SIMULATION OF THE BIOREMEDIATION OF POLYCYCLIC AROMATIC HYDROCARBONS (PAHS) IN STIRRED REACTORS

C.N. Owabor\textsuperscript{a}, J.I. Achebo\textsuperscript{b}

\textsuperscript{a}Department of Chemical Engineering, University of Benin, Benin City, Nigeria.
\textit{Email: owabor4you@yahoo.com}

\textsuperscript{b}Department of Production Engineering, University of Benin, Benin City, Nigeria.
\textit{Email: josephachebo@yahoo.co.uk}

Abstract

The mathematical solution to a one-dimensional advective-dispersive solute transport model with linear equilibrium sorption and first-order degradation was carried out in this study. Simulation was carried out using MathCad software. The model solution predicted time approximated concentration distribution at varying depths of the selected PAHs (naphthalene, anthracene and pyrene) used in this study at distances. Simulation results showed that the concentrations of naphthalene, anthracene and pyrene within a contact period of 40, 55, and 50 days respectively, decreased in the direction of flow from 200 mg/l at the surface to zero at 9cm subsurface depth within the porous media. The residual concentrations of naphthalene, anthracene and pyrene were found to be 14\% (35\textsuperscript{th} day), 44\% (50\textsuperscript{th} day) and 29\% (45\textsuperscript{th} day) respectively. The simulation results closely fit the data from experiments an indication that the technique significantly provides solution to non-steady state model concerned with contaminant solute transport and degradation.

Keywords: contaminant solutes, finite element method, degradation, mobility, availability

1. Introduction

The frequency of the occurrence of oil spills in transmission pipelines is continuously eliciting attention in the Niger-Delta region of Nigeria. This may not be unrelated to the incidences/widespread releases of toxic chemicals such as polycyclic aromatic hydrocarbons, and volatile organic compounds associated with these spills [1-4]. Generally, the Niger Delta region environment has been subjected to a constant and consistent pollution of its air, land and sea. Some of the spills have been known to seep into the ground and contaminate ground water. Many in the region have complained that water from freshly sunk boreholes showed evidence of oil contamination which renders the water undrinkable even after some treatment. Aside contamination of the water environment, areas that have been known to be fertile for farming in the past have suddenly become barren or are getting close to being so. The mangrove forest is slowly withering away and the agricultural industry is suffering. This is particularly sad because the natives, who used to make their living through subsistent farming, have to look elsewhere [5-7]. The potential negative effects posed by these chemicals has therefore made the quick and safe decontamination of locations that have had shock loading of petroleum or petroleum products very imperative and very desirable. An effective method for detoxifying the contaminants and hence cleaning up the soil is via bioremediation [4,8-12]. However, the process is complex and involves the diffusion of contaminants in the porous soil matrix, adsorption to the soil surface, biodegradation in the biofilm existing on the soil particle surface and in the large pores as well as in the bound and free water phase after desorption from the soil surface [13,14]. The type of reactor forms the basis of many new bioremediation techniques and for the process to be commercially viable, it is important to obtain the best performance from the reactor. This is feasible when there is available information on accurate design parameters and methods. The development of remedial techniques to remove these contaminant solutes and assess their behaviour over relatively long spatial and temporal scales therefore seem to be the only viable solution or management strategy to maintaining the integrity of the environment.

Following the challenges of cost implications and
the cumbersome nature of experimental studies over long distances and/or time periods, engineers and researchers are making concerted efforts on the use of theoretical models to describe the process of bioremediation.

A number of mathematical and computer models have been developed for simulating contaminant solute transport and degradation through soil columns and fixed bed reactors in porous media [15-23]. Lobos-Ferreira et al [15] developed a model to determine and quantify the important processes that control the chemical behavior of heavy metals and nitrate. The model by [17] based on the mass balance equation including convective transport, dispersive transport, surface adsorption, oxidation and reduction, volatilization, chemical and biological transformation indicated that as the time of simulation increases, the concentration of different selenium species approaches the measured values. Elsewhere, literature report [18] showed the development of mathematical model based on equilibrium sorption approaches to simulate transport and retardation of organic contaminants such as polycyclic aromatic hydrocarbons in a multi-phase groundwater system. The solute transport model of [16, 19] was aimed at analyzing the interplay of degradation and sorption. The modeling results from [20-22] showed that the occlusion of these compounds within the fissures and cavities of the soil particles, renders them not readily bioavailable and thus inaccessible to microbial degradation. Predictions from the feed forward neural network model [23] closely fitted the measured values. Solving these problems presented as computational schemes using the parameters implicated during transport provides a comprehensive information and database on the rate and extent of biodegradation with a view to averting considerably, the prolonged effects of polycyclic aromatic hydrocarbons.

