

Modelling the Simultaneous Adsorption and Biodegradation of Aromatic Hydrocarbons onto Non-Carbonized Biological Adsorbent in Batch System

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Abstract

In this study, a modified two-site sorption kinetic numerical model that differentiates between the adsorption and biodegradation quantities of a non-carbonized biological activated adsorbent (NCBAA) was developed and validated. Also, the effects of initial naphthalene and phenol concentrations on the simultaneous adsorption-biodegradation performances of orange and pineapple peel immobilized *Pseudomonas aeruginosa* NCIB 950 in naphthalene and phenol removal was respectively evaluated. Adsorption-biodegradation model was developed from the modification of a two-site kinetic numerical model by combining the elements of adsorption and biodegradation models and validation of the model carried out through the application of batch adsorption-biodegradation equilibrium and kinetic experimental data. Results showed that the model predictions of the naphthalene and phenol concentrations are in good agreement with the experimental data. For simultaneous adsorption-biodegradation of naphthalene by orange peel immobilized *Pseudomonas aeruginosa*, adsorption rate coefficient increased with initial naphthalene concentration and biodegradation rate coefficient decreased with increased initial concentration; and for phenol simultaneous adsorption-biodegradation by pineapple peel immobilized *Pseudomonas aeruginosa*, adsorption rate coefficient decreased with increased initial phenol concentration and biodegradation rate coefficient increased with increased initial phenol concentration. Thus, the adsorption-biodegradation model is a reasonable tool for simulating the adsorption-biodegradation behaviors of aromatic hydrocarbons in NCBAA.

Keywords: Bacteria; Simultaneous adsorption-biodegradation; Phenol; Naphthalene; Non-carbonized biological activated adsorbent; Numerical model.

1. Introduction

In many industrial waste water treatment plants, adsorption and biodegradation mechanisms has been widely used in water and waste water treatments for lowering the regeneration cost of biological adsorbents and reducing the concentration of toxic organic compounds in waste water (Liang *et al.*, 2007). Support media known as bio-carriers have often been used with immobilized or attached cells to increase the potential removal efficiency of gaseous or aqueous phase organic compound on one hand and to provide a surface for microbial growth (Choi *et al.*, 2007). For instance, activated carbon as a support medium was used for immobilization of bacteria (biological activated carbon) to remove organic compound (Ehrhardt and Rehm, 1985; Morsen and Rehm, 1990; Orshansky and Narkis, 1997; Pazarliogu and Telefoncu, 2005; Mondal and Balomajumder, 2007). Immobilization of cells using other solid matrices that are not carbonized such as alginate beads, chitin and chitosan has also been used for adsorption and biodegradation of organic compounds (Annadurai *et al.*, 2000; Choi *et al.*, 2007; Annadurai *et al.*, 2007). Choi *et al.* (2007) have reported that simultaneous adsorption and biodegradation of benzene treatment with alginate bead immobilized bacteria showed lower fast sorption but higher overall reduction of benzene concentration due to biodegradation by bacteria attached on the surface of the bead, while for activated carbon the treatment with bacteria did not show any evidence of biodegradation but showed only fast sorption. The absence of biodegradation for the activated carbon was attributed to the relatively high sorption capacity compared to the alginate bead.

Researchers and operators have been attempting to elucidate the mechanism of adsorption and biodegradation in biological adsorbents for the purpose of simulation and optimization. Two major mechanisms concerning simultaneous adsorption and biodegradation were found in the literature. The first one suggests a mutual effect of the microorganisms and the adsorbent (Spetiel, 1989; Orshansky and Narkis, 1997; Chaudhary *et al.*, 2003). In this case, microbial enzymes excreted into the adsorbent micro pores bring about extracellular biodegradation of adsorbed organic compound and bioregeneration of the adsorbent. The adsorbent adsorption capacity controlled by the regeneration is highly increased and thus the adsorbent adsorption column cycle is prolonged as compared to pure adsorption alone. While the second mechanism suggests that there are no mutual effects of microbial cells and the adsorbent, but rather a simple combination of adsorption and biodegradation (Xiaojian *et al.*, 1991). Xiaojian *et al.* (1991) explained that in this mechanism, the adsorbent surface gets saturated such that

microbial enzyme reactions cannot take place within the sorbent's tiny micro pores since the enzyme molecules are larger than the micro pore size.

