Biodegradation kinetics of highly chlorinated biphenyls by Alcaligenes sp. JB1 in an aerobic continuous culture system.
Commandeur, L.C.M.; van Eyseren, H.E.; Opmeer, M.R.; Govers, H.A.J.; Parsons, J.R.

Published in: Environmental Science and Technology

DOI: 10.1021/es00012a022

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: http://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
Biodegradation Kinetics of Highly Chlorinated Biphenyls by Alcaligenes sp. JB1 in an Aerobic Continuous Culture System

LAETITIA C. M. COMMANDEUR,* HANS E. VAN EYSEREN, MAARTEN R. OPMEE, HARRIE A. J. GOVERS, AND JOHN R. PARSONS

Department of Environmental and Toxicological Chemistry, Amsterdam Research Institute for Substances in Ecosystems, University of Amsterdam, Nieuwe Achtergracht 186, NL-1018 WV Amsterdam, The Netherlands

A mixture of nine polychlorinated biphenyl (PCB) congeners with four to six chlorine substituents was cometabolized in an aerobic chemostat culture of Alcaligenes sp. JB1, grown on 3-methylbenzoate. Pseudo-first-order biodegradation rate constants \( k_b \) were calculated using a steady-state kinetic model. These rate constants varied from 7.8 to 0.44 h\(^{-1}\). Comparable results for exposure to high and low influent concentrations confirmed the assumption of pseudo-first-order kinetics for most of the congeners studied. Alcaligenes sp. JB1 was found to degrade 2,3-dichlorobiphenyl rings very rapidly and 2,5-dichlorobiphenyl rings relatively slowly. Certain penta- and hexachlorobiphenyls were degraded faster than some tetrachlorobiphenyls. For example, 2,2',3,3',6,6'-hexachlorobiphenyl was degraded faster than 2,2',6,6'-tetrachlorobiphenyl. On the other hand, 2,2',3,3',4,4'-HCB was degraded much more slowly than 2,2',3,3'-TCB. A control experiment with Pseudomonas fluorescens NCTC10038, a bacterium incapable of PCB (co)metabolism, showed that losses caused by physical or chemical phenomena were negligible.

Introduction

Despite their apparent recalcitrance in the environment, the lower chlorinated (Cl < 5) biphenyls have been mineralized aerobically by several microbial consortia in laboratory studies (1–3). Biphenyl and monochlorobiphenyls can serve as growth substrates for several microorganisms, including the organism dealt with in this study, Alcaligenes sp. JB1. The other chlorinated biphenyls can only be degraded by cometabolism, i.e., degradation of PCBs during growth on another substrate. Highly chlorinated PCBs (Cl > 4) are presumed to be persistent under aerobic conditions. However, exceptions to this presumption are demonstrated by the reported degradation of penta- (PnCB) and hexachlorobiphenyls (HCB) by Alcaligenes Y42 (4), Pseudomonas sp. LB400 (5), and Alcaligenes eutrophus H850 (6).

The anaerobic reductive dehalogenation of highly chlorinated biphenyls to lower chlorinated analogues has been shown to be an important initial step in their destruction (3, 7). It has been recently shown that complete reductive dehalogenation to biphenyl is possible (8). However, to our knowledge, anaerobic carbon metabolism of (chloro)biphenyls has never been detected. Thus, oxidative degradation may be essential for the complete mineralization of PCBs to \( \text{CO}_2 \), \( \text{H}_2\text{O} \), biomass, and chloride.

Little is known about the kinetics of PCB degradation. At the moment, only overall anaerobic dehalogenation rates are available, measured in poorly defined mixed cultures and in most cases in the presence of sediment. Different anaerobic enrichments show great variation in dehalogenation rates. In contrast, aerobic biodegradation rates can be determined for pure cultures grown under well-defined conditions. The advantage of using a pure culture instead of a mixed culture is that only one enzyme system is involved in the degradation, the action of which may be described by Michaelis–Menten kinetics. This gives rate constants characteristic of the congener and the enzyme system studied. However, such rate constants are scarce in the literature.

In this study, the aerobic biodegradation kinetics of tetra-, penta-, and hexachlorinated biphenyls were studied in a chemostat culture. The advantages of using such a system for kinetic studies are that the conditions under which degradation takes place are controlled and constant and that the continuous limitation of growth provides a constant biomass in the exponential growth phase. The liquid culture is homogeneously mixed, and growth substrate and PCBs are dissolved in the aqueous medium. This simplifies the kinetics compared to batch cultures, in which the PCBs are often added at concentrations far above their water solubilities, or biofilm reactors, in which the biomass concentration is neither homogeneous nor constant.