This study is aimed at predicting contaminant solute concentration over time given varying distances by employing the numerical method of the finite element technique for the solution of a second-order partial differential equation which was used to model the ex-situ bioremediation of contaminated soil.

2. Materials and Methods

2.1. Materials

The data used in this study were obtained from the previous investigation of Owabor et al [24]. The theoretical framework applied here is as described by Owabor and Ekwonu [25].

2.2. Methods

The experimental procedure for determining the concentration of contaminant solutes with time is as correlated by Reardon et al [26] and described by Owabor et al [24]. 1.6 kg of soil sample and 0.4 kg of poultry dung were mixed and put in a clean sterile bowl. 4 litres of distilled water was added to the mixture and stirred to form soil slurry. The slurry was spiked with a mixture of 200mg each of the contaminant solutes. The contaminant-soil slurry was charged into the bioreactor which was continuously agitated and supplied with oxygen at a rate of 2 cc/min. The temperature and pressure of the bioreactor was monitored throughout the period of experiment using digital multimeter and pressure gauge. Sampling was done at an interval of 5 days.

2.2.1. Development of the finite element method

The governing transport equation for the advective-dispersion model for one-dimensional flow of solutes through a homogenous soil matrix to which the finite element technique has been applied in this study was described by Najafi and Hajinezhad [20].

\[ \frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - V \frac{\partial C}{\partial x} - \lambda C \]  

The same initial and boundary conditions as well as the method of solution described by Owabor and Ekwonu [25] is applied here in resolving the second-order differential equation. The initial condition is:

\[ c(0, 0) = c; \quad 0 \leq t \leq 63 \]

\[ c(x, 0) = 0; \quad 0.01 \leq x \leq 0.09 \]

and the boundary condition:

\[ \frac{\partial C}{\partial x} \bigg|_{x=L} = 0 \]

Therefore rearranging equation (1), we have

\[ 0 = D \frac{\partial^2 C}{\partial x^2} - V \frac{\partial C}{\partial x} - \frac{\partial C}{\partial t} - \lambda C \]  

In developing the weak form of equation (2), it was multiplied with the weight function \( w \):

\[ 0 = w \left[ D \frac{\partial^2 C}{\partial x^2} - V \frac{\partial C}{\partial x} - \frac{\partial C}{\partial t} - \lambda C \right] \]  

Equation (3) is integrated over an element, \( \Omega_e \) to obtain the weighted residual equivalent of the equation:

\[ 0 = \int_{x_a}^{x_{a+1}} w \left[ D \frac{\partial^2 C}{\partial x^2} - V \frac{\partial C}{\partial x} - \frac{\partial C}{\partial t} - \lambda C \right] \]  

Further integration using the method of integration by parts yields:

\[ 0 = w \left[ \frac{\partial C}{\partial x} \bigg|_{x_a}^{x_{a+1}} - \int_{x_a}^{x_{a+1}} \left[ D \frac{dw}{dx} \frac{\partial C}{\partial x} + V w \frac{\partial C}{\partial x} - R w \frac{\partial C}{\partial t} \right] \right] \]
Table 1: Model simulation parameters.

<table>
<thead>
<tr>
<th>Solutes [PAHs]</th>
<th>Retardation factor (R)</th>
<th>Dispersion coefficient/ Diffusivity (D)</th>
<th>Pore – water velocity (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naphthalene</td>
<td>25.77</td>
<td>8.61 E-6 m²/day</td>
<td>0.36 m/day</td>
</tr>
<tr>
<td>Anthracene</td>
<td>41.62</td>
<td>8.59 E-6 m²/day</td>
<td>0.36 m/day</td>
</tr>
<tr>
<td>Pyrene</td>
<td>35.66</td>
<td>8.597 E-6 m²/day</td>
<td>0.36 m/day</td>
</tr>
</tbody>
</table>

Table 2: Concentration distribution of naphthalene in a stirred reactor.