In recent years, extensive research has been undertaken to develop alternative and economic adsorbents from microbial biomass and agricultural by-products (Agarry and Aremu, 2012a). This is due to their relative high sorption affinity, ubiquitous presence in the environment, and the ease of being modified to materials with higher efficiency (Li *et al.*, 2010; Chen *et al.*, 2011). Most of the agricultural waste products developed as adsorbents have been used for the removal of heavy metals from waste waters (Marshall *et al.*, 2000; Reddad *et al.*, 2002; Popuri *et al.*, 2007; Li *et al.*, 2008; Li *et al.*, 2010) but very few reports on its use as adsorbent for the removal of organic pollutants (Lin *et al.*, 2007; Crisafully *et al.*, 2008; Gayatri and Ahmaruzzaman, 2010; Chen *et al.*, 2011; Agarry and Aremu, 2012a). Furthermore, there are no reports on the use of these developed agricultural waste adsorbent as solid support matrix for microbial cell immobilization to be used for simultaneous adsorption and biodegradation process except for the works of Agarry and Aremu (2012a, b).

In Nigeria, huge amounts of waste are produced by large scale agriculture like orange peels which is composed of soluble sugars, 16.9 % wt; starch, 3.75 % wt; fiber (cellulose, 9.21 % wt; hemicelluloses, 10.5 % wt; lignin 0.84 % wt; and pectin, 42.5 % wt), ashes, 3.50 % wt; fats, 1.95 % wt; and proteins, 6.50 % wt. (Rivas *et al.*, 2008) and pineapple peels composed of cellulose, 11.2%wt, hemicelluloses, 7%wt; lignin, 11.52%wt; pectin, 6.7%wt; protein, 3.13%wt and ash, 3.88%wt (Rani and Nand, 2004) for which applications are only sparingly available. The use of these orange peel and pineapple peel as adsorbent and solid support matrix for the immobilization of *Pseudomonas aeruginosa* NCIB 950 and subsequently used for the simultaneous adsorption and biodegradation of naphthalene and phenol, respectively, has been reported by Agarry and Aremu (2012a, b).

Naphthalene being a poly aromatic hydrocarbon (PAH) and phenol a mono aromatic hydrocarbon were respectively chosen as model candidates for simultaneous adsorption and biodegradation studies because of their common presence in a variety of waters and wastewaters (Williams, 1990; Douben, 2003) of industrial processes such as oil refining, pharmaceuticals, pesticide production, resin production, wood preservatives and coke making (Bandyopadhyay *et al.*, 1998; Cabal *et al.*, 2009). Despite this, they are highly toxic environmental pollutant with mutagenic and carcinogenic properties (Keith and Telliard, 1979; ATDSR, 2003; Ania *et al.*, 2007) and due to their high mobility and persistence in the environment they are included in the list of priority pollutants of the European Environmental Agency (Directive 2000/60/EC) and United State Environmental Protection Agency (US.EPA, 1979; Keith and Telliard, 1979); thus, their concentration is regulated in drinking water (WHO, 2006).

Some well-validated mathematical models have been developed to assess and predict the performance of biological activated carbons (Chang and Rittmann, 1987; Sakoda *et al.*, 1996; Walker and Weatherley, 1997; Abumaizar *et al.*, 1997; Hozalski and Bouwer, 2001; Badriyha *et al.*, 2003; Liang *et al.*, 2007). However, to the best of our knowledge in the literature, a well-validated mathematical model which can provide valuable information to assess and predict the performance of non-carbonized biological activated adsorbents has not been developed.

The purpose of this study is to develop and validate a modified form of two-site kinetic numerical model under an irreversible sorption condition that combines the elements of sorption and degradation models to simulate both adsorption and biodegradation quantities of a non-carbonized biological activated adsorbent (NCBAA) as well as be able to predict final effluent organic contaminant concentration. To validate the model, experimental data of Agarry and Aremu (2012a, b) on the simultaneous adsorption-biodegradation of naphthalene and phenol using orange peel and pineapple peel immobilized *Pseudomonas aeruginosa* NCIB 950, respectively, were used.

2. Materials and Methods

2.1 Preparation of Adsorbent

Orange peel and pineapple peel being an agricultural waste product to be used as adsorbent and solid support matrix for microbial cell immobilization were obtained from orange and pineapple fruits bought from a local market in Ogbomoso, Nigeria. The orange peel and pineapple peel were separately sundried and then reduced to small-sized particles by grinding using a serrated disk grinder. The powdered particles were sieved to obtain different desired average particle sizes (0.125 – 0.422 mm). They are washed thoroughly with sterilized de-ionized water and dried in the oven for 2 – 3 h at 60°C. The powdered orange peel (POP) and pineapple peel (PPP) was pretreated as to increase the naphthalene and phenol uptake efficiency. 10 g of the separate peels were each treated with 100 ml of 1M HCl for 24 h and then kept on water bath (70°C) for 30 min. It was later cooled and neutralized with 50 ml of 1M NaOH. The filtrates were separated and dried in the oven at 60°C for 4 – 5 h. The pretreated powdered orange peel and pineapple peel were separately used as adsorbent and solid support for the physical immobilization of *Pseudomonas aeruginosa*.