The bacterium used to study PCB degradation was Alcaligenes sp. JB1. This organism, previously identified as Pseudomonas sp. JB1, is able to grow on benzoate, 3-methylbenzoate, biphenyl, and monochlorobiphenyls and to cometabolize various chlorinated benzoates and biphenyls during growth on 3-methylbenzoate (9, 10). A control experiment was conducted by exposing strain Pseudomonas fluorescens NCTC10038 to PCBs in the chemostat under the same conditions. This latter strain is unable to grow on biphenyl or to cometabolize PCBs. From this experiment, the disappearance rates due to processes other than biodegradation were determined. Differences in biodegradation rate constants of PCB congeners are discussed.

Materials and Methods

Bacterial Strains. Alcaligenes sp. JB1 (previously tentatively identified as Pseudomonas strain JB1) was isolated as described by Parsons et al. (10). Identification by the API-20NE test system (API systems S.A., Montalieu, France)
revealed that it was an *Alcaligenes denitrificans* strain (91.5% certainty). However, as this organism is not able to reduce nitrite to nitrogen, we describe it as *Alcaligenes* sp. JB1. *Alcaligenes* was maintained on agar slopes with 0.25 mM 3-methylbenzoate. *P. fluorescens* NCTC10038 was a gift from the Department of Microbiology, University of Amsterdam. This organism is able to grow on benzoate, but not on 3-methylbenzoate or biphenyl. We assumed this organism to be unable to cometabolize PCBs. The purity of both strains was controlled by frequent plating on nutrient agar and API-20NE tests.

**Culture Conditions.** Precultures were grown in batch at 25 °C on 8.3 mM benzoate in an Evans mineral medium with the following composition: Na2SO4·10H2O (1.0 mM), CaCl2·2H2O (0.01 mM), MgCl2·6H2O (0.625 mM), NH4Cl (50 mM), KH2PO4 (30 mM), Na2CO3·10H2O (1 mM), MnCl2·4H2O (25.3 μM), CuCl2·2H2O (2.54 μM), CoCl2·6H2O (5 μM), HCO3 (2.58 μM), and Na2MoO4·2H2O (0.046 μM). The pH was adjusted to 7.0 ± 0.1.

**Chemostat.** The design of the chemostat system is shown in Figure 1. The culture was supplied continuously with Evans medium containing 7.5 mM 3-methylbenzoate as the growth substrate for *Alcaligenes* sp. JB1 cultures or 8.3 mM benzoate for *P. fluorescens* NCTC10038. The medium flow rate was 20 mL/h, resulting in a dilution rate of 0.040 ± 0.004 h⁻¹ or a hydraulic residence time of approximately 1 day. Under these conditions, the concentration of the carbon source limits the growth, resulting in a constant biomass concentration during steady state. The dry weight, measured by the procedure of Herbert et al. (11), was approximately 0.6 ± 0.06 g dryweight/L (g dw L⁻¹) in all cases. The aeration rate was ± 1200 mL/h, the stirring speed was 300 rpm, and the temperature was kept constant at 25 °C.

This study consisted of three experiments. Two experiments were carried out with *Alcaligenes* sp. JB1 (one with relatively high influent concentrations and another with relatively low influent concentrations) and the control experiment with *P. fluorescens* NCTC10038. The chemostat cultures were exposed to a mixture of the following PCB congeners: 2,2',3,3'-, 2,2',5,5'-, and 2,2',6,6'-tetrachlorobiphenyls (TCBs); 2,2',4,4',6-, 2,2',4,5,5'-, 2,3',4,4',6-, and 2,3',5,6-pentachlorobiphenyls (PnCBs); and 2,2',3,3',4,4'- and 2,2',3,3',6,6'-hexachlorobiphenyls (HCBs). All PCB congeners were obtained from C. N. Schmidt B.V., Amsterdam, The Netherlands. This mixture was dissolved in 50 mL of pentane containing 8–12 g of Chromosorb GAW 45–60 Mesh (Chrompack, Middelburg, The Netherlands). The pentane layer was evaporated under a gentle nitrogen stream. The Chromosorb coated with PCBs was transferred to a glass column, in which it was held in position by a glass filter on top and glass wool on the bottom. The column was closed with silicon rubber-lined screwcaps. The column was sterilized by circulating a formaldehyde/H2O (1/1 v/v) mixture for 24 h. Three liters of sterile medium was then pumped through the column to remove the formaldehyde. A separate column was prepared for each experiment.