<table>
<thead>
<tr>
<th>t (days)</th>
<th>Concentration (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>0.000</td>
</tr>
<tr>
<td>10</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>0.000</td>
</tr>
<tr>
<td>20</td>
<td>0.000</td>
</tr>
<tr>
<td>25</td>
<td>0.000</td>
</tr>
<tr>
<td>30</td>
<td>0.000</td>
</tr>
<tr>
<td>35</td>
<td>0.000</td>
</tr>
<tr>
<td>40</td>
<td>0.000</td>
</tr>
<tr>
<td>45</td>
<td>0.000</td>
</tr>
<tr>
<td>50</td>
<td>0.000</td>
</tr>
<tr>
<td>55</td>
<td>0.000</td>
</tr>
<tr>
<td>60</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Let \( x_e = x_A \) and \( x_{e+1} = x_B \)

\[-Q_A = \left[ D \frac{dC}{dx} \right]_{x_A} \quad \text{and} \quad Q_B = \left[ D \frac{dC}{dx} \right]_{x_B}

Representing the values of the secondary variable at the boundary \( x_A \) and \( x_B \) respectively, we have

\[
0 = w(x_A) \left[ D \frac{dC}{dx} \right]_{x_A} - w(x_B) \left[ D \frac{dC}{dx} \right]_{x_B} + \int_{x_B}^{x_A} -w(x) \left[ D \frac{dC}{dx} \right]_{x_B} dx
\]

(6)

\[
0 = \int_{x_B}^{x_A} -w(x) \left[ D \frac{dC}{dx} \right]_{x_B} dx - w(x_A)Q(x_A) - w(x_B)Q(x_B)
\]

(7)

Where \( w(x) \) is the weight function and \( \Omega^e = (x_A, x_B) \) is the domain of a typical element. Substituting the finite element approximation function \( C \approx \sum_{i=1}^{n} C_i^e(t) \psi_i(x) \) into equation (7);

\[
0 = \int_{x_B}^{x_A} \left[ -V \frac{dC}{dx} \left( \sum_{j=1}^{n} C_j^e(t) \frac{d\psi_j}{dx} \right) - D \frac{d^2\psi_j}{dx^2} \left( \sum_{j=1}^{n} C_j^e(t) \frac{d\psi_j}{dx} \right) \right] dx
\]

\[-R \psi_j \left( \sum_{j=1}^{n} C_j^e(t) \frac{d\psi_j}{dx} \right) - \lambda \psi_j \left( \sum_{j=1}^{n} C_j^e(t) \frac{d\psi_j}{dx} \right)
\]

\[-Q_i \]

(8)

where \( w = \psi_i \)

Rearranging equation (8), we have

\[
0 = \sum_{j=1}^{n} \int_{x_B}^{x_A} -V \frac{dC}{dx} \left( \sum_{j=1}^{n} C_j^e(t) \frac{d\psi_j}{dx} \right) dx - D \frac{d^2\psi_j}{dx^2} \left( \sum_{j=1}^{n} C_j^e(t) \frac{d\psi_j}{dx} \right) dx
\]

\[-R \psi_j \left( \sum_{j=1}^{n} C_j^e(t) \frac{d\psi_j}{dx} \right) - \lambda \psi_j \left( \sum_{j=1}^{n} C_j^e(t) \frac{d\psi_j}{dx} \right) dx
\]

\[-Q_i \]

(9)

The finite element model is represented as:

\[
0 = \left[ K_i^e \right] \{ C_i^e(t) \} - \left[ M_i^e \right] \left\{ \frac{dC_i^e}{dt} \right\} - \{ Q_i^e \}
\]

\[
\left[ K_i^e \right] \{ C_i^e(t) \} - \left[ M_i^e \right] \left\{ \frac{dC_i^e}{dt} \right\} = \{ Q_i^e \}
\]

where,

\[
[K_i^e] = \int_{0}^{h_i} \left( -V \frac{d\psi_j}{dx} dx - D \frac{d^2\psi_j}{dx^2} dx - \lambda \psi_j dx \right) d\psi_j
\]

\[
[M_i^e] = \int_{0}^{h_i} R \psi_j dx d\psi_j
\]

\[
Q_i^e = n \sum_{j=1}^{n} \psi_j(x_j) Q_j
\]

Over the domain \( \Omega^e = (0, h_i) \), \( h_i \) is the height of the element and \( \pi \) is the local coordinate.

For a quadratic element mesh, \( \psi_i \) is defined as the quadratic Lagrange interpolation functions given as:

\[
\psi_i(\pi) = \left( 1 - \frac{\pi}{h} \right) \left( 1 - \frac{2\pi}{h} \right)
\]
Table 3: Concentration distribution of anthracene in a stirred reactor.