2.2 Chemical and Synthetic waste water

Naphthalene and phenol (99% pure, chemical grade) being products of Sigma-Aldrich, USA were purchased

from a chemical store, Lagos, Nigeria. All chemicals used as mineral salt medium are of analytical or biochemical grade. The synthetic waste water used in this work was composed of: K_2HPO_4 1.0 g , KH_2PO_4 0.5 g , $(NH_4)_2SO_4$ 0.5 g , NaCl 0.5 g , $CaCl_2$ 0.02 g , $MnSO_4$ 0.02 g , $CuSO_4 \cdot 5H_2O$ 0.02 g , H_3BO_3 0.01 g , $MgSO_4 \cdot 7H_2O$ 0.5 g , $FeSO_4$ 0.02 g , Molybdenum powder 0.02 g , deionized water 1000 ml.

2.3 Microorganism and Preparation of Inoculum

The microorganism, *Pseudomonas aeruginosa* NCIB 950 which has the potential to degrade aromatic hydrocarbons such as naphthalene and phenol (Chang *et al.*, 1997; Abou Seoud, 2003; Agarry *et al.*, 2008) was obtained from the Department of Microbiology, Obafemi Awolowo University, Ile-Ife, Nigeria. The microorganism was maintained in a standard nutrient agar medium. A primary culture was prepared by transferring two loops full of microorganisms from an agar slant culture into 100 ml of feed medium containing 20 ml of mineral salt medium and 80 ml of 50 mg/l naphthalene or phenol solution in a 250 ml Erlenmeyer conical flask. This was then incubated in a New Brunswick gyratory shaker (G25-R model, New Jersey, U.S.A) for 48 h at a temperature of 30°C and agitated with a speed of 120 rpm. Thereafter, 10 ml of the primary culture was transferred into another 100 ml of feed medium in a 250 ml Erlenmeyer conical flask and the incubation process was repeated. This was the secondary culture that was used as the inoculum for the degradation studies as this ensures that the organisms had fully adapted to growth on the naphthalene or phenol as sole source of carbon and energy.

2.4 Batch Simultaneous Adsorption-Biodegradation Equilibrium and Kinetic Studies

Batch adsorption-biodegradation studies were carried out by adding a known volume (100 ml) of prepared inoculums of *P. aeruginosa* into a number of glass bottles containing a known amount of biological adsorbent (orange peel or pineapple peel) (2 g). Definite volume (150 ml) of synthetic waste water with different initial aromatic hydrocarbon (naphthalene or phenol) concentration between 10 and 500 mg/l was added to each flask and the pH of the waste water was maintained at 7. The flasks were placed in a rotary mechanical shaker for 72 h at a speed of 180 rpm and temperature of 30°C so as to reach equilibrium. In every 6 h intervals, samples were taken to determine the amount of aromatic hydrocarbon (naphthalene or phenol) adsorbed and degraded. At time $t = 0$ and equilibrium, the aromatic hydrocarbon (naphthalene or phenol) concentrations were determined using UV-spectrophotometer. The amount of adsorption at equilibrium, q_e (mg/g) was calculated according to Eq. (1) (Crisafully *et al.*, 2008):

$$q_e = \frac{(C_o - C_e)V}{W} \quad (1)$$

The amount of aromatic hydrocarbon (naphthalene or phenol) adsorbed and degraded at time t , q_t was calculated according to Eq. (2) (Xun *et al.*, 2007):

$$q_t = \frac{(C_o - C_t)V}{W} \quad (2)$$

Where C_o and C_e (mg/l) are the initial and final (equilibrium) concentrations of aromatic hydrocarbon (naphthalene or phenol) in waste water; C_t is the concentration of aromatic hydrocarbon (naphthalene or phenol) in waste water at time t ; V (ml) is the volume of the waste water and W (g) is the mass of dry adsorbent used.

