquid phase concentration of phenol (mg/l); V is the volume of the solution (ml), M is the mass of adsorbent (g).

The equilibrium data was fitted to adsorption isotherm models, Linear (equation 6), Langmuir (equations 7 and 8) and Freundlich (equations 9 and 10) models. The linear adsorption isotherm is expressed in terms of the distribution coefficient K_d.

$$q_e = K_d C_e \qquad (6)$$

Langmuir equation is valid for monolayer sorption onto a surface with a finite number of identical sites and is given as:

$$q_e = \frac{q_o K_L C_e}{1 + K_L C_e} \qquad (7)$$

Where q_o is the maximum adsorption capacity (mg/g) and K_L is the equilibrium adsorption coefficient (l/mg) related to free energy of adsorption. C_e is the equilibrium concentration of phenol in the aqueous solution and q_e is the equilibrium adsorption capacity of adsorbent. The linearized form of Langmuir equation can be written as:

$$\frac{1}{q_e} = \frac{1}{q_o} + \frac{1}{q_o K_L} \cdot \frac{1}{C_e} \qquad (8)$$

The Langmuir constant q_o and K_L can be calculated by plotting $1/q_e$ versus $1/C_e$. The Freundlich model is an empirical equation based on sorption on heterogeneous surface. It is given as:

$$q_e = K_f C_e^{\frac{1}{n}} \qquad (9)$$

Where K_f and n are the Freundlich constants that indicate adsorption capacity and adsorption intensity respectively. The linearized form of Freundlich isotherm can be written as:

$$Ln\, q_e = Ln\, K_f + \frac{1}{n} Ln\, C_e \qquad (10)$$

The value K_f and n can be calculated by plotting $Ln\, q_e$ versus $Ln\, C_e$

The values of q_o, K_L, K_f and n obtained from the linear models are used as initial estimates to estimate their values with non-linear models using iterative method.

Results and discussion

The initial pH of adsorption medium is one of the most important parameters affecting adsorption process. The effects of pH on the adsorption of phenol onto activated carbon and *Aspergillus niger* biomass is shown in Fig. 1. It was observed that the uptake of phenol by activated carbon was constant in the pH range of 1 – 10, thus pH had no significant effect on adsorption of phenol by activated carbon. Optimum adsorption was obtained by the H_2SO_4-treated *Aspergillus niger* biomass at pH of 3.0. An increase or decrease in pH resulted in reduction of phenol adsorption by *A. niger* biomass. An optimum pH for phenol adsorption by fungal biomass have been reported as 5.1 (Rao and Viraraghavan, 2002) and 4.5 (Wu and Yu, 2006). It is important to note that activated carbon adsorbed phenol better than *A. niger* biomass and that pH did not significantly affect the adsorption of phenol by activated carbon. It shows that the surface of the activated carbon is more positively charged to attract the negatively charged phenol molecules. The positive charge probably could not be modified at low and high pH. It could also be attributed to larger surface area and microporous nature that increased the attraction of phenol to carbon particles.

Table 1. Characteristics of activated carbon.

Parameter	Value
Moisture content	10.0 %
Ash content	5.0 %
Acid solubles	4.0 %
Water solubles	3.6 %
pH	6.5 – 7.5
Particle size (300 mesh)	68 %
Methylene blue adsorption (0.15 % solution, Min. 12 ml/0.1g)	180 mg/g

In order to investigate the effect of adsorbent dose on the adsorption of phenol, a series of experiments were carried out with different doses of H_2SO_4-treated *A. niger* biomass at initial phenol concentration of 50 mg/l and mass of adsorbent varying from 0.02 – 0.2 g. Fig. 2 showed that the adsorption capacity at equilibrium (q_e) decreased with an increase in adsorbent dose. This is explained as a consequence of partial aggregation, which occurs at high biomass concentration resulting in decreased active sites. This corroborates the reports of Rubin *et al.* (2006) and Uddin *et al.* (2007).

Table 2. Pseudo-second-order kinetic constants for adsorption of phenol onto activated carbon and *Aspergillus niger* biomass.

Constants (units)[a]	Adsorbent			
	Activated Carbon		*Aspergillus niger*	
	Linear	Non linear	Linear	Non linear
q_e exp (mg/g)	19.846	19.846	7.399	7.399
q_e cal (mg/g)	19.881	19.843	7.813	7.584
K_2 ($gmg^{-1}min^{-1}$)	1.406	3.02	0.012	0.018
R_2^2	1.0000	0.9999	0.9985	0.9963

[a] constants obtained experimentally and as calculated from linear and non-linear models.

Table 3. Pseudo-first-order kinetic constants for adsorption of phenol onto activated carbon and *Aspergillus niger* biomass .