<table>
<thead>
<tr>
<th>(days)</th>
<th>0.000</th>
<th>0.010</th>
<th>0.020</th>
<th>0.030</th>
<th>0.040</th>
<th>0.050</th>
<th>0.060</th>
<th>0.070</th>
<th>0.080</th>
<th>0.090</th>
<th>Experimental Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>200</td>
</tr>
<tr>
<td>5</td>
<td>124.000</td>
<td>192.712</td>
<td>64.957</td>
<td>100.395</td>
<td>82.995</td>
<td>72.556</td>
<td>64.601</td>
<td>61.210</td>
<td>57.896</td>
<td>55.115</td>
<td>124</td>
</tr>
<tr>
<td>10</td>
<td>107.730</td>
<td>72.039</td>
<td>58.530</td>
<td>87.206</td>
<td>72.102</td>
<td>63.657</td>
<td>56.993</td>
<td>53.178</td>
<td>50.297</td>
<td>47.883</td>
<td>107.73</td>
</tr>
<tr>
<td>15</td>
<td>94.980</td>
<td>67.918</td>
<td>49.743</td>
<td>76.893</td>
<td>63.570</td>
<td>55.574</td>
<td>50.247</td>
<td>46.885</td>
<td>44.344</td>
<td>42.216</td>
<td>94.98</td>
</tr>
<tr>
<td>20</td>
<td>75.000</td>
<td>53.650</td>
<td>39.276</td>
<td>60.714</td>
<td>50.194</td>
<td>43.855</td>
<td>39.678</td>
<td>37.022</td>
<td>35.016</td>
<td>33.536</td>
<td>75.00</td>
</tr>
<tr>
<td>25</td>
<td>50.950</td>
<td>36.426</td>
<td>26.677</td>
<td>41.246</td>
<td>34.102</td>
<td>29.811</td>
<td>26.953</td>
<td>25.151</td>
<td>23.788</td>
<td>22.646</td>
<td>50.95</td>
</tr>
<tr>
<td>50</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>55</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>60</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

\[ \psi_2(x) = 4 - \frac{x}{h} \left(1 - \frac{x}{h}\right) \]
\[ \psi_3(x) = \frac{x}{h} \left(1 - \frac{2x}{h}\right) \]

The coefficients of \( K_{ij} \) and \( M_{ij} \) were evaluated using MathCad software and for one element, the following matrices in the form shown below were generated.

\[
\begin{align*}
K_{ij} &= \begin{bmatrix}
K_{11} & K_{12} & K_{13} \\
K_{21} & K_{22} & K_{23} \\
K_{31} & K_{32} & K_{33}
\end{bmatrix} \\
M_{ij} &= \begin{bmatrix}
M_{11} & M_{12} & M_{13} \\
M_{21} & M_{22} & M_{23} \\
M_{31} & M_{32} & M_{33}
\end{bmatrix}
\end{align*}
\]

\[

\begin{align*}
K_{ij} &= \begin{bmatrix}
\frac{V}{D} - \frac{2h}{D} & -\frac{2h}{D} - \frac{V}{D} & -\frac{h}{D} \\
-\frac{h}{D} & \frac{h}{D} & 0 \\
-\frac{2h}{D} & 0 & \frac{V}{D}
\end{bmatrix} \\
M_{ij} &= \begin{bmatrix}
\frac{2Rh}{h^2} & \frac{Rh}{h^2} & -\frac{Rh}{h^2} \\
-\frac{Rh}{h^2} & \frac{Rh}{h^2} & 0 \\
-\frac{2Rh}{h^2} & 0 & \frac{V}{D}
\end{bmatrix}
\end{align*}
\]

The Assemblage of two-element mesh was given as:

\[
K = \begin{bmatrix}
\frac{V}{D} - \frac{2h}{D} & -\frac{2h}{D} & -\frac{2h}{D} & \frac{V}{D} & -\frac{h}{D} & 0 & 0 \\
-\frac{h}{D} & \frac{h}{D} & 0 & \frac{h}{D} & -\frac{2h}{D} & \frac{V}{D} & 0 \\
-\frac{2h}{D} & 0 & \frac{V}{D} & \frac{2h}{D} & \frac{h}{D} & 0 & \frac{h}{D} \\
0 & \frac{h}{D} & \frac{2h}{D} & \frac{V}{D} & \frac{V}{D} & \frac{2h}{D} & \frac{h}{D} \\
0 & 0 & 0 & \frac{V}{D} & \frac{2h}{D} & \frac{h}{D} & \frac{2h}{D} \\
0 & 0 & 0 & 0 & \frac{V}{D} & \frac{2h}{D} & \frac{h}{D} \\
0 & 0 & 0 & 0 & 0 & \frac{V}{D} & \frac{2h}{D}
\end{bmatrix}
\]

\[
M = \begin{bmatrix}
\frac{2Rh}{h^2} & \frac{Rh}{h^2} & \frac{Rh}{h^2} & 0 & 0 & 0 \\
\frac{Rh}{h^2} & \frac{Rh}{h^2} & \frac{Rh}{h^2} & 0 & 0 & 0 \\
\frac{Rh}{h^2} & \frac{Rh}{h^2} & \frac{Rh}{h^2} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{V}{D} & \frac{2h}{D} & \frac{V}{D} \\
0 & 0 & 0 & \frac{2h}{D} & \frac{V}{D} & \frac{V}{D} \\
0 & 0 & 0 & \frac{V}{D} & \frac{2h}{D} & \frac{V}{D}
\end{bmatrix}
\]