2.5 Development of Simultaneous Adsorption - Biodegradation Model

The process was modelled by combining the elements of adsorption and biodegradation models. One-site kinetic numerical sorption model with limited sorption (OSLS) was described where one-stage sorption of aqueous organic compound occurred at the interior sites of non-carbonized biological activated adsorbent as well as its biodegradation at the sorbent surface (Figure 1). This is a modification of Kim *et al.* (2003) sorption kinetic model. The one stage is assumed to be a limited irreversible adsorption process.

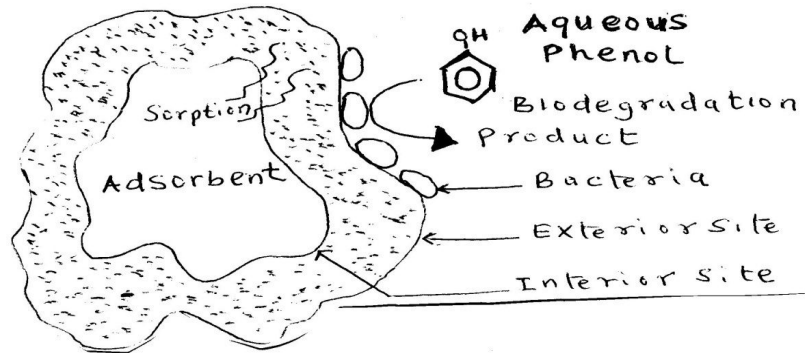


Figure 1: Schematic Diagram of Sorption and Biodegradation of Pollutant at the Surface of Adsorbent in a Batch System

The basic assumptions of our model are:

- The powdered particles used in NCBAAs are spherical in shape, the bacteria is attached on the exterior surface of the NCBAAs and that the density of the bacteria is constant;
- The organic compound present in wastewater solution and on the exterior surface of the adsorbent is subject to biodegradation but once it is sorbed into the interior surface it is free from bacterial attack and degradation;
- Biodegradation reaction in the micro pores of the adsorbent is negligible since the size of the micro pores are less than the size of the bacteria;
- Adsorption is irreversible and desorption after the saturation of NCBAAs is not taken into consideration
- Adsorption is unaffected by biodegradation

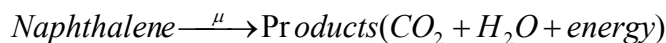
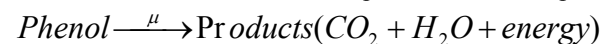
The governing equation for the adsorption kinetic model is based on mass balance for the contaminant (substrate) concentration in the liquid phase and on the irreversible (non-equilibrium) sorption of the sorbate (Kim *et al.*, 2003):

$$V_w \frac{dC}{dt} + M_s \frac{dq}{dt} = -V_w \mu(t)C \quad \text{Mass balance} \quad (3)$$

$$\frac{dC}{dt} = -\alpha C \left[1 - \frac{q_t}{q_e} \right] \quad \text{Kinetic irreversible sorption} \quad (4)$$

Where C is aqueous naphthalene or phenol concentration (mg/l); C_0 is initial phenol or naphthalene concentration; V_w is wastewater volume (l); M_s is mass of adsorbent; (g); q_t is the adsorption capacity of adsorbent at time, t (i.e. mass of naphthalene or phenol adsorbed irreversibly per mass of adsorbent, (mg/g); q_e is the equilibrium adsorption capacity of adsorbent (i.e. maximum equilibrium amount of naphthalene or phenol adsorbed per mass of adsorbent, (mg/g); α is the adsorption rate coefficient (h^{-1}) and $\mu(t)$ is biodegradation rate coefficient (h^{-1}).

The biodegradation process is based on first-order kinetic equation which is represented as follows;



$$-r = \frac{dC}{dt} = \mu(t)C \quad (5)$$

Where, C is the concentration of naphthalene and phenol in wastewater solution (mg/l), and $\mu(t)$ is the biodegradation rate coefficient (h^{-1}).

After integration and applying conditions, ($C = C_0$) at $t = 0$ and $C = C_t$ at $t = t$, then Eq. (5) becomes

$$\ln\left(\frac{C_o}{C_t}\right) = \mu t \quad (6)$$

Combining Eq. (4) and Eq. (5):

$$\frac{dC}{dt} = -\alpha C \left[1 - \frac{q_t}{q_e}\right] - \mu(t)C \quad (\text{Kinetic irreversible adsorption-biodegradation}) \quad (7)$$

Eq. (7) is subject to the initial conditions:

$$C(0) = C_o \quad q(0) = 0 \quad (8)$$

The solution of Equations (3), (7) and (8) was obtained numerically by first-order Runge Kutta integration using MATLAB 7.0 software package. The biodegradation rate coefficient $\mu(t)$ as obtained by regression analysis, fitting the experimental data to Eq. (5), by making a plot of C_t/C_o versus time (t) and the slope of the plot gave the rate coefficient μ which was subsequently used to solve the model equations.