Constants (units)[a]	Adsorbent			
	Activated Carbon		*Aspergillus niger*	
	Linear	Non linear	Linear	Non linear
q_e exp (mg/g)	19.846	19.846	7.399	7.399
q_e cal (mg/g)	0.397	19.815	4.411	7.108
K_1 (min^{-1})	0.012	2.758	0.024	0.065
R_1^2	0.6182	0.9999	0.8779	0.9890

[a] constants obtained experimentally and as calculated from linear and non-linear models

The equilibrium adsorption time of phenol on activated carbon and H_2SO_4-treated *A. niger* was investigated. The results shown in Fig. 3 indicated that the adsorption of phenol on activated carbon is almost instantaneous and attained equilibrium within 2 mins. This rapid establishment of equilibrium indicates high affinity of the active carbon for phenol. Qadeer and Rehan (2002) have also reported rapid adsorption of phenol by activated carbon. In contrast, the adsorption of phenol by H_2SO_4-treated *A. niger* occurred more slowly reaching equilibrium at 180 min. The results indicated that adsorption of phenol onto activated carbon is about 90 times faster than on H_2SO_4-treated *A. niger* biomass and that about 3 times more phenol was adsorbed by activated carbon than *A. niger* biomass at quilibrium. The higher adsorption capacity of activated carbon is attributable to the larger surface area of carbon particle.

Table 4. Adsorption parameters for phenol adsorption onto activated carbon and *A. niger* biomass.

Adsorbent/ model type	Langmuir		
	q_o (mg/g)	K_L (l/mg)	R^2
Linear			
Activated carbon	49.751	0.905	0.967
A. niger	40.816	4.672×10^{-3}	0.966
Non-linear			
Activated carbon	165.941	0.035	0.983
A. niger	-	-	-
	Freudlich		
	K_f (l/g)	n	R^2
Linear			
Activated carbon	14.057	2.028	0.995
A. niger	0.182	1.055	0.993
Non-linear			
Activated carbon	17.519	2.307	0.997
A. niger	0.145	1.015	0.999

The kinetic data obtained from the batch studies were analyzed by using pseudo-first-order and pseudo-second-order kinetic models. Adsorption data fitted the pseudo-second-order model better with correlation coefficients (R^2) greater than 0.99 for activated carbon and H_2SO_4-treated *A. niger*. Thus, the adsorption of phenol onto activated carbon and *A. niger* biomass would better be described with pseudo-second order model. Generally, the R^2 values obtained with non-linear model is higher than those obtained with linearized models. The plots and the kinetic parameter estimates are shown in Figs. 3 and 4 and Tables 2 and 3.

The amount of adsorption increased with initial phenol concentration. The maximum adsorption capacities of activated carbon and H_2SO_4-treated *A. niger* biomass in the studied range were 146.08 mg/g and 67.11 mg/g respectively. The Linear, Freundlich and Langmuir isotherms were used to study the kinetics of phenol adsorption with respect to effect of initial concentration of phenol on adsorption (Figs. 5 – 7). The results showed that adsorption increases with increase in initial concentration of phenol. This is attributable to higher probability of collision between phenol and the adsorbent (Aksu and Yener, 1998). The absorption of phenol on *A. niger* biomass fitted linear model with a K_d of 0.134 l/mg (Fig. 5). Adsorption of phenols on activated carbon could be described with Freundlich and Langmuir models with non-linear models performing better than the linearized models. The linear transformation of the model has been seen to underestimate the kinetic parameters. The various parameter estimates and correlation coefficients are shown in Table 4.

Table 5. Adsorption parameters calculated from Freundlich isotherm equations at room temperature.

Adsorbent	K_f (l/g)	n	R^2	Reference
Sargassum muticum (pH1.0)	0.032 ± 0.04	1.3 ± 0.2	0.931	Rubin *et al.* (2006)
Sargassum muticum (pH2.5)	0.16 ± 0.02	1.8 ± 0.1	0.945	Rubin *et al.* (2006)
Sargassum muticum (pH4.5	0.25 ± 0.04	1.9 ± 0.1	0.971	Rubin *et al.* (2006)
Aspergillus niger (pH 5.1)	3.46	1.51	0.730	Rao and Viraraghavan (2002)
Phanerochaete chrysosporium	0.1951	2.2182	0.9844	Wu and Yu (2006)
Aspergillus niger (pH 3.0)	0.145	1.015	0.999	This study
Activated carbon (pH 4.0)	17.519	2.307	0.997	This study