**Sample Preparation, Cleanup, and Analysis.** Medium samples (50 mL) were collected from the culture vessel, and culture samples (50 mL) were collected from the culture vessel of a syringe through the sample ports. The cleanup procedure and analysis were adapted from the method described by Parsons et al. (9). Hexachlorobenzene (25 ng) was added to these samples as an internal standard. Culture samples were acidified with 4 M H2SO4 to pH = 1 and extracted with 50 mL of pentane to which 1.5 mL of 2,2,4-trimethylpentane (TMP) was added. After centrifugation (500g) and removal of the pentane layer, the extracts were concentrated to ca. 1 mL under a gentle nitrogen stream or by Kuderna–Danish distillation (in the case of the *P. fluorescens* experiment). The medium samples were extracted with 1.5 mL of TMP by shaking for 2 min. Both extracts were eluted with 10 mL of TMP through a column (cross-section 5 mm) containing 1 g of 100–120 mesh silica + 40% w/w H2SO4 above 1 g of 100–120 mesh silica + 33% w/w 1 M NaOH to remove polar compounds. The samples were then concentrated to a final volume of 1 mL under a gentle nitrogen stream. Analysis was GC with cold-on-column injection (Carlo Erba 6000 Vega Series 2 or Hewlett Packard 5890, 30 m × 0.32 mm DB5 columns). The detection occurred with a 63Ni electron capture detector (ECD). For the PCBs used in these experiments, this detector was least sensitive for detection of 2,2',6,6'-TeCB, of which the detection limit amounted to 0.02 pg (corresponding with a concentration of 0.0004 μg/L in the experiments).

**Calculation.** Triplicate 50-mL samples of the medium and culture were taken at each time point. A period of at least 4 days was allowed for the re-establishment of the steady state between sampling. The biodegradation experiment with *Alcaligenes* sp. JB1 was sampled four times at steady state for both high and low influent (medium) PCB concentrations, whereas the control experiment with *P. fluorescens* NCTC10038 was sampled five times. Average medium (Cₘ) and culture concentration (Cₗ) were calculated for each time point.

At steady state in a chemostat, the rate at which a chemical enters the chemostat is equal to the rate at which it is lost by dilution, degradation, and abiotic processes such as adsorption and volatilization. The mass balance is then be described by

\[
DC_c = DC_m + ν
\]

(1)

in which \(D\) is the dilution rate of the culture (h⁻¹), \(C_m\) is the concentration of PCB in medium influent (μg L⁻¹), \(C_c\) is the concentration of PCB in the culture (μg L⁻¹), and ν is the disappearance rate. Assuming the disappearance is caused by biodegradation, the disappearance rate can be expressed by

\[
ν = qX
\]

(2)

in which q is the specific substrate consumption rate (μg
Equations 3, 5, and 6 can be combined to give

\[ q = k_a \frac{C_m - C_c}{C_c} \]  

(9)

Recovery Experiments. The analytical recoveries of the PCBs were determined by analyzing 50 mL of sterile medium and acid-killed culture samples containing known concentrations of PCBs, comparable to the values of \( C_m \) and \( C_c \) in the degradation experiments. The ratios of the amounts measured by GC-ECD and those added were used to calculate the recoveries of the analytical procedure. The recoveries were essentially quantitative (90–110% for medium samples and 80–120% for culture samples).

**Results**

Continuous Cometabolism of Highly Chlorinated PCBs by Alcaligenes sp. JB1. Chemostat cultures of Alcaligenes sp. JB1, grown on 3-methylbenzoate, were exposed to a mixture of PCB congeners with four to six chlorine substituents. The steady-state concentrations of the PCBs in the culture and the medium influent to which the cultures were exposed are listed in Table 1, as are the results of the control experiment. The concentrations of two representative PCB congeners (2,2′,3′,3′-TCB and 2,2′,4′,4′-HCB) in the three experiments are also shown in Figure 2a–f. Due to their low solubilities, the PCB concentrations in the experiments reported here were very low (less than 50 nM). So it seems reasonable to assume that the affinity of these enzymes for PCBs is very low and \( C_c \ll K_m \). In this case, the Michaelis–Menten equation simplifies to

\[ q = \frac{q_{max} X}{K_m} C_c \]  

(5)

Assuming a constant biomass concentration \( X \), the pseudo-first-order biodegradation rate constant \( k_b \) (h\(^{-1}\)) is defined as

\[ k_b = \frac{q_{max} X}{K_m} \]  

(6)

Equations 3, 5, and 6 can be combined to give

\[ k_b = D \frac{C_m - C_c}{C_c} \]  

(7)

The possible losses of PCBs due to abiotic processes such as volatilization will also follow first-order kinetics, described by a rate constant \( k_v \).

\[ \nu = k_v C_c \]  