3. Results and Discussion

3.1 Model Parameters of Naphthalene and Phenol

The model parameters used in solving the simultaneous adsorption and biodegradation model were derived from the simultaneous adsorption-biodegradation experimental data for naphthalene (Agarry and Aremu, 2012a) and for phenol (Agarry and Aremu, 2012b), respectively. The parameters are presented in Table 1. Each of the model parameters contributes a portion to the model prediction, but the sensitivity of each parameter varies, if a slight adjustment of a parameter affects the simulation result drastically then the model is said to be sensitive to such parameters. Parameters like initial concentration, mass of adsorbent and volume of waste water may not be as sensitive as the adsorption rate coefficient (α) and the modified biodegradation rate ($\mu(t)$). Slight changes in the values of α and μ results in major changes to the simulation result.

Table 1. Model Parameters for Naphthalene and Phenol

Contaminant	Adsorbent and Size	C_o (mg/l)	q_e (mg/g)	$\mu(t)(h^{-1})$	$\alpha(h^{-1})$
Naphthalene	Orange Peels (0.125mm)	10	1.1750	0.0255	0.0030
		20	2.3125	0.0250	0.0032
		30	3.3750	0.0230	0.0034
		40	4.3750	0.0220	0.0036
		50	5.3125	0.0210	0.0038
Phenol	Pineapple Peels (0.152mm)	100	12.35	0.041	0.00055
		200	24.69	0.050	0.00050
		300	37.49	0.054	0.00040
		400	49.26	0.055	0.00036
		500	61.50	0.057	0.00032

3.2 Fitting and Validation of the Model with Experimental data

The results of the irreversible adsorption-biodegradation model after solving for various initial concentration of naphthalene (10 – 50mg/l) and phenol (100 – 500 mg/l) using 0.125mm particle size of powdered orange peel (POP) and 0.152 mm of powdered pineapple peels, respectively, is shown as a plot of C_t/C_o versus t (time) (Figure 2 (a – e)) for naphthalene, and Figure 3 (a – e) for phenol, respectively. Figures 2 and 3 shows the experimental data as well as simulated data in which adsorption and biodegradation occurred simultaneously in non-carbonized adsorbent (orange peel and pineapple peel) inoculated with *P. aeruginosa* bacteria. Both the naphthalene and phenol curves showed the same pattern with an initial fast phase followed by a slow decline. A similar observation has been reported for the simultaneous adsorption and biodegradation of benzene in soil amended with activated carbon (Kim *et al.*, 2003). The process was modelled by combining the elements of the biodegradation and adsorption models (Eq. (5) – (8)). The simulations shown in Figure 2(a - e) and Figure 3 (a – e) compares the concentration data obtained from experiment with that obtained from the model to verify if the model fits the experimental data sufficiently and can predict the concentration reduction in the waste water solution. As seen in Figure 2 (a – e), it is evident that at low naphthalene concentration the model result and that

of the experimental data approach each other closely with minimal errors. However, as the concentration of naphthalene increases the model represents the data well but with slight inaccuracy. This indicates that the adsorption rate coefficient α which is a sensitive parameter may need adjustment so as to reduce the variation between the model and the experimental data.