The Langmuir model is valid for monolayer sorption onto a surface with a finite number of identical sites. The Freundlich model is an empirical equation based on adsorption on heterogeneous surfaces. It was observed that the experimental data for both activated carbon and H_2SO_4-treated *A. niger* biomass fitted the Freundlich model. The higher regression coefficients suggest that the Freundlich model was able to adequately characterize the sorption of phenol by activated carbon and *A. niger* biomass, thus predicting sorption on heterogeneous surface of adsorbents. Table 5 compares the Freundlich parameter value with values from other studies. The result of this study corroborated the report of Liu *et al.* (2012), that the pseudo-second-order model and the Freundlich isotherms described the adsorption of phenol on *Penicillium simplicissimum* better than the pseudo-first-order model and the Langmuir isotherms, respectively. The maximum adsorption capacity predicted for activated carbon is 165.941 mg/g. Although, the maximum adsorption capacity of *A. niger* biomass was not determined in the present study, it performed better than the *A. niger* biomass reported by Rao and Virarghavan (2002). The maximum adsorption capacity of 0.328 mg/g was reported by Rao and Virarghavan (2002). This value is less than the maximum value (49.96 mg/g) shown in Fig. 5 or 7.813 mg/g equilibrium adsorption capacity predicted from pseudo-second order model (Table 3). Adsorption of phenol on various adsorbents has been studied by many researchers. Table 6 summarizes the adsorption capacities reported by other researchers. The comparison shows that the maximum adsorption capacity of activated carbon reported in this work is comparably high. However, it is important to note that absolute comparison cannot be made because of the variations in experimental conditions.

The results indicated that adsorption capacity of the *A. niger* was affected by pH, adsorbent dose, contact time and phenol concentration. Pseudo-second order and Freundlich model described the experimental data, thus indicating the heterogeneous nature of the adsorbents. The kinetic parameters indicated that activated carbon could effectively be used to remove phenol from wastewater. Although activated carbon is a better adsorbent, it is limited by its high cost. This stimulated interest in the use of low cost adsorbents. In this regard, *A. niger* biomass provides promising alternative for effective removal of phenol from aqueous solutions.

Table 6. The maximum sorption capacity of phenol on various adsorbents.

Adsorbent	q_{max}(mg/g)	Reference
Activated carbon	602.3	Ravi *et al.* (1998)
Activated sludge	236.8	Aksu and Yener (1998)
Fly ash	3.85	Singh and Rawat (1994)
Sargassum muticum	4.6	Rubin *et al.* (2006)
Aspergillus niger	0.328	Rao and Viraraghavan (2002)
Rice husk	42.2	Munaf *et al.* (1997)
Bentonite	1.712	Banat *et al.* (2000)
Sewage sludge	94.0	Thawornchaisit Pakulanon (2007)
Activated sewage sludge	29.46	Otero *et al.*, (2003)
Activated carbon	49.72	Özkaya (2006)
Activated carbon	13.22	Kaleta (2006)
Activated carbon	97.36	Karabacakoğlu *et al.* (2008)
Activated carbon	165.941	This study

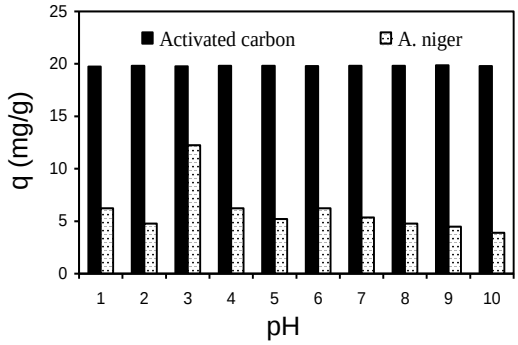

Fig. 1. Effects of pH on the adsorption of phenol onto adsorbents. Initial concentrations of phenol = 50mg/l; working volume = 20 ml; temperature 28 ± 2°C; agitation rate = 150 rpm; agitation time = 1h

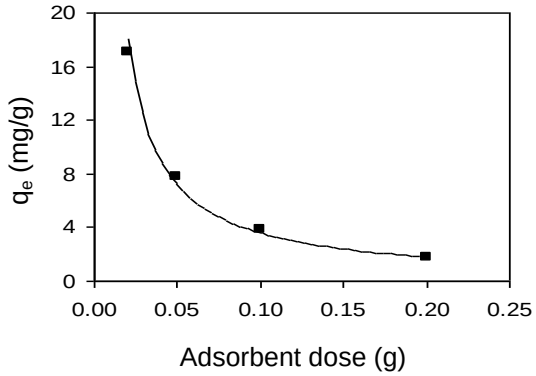

Fig. 2. Effect of adsorbent dose on the adsorption of phenol onto H_2SO_4-treated *Aspergillus niger* biomass. Initial concentrations of phenol = 50mg/l; working volume = 20 ml; contact time = 2h; temperature 28 ± 2°C; agitation rate = 150 rpm, pH = 3