For the final solution of the developed model, the time approximated solution was given as:

\[ [M]C_s = [M] - \Delta t_{s+1} [K]C_{s+1} + \Delta t_{s+1} [Q]_{s+1} \]
differences in the physical properties of the solutes such as molecule topology and number of rings as well as their solubility and diffusivity (Table 1) in solution.

Mineralization was found to be faster for low molecular weights PAHs with less degree of fusion. This was evident in the simulations results which followed same trend with experimental laboratory data. The trends observed for anthracene and pyrene within the same contact period were not particularly different from the behavior exhibited by naphthalene. These observations are consistent with previous literature results of Barkay et al [28], Pravecek et al [29], Rodríguez and Bishop [30], Owabor et al [22].

Result from Table 2 shows that with increasing time, the concentration of naphthalene decreases from 200mg/l at the surface to zero by the 40th day of exposure within the soil matrix. The percentage solute concentration left was 44% (50th). The concentration of naphthalene decreased in the direction of flow with the least value at the subsurface distance of 9 cm. The concentrations of naphthalene at the surface and at a subsurface distance of 9cm were 4.30mg/l and 0.614 mg/l respectively.

Similarly, the concentration of anthracene decreased from 200mg/l at the onset of the experiment to zero by the 55th day of exposure within the soil matrix. The percentage solute concentration left was 14% (35th). The concentration of anthracene decreased in the direction of flow with the least value at the subsurface distance of 9 cm. The concentrations of anthracene at the surface and at a subsurface distance of 9cm were 4.30mg/l and 0.614 mg/l respectively.

The pattern of distribution of the pyrene followed closely that observed with naphthalene and anthracene. The concentration of the solute decreased from 200mg/l at the surface to zero by the 50th day of exposure within the soil matrix. The residual concentration was 29% by the 45th day.

The result for anthracene and pyrene present some degree of variation, which explains the observed selective decay of one over the other. Anthracene exhibits a lower solubility in water and hence it was not readily available for microbial uptake. The effects of these limitations are reflected in the simulated residual concentrations

<table>
<thead>
<tr>
<th>x(m)</th>
<th>0.000</th>
<th>0.010</th>
<th>0.020</th>
<th>0.030</th>
<th>0.040</th>
<th>0.050</th>
<th>0.060</th>
<th>0.070</th>
<th>0.080</th>
<th>0.090</th>
</tr>
</thead>
<tbody>
<tr>
<td>t(days)</td>
<td>Concentration(mg/l)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>200.00</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>1</td>
<td>95.060</td>
<td>79.387</td>
<td>34.19</td>
<td>0.050</td>
<td>0.030</td>
<td>24.83</td>
<td>0.102</td>
<td>24.830</td>
<td>0.010</td>
<td>20.783</td>
</tr>
<tr>
<td>35</td>
<td>8.610</td>
<td>7.185</td>
<td>5.643</td>
<td>4.307</td>
<td>3.634</td>
<td>3.233</td>
<td>2.958</td>
<td>2.767</td>
<td>2.635</td>
<td>2.320</td>
</tr>
<tr>
<td>45</td>
<td>1.102</td>
<td>0.885</td>
<td>0.685</td>
<td>0.553</td>
<td>0.442</td>
<td>0.358</td>
<td>0.285</td>
<td>0.233</td>
<td>0.202</td>
<td>0.162</td>
</tr>
<tr>
<td>50</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>55</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>60</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

| Experimental Result | | | | | | | | | | |

4. Conclusion

The finite element method has been found to be effective in solving non-steady state model equations as it has been shown to be capable of serving as an alternative mathematical tool for predicting the extent of degradation of contaminant solutes during remedial studies involving long distances.

The role of bioavailability of the organic chemicals can certainly not be overemphasized as contributions of some functional transport properties such as dispersion coefficient and retardation factor can be seen to be interfering with degradation.

The residual concentrations confirmed that naphthalene was more selectively mineralized in the stirred reactor and that the microbial utilization of pyrene and anthracene for metabolic activities were greatly limited by their resistance to mass transfer due to their low aqueous solubility.

References