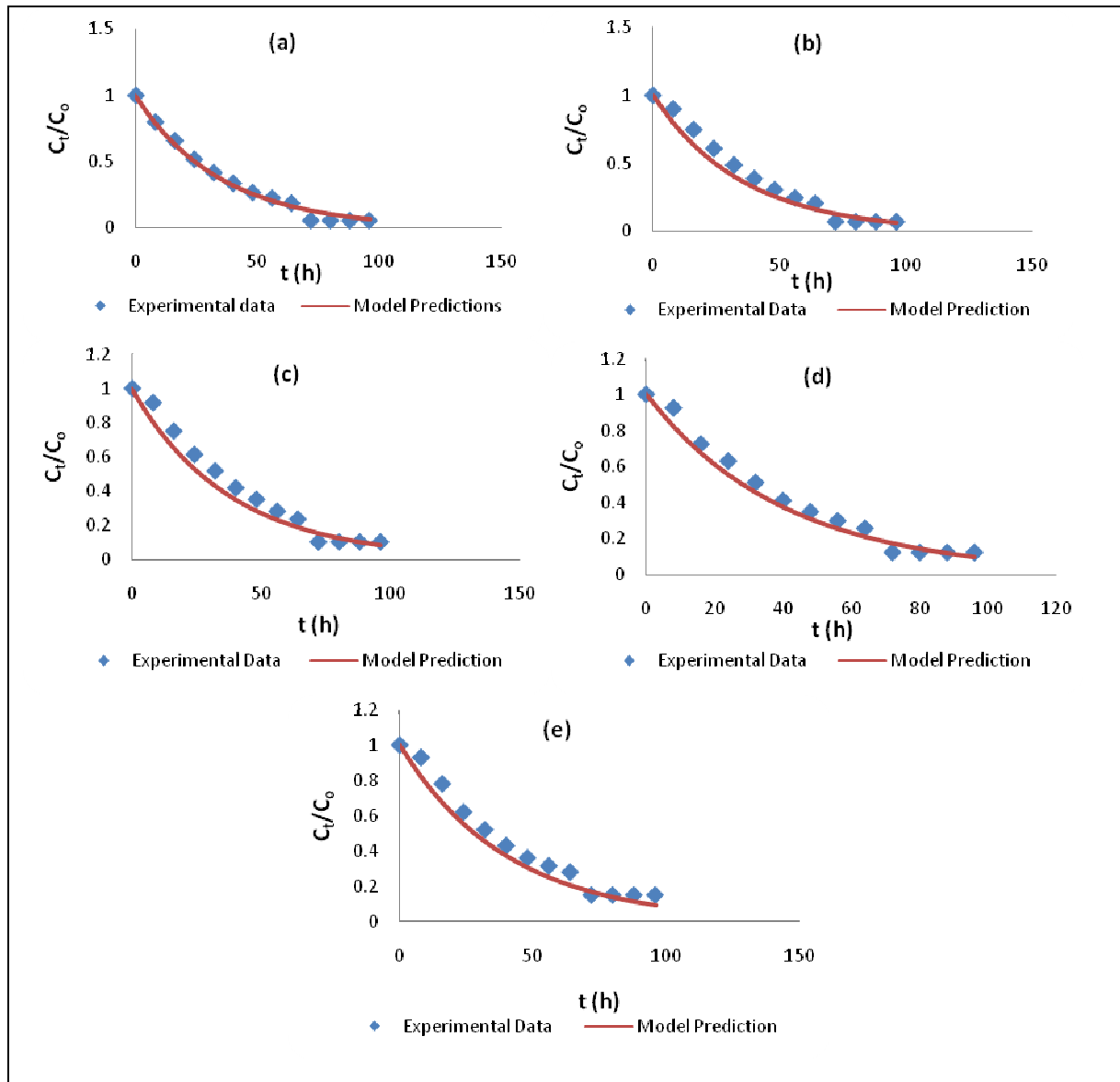


Figure 2: Experimental and Predicted Aqueous Naphthalene Concentration during Adsorption-Biodegradation on the Surface of Orange Peels Immobilized *P. Aeruginosa* at Initial Naphthalene Concentration of (a) 10 mg/l, (b) 20 mg/l, (c) 30 mg/l, (d) 40 mg/l, (e) 50 mg/l

On application of the model to phenol experimental data as shown in Figure 3 (a – e), it is evident that the model was able to predict the experimental data with sufficient accuracy and with minimal errors, however at low concentration of phenol and after 48 h when equilibrium has been attained, the magnitude of the error increased slightly due to equilibrium attainment. From Figure 3 (a – e), it is seen that a higher concentration of phenol in the waste water brings about minimal error between the model prediction and the experimental data, this implies that the model is sensitive to changes in the initial concentration and a subsequent increase in initial concentration brings about a better fit between the experimental and the model result.