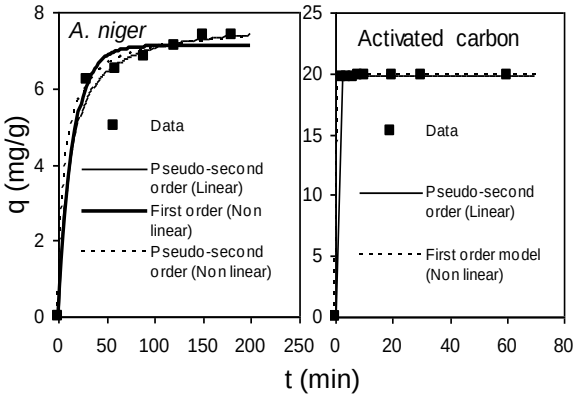

Fig. 3. Effect of time on the adsorption of phenol onto *Aspergillus niger* biomass. Initial concentrations of phenol = 50mg/l; temperature 28 ± 2°C; agitation rate = 150 rpm; pH= 3.0 (*A. niger*), 4.0 (activated carbon)

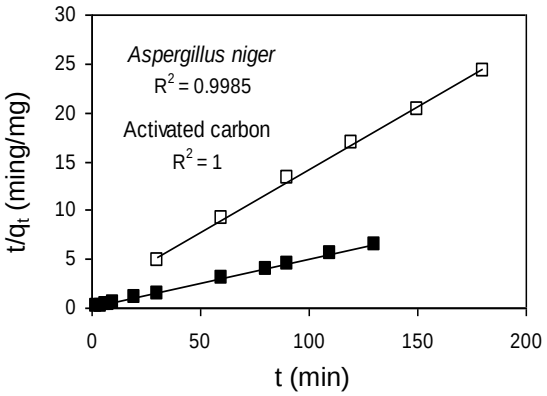

Fig. 4. Pseudo second order plot for the adsorption of phenol onto activated carbon (■) and H_2SO_4-treated *Aspergillus niger* biomass (□).

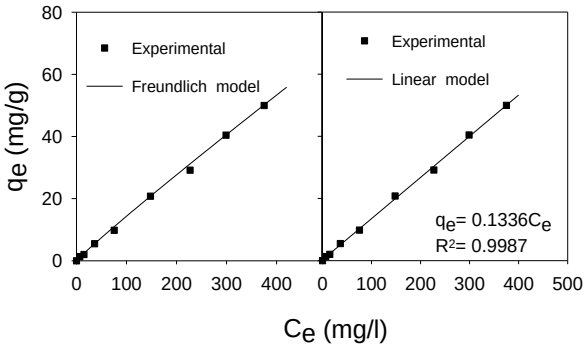

Fig. 5. Linear and Freundlich isotherms for adsorption of phenol onto H_2SO_4-treated *Aspergillus niger* biomass. Mass of adsorbent = 50 mg; working volume 20 ml; initial concentrations of phenol = 10 – 600 mg/l; temperature 28 ± 2°C; agitation rate = 150 rpm.

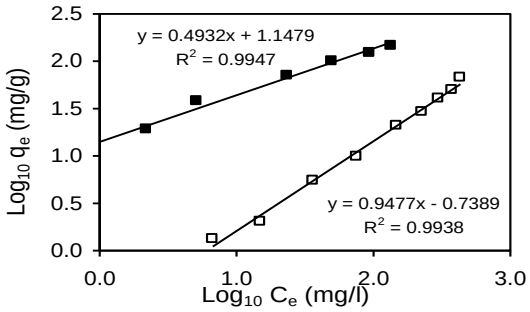

Fig. 6. Linear plot of Freundlich isotherm for the adsorption of phenol onto activated carbon (■) and H_2SO_4-treated *A. niger* biomass (□). Mass of adsorbent = 0.05g; initial concentrations of phenol = 10 – 600 mg/l; temperature 28 ± 2°C; agitation rate = 150 rpm; pH = 3.0 (*A. niger*) and 4.0 (activated carbon).

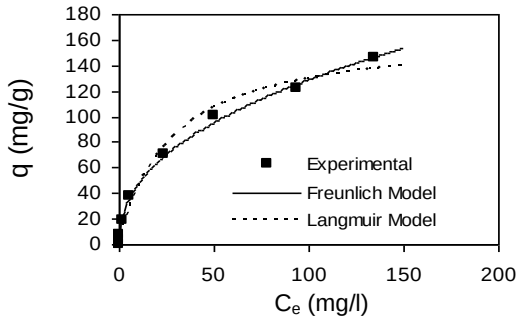

Fig. 7 Freundlich and Langmuir isotherms for adsorption of phenol onto activated carbon. Data were simulated from non-linear models. Mass of adsorbent = 0.05g; initial concentrations of phenol = 10 – 600 mg/l; working volume = 20 ml; temperature 28 ± 2°C; agitation rate = 150 rpm.

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