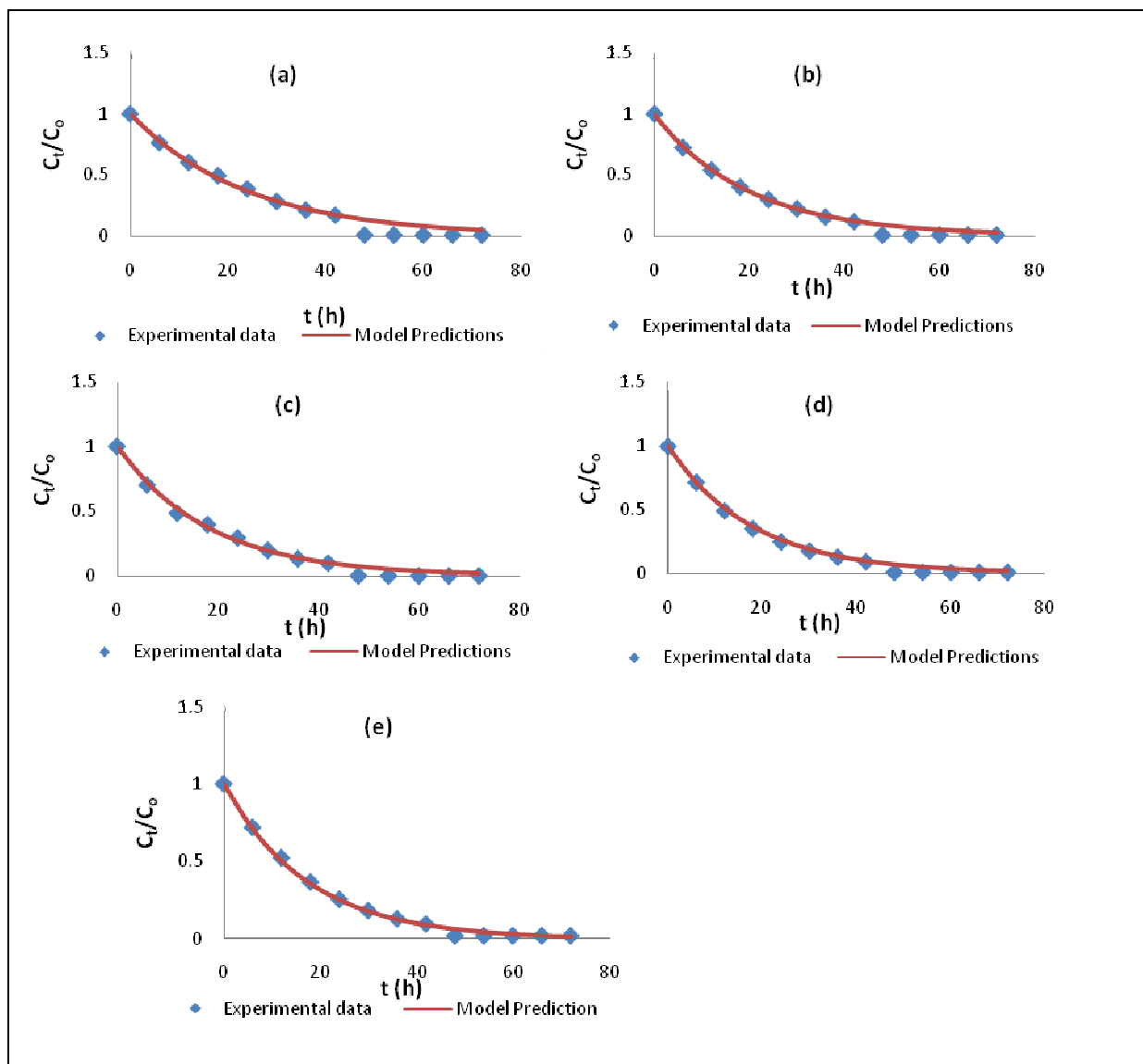


Figure 3: Experimental and Predicted Aqueous Phenol Concentration during Adsorption-Biodegradation on the Surface of Pineapple Peels Immobilized *P. Aeruginosa* at Initial Phenol Concentration of (a) 100 mg/l, (b) 200 mg/l, (c) 300 mg/l, (d) 400 mg/l, (e) 500 mg/l

3.3 Effect of Model Parameters on Simultaneous Adsorption and Biodegradation

From the model parameters shown in Table 1, the biodegradation rate coefficient $\mu(t)$ decreases with increase in the initial naphthalene concentration (from 10 – 50mg/l). This might be due to inhibitory effect of naphthalene on metabolic activities of the immobilized organism which reduces its bioavailability (Abou Seoud and Maachi, 2003; Jegan *et al.*, 2010). While the adsorption rate coefficient α increased with increase in the initial naphthalene concentration. This increase in the adsorption rate coefficient showed that the cavities (micro pores) of the orange peels adsorbent surface was easily more accessible (due to small particle size and large surface area) for naphthalene adsorption as the initial concentration increased. Smaller particle size means more interior surface and micro pore volume and hence more will be the area of active sites for adsorption (Annadurai *et al.*, 2000; Kumar *et al.*, 2007; Agarry and Aremu, 2012a, b). This observation indicates that adsorption predominates over biodegradation in simultaneous adsorption-biodegradation process until adsorption equilibrium has been reached after which biodegradation predominates as indicated by the greater biodegradation rate coefficient values ($0.0210 - 0.0255 \text{ h}^{-1}$) over the adsorption rate coefficient values ($0.0030 - 0.0038 \text{ h}^{-1}$). A similar observation has been reported (Mondal and Balomajumder, 2007).

Also for phenol (Table 1), it is seen that the biodegradation rate coefficient $\mu(t)$ increased with increase in the initial phenol concentration. This observation might be due to the fact that the attached bacteria on the surface of the pineapple peels adsorbent led to reduction in the adsorption of phenol as fewer cavities (micro pores) were accessible for adsorption due to relatively larger particle size (0.152 mm) as compared to the particle size of orange peel (0.125 mm) used for the study. On the other hand, the adsorption rate coefficient α decreased with an increase in initial phenol concentration which might probably be due to small surface area as well as small micro pore volume as a result of large particle size. For larger particles, the diffusion resistance to mass transfer is higher and most of the internal surfaces of the particle may not be utilized for adsorption and consequently the amount of phenol adsorbed is small (Annadurai *et al.*, 2000; Lakshmi *et al.*, 1998; Dabhade *et al.*, 2009). This indicate that only phenol molecules which are undegraded could be sorbed into the adsorbent and since the microbe was immobilized on the pineapple peel, a large portion of the phenol might have been biodegraded while the remaining portion is sorbed into the adsorbent; thus, biodegradation predominates as reflected by the greater values of biodegradation rate coefficient ($0.041 - 0.057 \text{ h}^{-1}$) over the values of the adsorption rate coefficient ($0.00032 - 0.00055 \text{ h}^{-1}$). Therefore, for the simultaneous adsorption-biodegradation of naphthalene by the orange peel immobilized *Pseudomonas aeruginosa* and phenol by the pineapple peel immobilized *Pseudomonas aeruginosa*; biodegradation has enhanced the removal of naphthalene as well as phenol from the aqueous solution, respectively. This agrees with the mechanism of bio-filtration (Chaudhury *et al.*, 2003) where bio-layer is formed followed by degradation of compounds. Ehrhardt and Rehm (1985) and Kim *et al.* (2003) have also reported a decrease in the adsorption of phenol and benzene, respectively, onto activated carbon due to attachment of bacteria or formation of a biofilm on the activated carbon surface; while Choi *et al.* (2007) reported a decrease in benzene adsorption onto alginate beads immobilized with bacteria. The effect of powdered activated carbon (PAC) on the degradation of benzene, toluene, ethyl benzene and xylene (BTEX) by a mixed culture of bacteria has been studied by Mason *et al.* (2000), who applied PAC in a completely mixed bioreactor system to immobilize bacteria and to adsorb BTEX compounds. They reported that bacteria attached to the surfaces of PAC resulted in the reduction of PAC adsorption capacity for compounds. In addition, the presence of PAC helped to continue metabolic activity of bacteria by buffering shock loads or by accumulating very low contaminant concentrations.

4. Conclusion

This study has demonstrated that phenol and naphthalene sorption and degradation in non-carbonized biological adsorbents (pineapple and orange peels) can be sufficiently represented by the adsorption – biodegradation model. The model provides a good approximation of the experimental data and the predictions were improved further by adjusting the adsorption rate coefficient (α). For simultaneous adsorption and biodegradation of naphthalene by orange peel immobilized *Pseudomonas aeruginosa*, adsorption rate coefficient increased with initial naphthalene concentration and biodegradation rate coefficient ($\mu(t)$) decreased with increased initial concentration. While for phenol simultaneous adsorption-biodegradation by pineapple peel immobilized *Pseudomonas aeruginosa*, α decreased with increased initial phenol concentration and $\mu(t)$ increased with increased initial phenol concentration. For the simultaneous adsorption-biodegradation of naphthalene by the orange peel immobilized *Pseudomonas aeruginosa* and phenol by the pineapple peel immobilized *Pseudomonas aeruginosa*; biodegradation has enhanced the removal of naphthalene as well as phenol from the aqueous solution, respectively. The concentration values obtained from the model was compared with those obtained from the experiment and there was similarity, acceptable errors exist between the model predictions and the experimental data; nonetheless, it implies that the irreversible-adsorption biodegradation model is a reasonable instrument for simulating the adsorption and biodegradation behaviors of the orange peel and pineapple peel, respectively

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