(8)

A combination of eqs 1 and 2 yields

\[ k_a = D \frac{C_m - C_c}{C_c} \]  

(9)

**TABLE 1**

Mean Concentrations of PCBs in the Medium \((C_m)\) and Culture \((C_c)\) for Two Experiments with Alcaligenes Strain JB1 and One with Pseudomonas fluorescens NCTC10038

<table>
<thead>
<tr>
<th>PCB congener</th>
<th>Alcaligenes sp. JB1 high influent concentration ((n = 4))</th>
<th>Alcaligenes sp. JB1 low influent concentration ((n = 4))</th>
<th>P. fluorescens NCTC10038 control ((n = 5))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( C_m ) (( \mu g \text{ g dw}^{-1} )) ± SD</td>
<td>( C_c ) (( \mu g \text{ g dw}^{-1} )) ± SD</td>
<td>( C_m ) (( \mu g \text{ g dw}^{-1} )) ± SD</td>
</tr>
<tr>
<td>2,2′,3′,3′-TCB</td>
<td>10.574 ± 1.011</td>
<td>0.055 ± 0.003</td>
<td>1.164 ± 0.045</td>
</tr>
<tr>
<td>2,2′,5′-TCB</td>
<td>25.309 ± 4.333</td>
<td>2.033 ± 0.491</td>
<td>0.656 ± 0.024</td>
</tr>
<tr>
<td>2,2′,6′-TCB</td>
<td>8.111 ± 1.272</td>
<td>0.770 ± 0.247</td>
<td>0.454 ± 0.016</td>
</tr>
<tr>
<td>2,2′,4′,4′,6′-PnCB</td>
<td>3.712 ± 0.899</td>
<td>0.133 ± 0.028</td>
<td>1.145 ± 0.067</td>
</tr>
<tr>
<td>2,2′,4′,5′,5′-PnCB</td>
<td>3.520 ± 0.544</td>
<td>0.235 ± 0.025</td>
<td>1.185 ± 0.071</td>
</tr>
<tr>
<td>2,3′,4′,4′,6′-PnCB</td>
<td>3.163 ± 0.396</td>
<td>0.109 ± 0.013</td>
<td>1.155 ± 0.070</td>
</tr>
<tr>
<td>2,3′,5′,5′,6′-PnCB</td>
<td>3.729 ± 0.300</td>
<td>0.190 ± 0.032</td>
<td>1.251 ± 0.074</td>
</tr>
<tr>
<td>2,2′,3′,3′,4′-HCB</td>
<td>0.534 ± 0.224</td>
<td>0.023 ± 0.010</td>
<td>0.401 ± 0.029</td>
</tr>
<tr>
<td>2,2′,3′,3′,6′-HCB</td>
<td>1.802 ± 0.160</td>
<td>0.050 ± 0.006</td>
<td>0.405 ± 0.035</td>
</tr>
</tbody>
</table>

Validation of Pseudo-First-Order Kinetics. We found in previous studies with chemostat cultures that at a flow rate of 20 mL/h PCBs dissolved in the medium at concentrations comparable to their reported aqueous solubilities (9). However, in these experiments the concentrations

\( (\text{g dw}^{-1} \text{ h}^{-1}) \) and \( X \) is the biomass concentration (g dw L\(^{-1}\)). A combination of eqs 1 and 2 yields

\[ q = D(C_m - C_c) \]  

(10)

Due to the restricted range in concentrations used in previous studies with chemostat cultures that at a flow rate of 20 mL/h PCBs dissolved in the medium at concentrations comparable to their reported aqueous solubilities (9). However, in these experiments the concentrations

\[ k_a = D \frac{C_m - C_c}{C_c} \]  

(11)
in the medium could not be kept constant. Insertion of a 1-L buffer vessel in the experimental setup (Figure 1) reduced these fluctuations considerably, and the concentration of PCBs entering the culture was almost constant (Figure 2a–f). Table 1 clearly shows that the influent concentrations varied for the different experiments due to the preparation of different columns. This enabled the validation of the assumption: $C_i \approx K_m$ and thus of pseudo-first-order kinetics (see Materials and Methods). If the degradation can be described by pseudo-first-order kinetics, experiments with different medium concentrations should give the same values of $k_b$. This is apparent from the data.
in Table 2. The rate constants obtained for high and low medium concentrations were the same (t-test, α = 5%; β = 5%) for all the PCBs apart from 2,2',4,4',6-PnCB and 2,2',3,3',6,6'-HCB for which the differences are small.

Control Experiment. Caution has to be taken in quantifying data from biodegradation assays, as many factors other than biodegradation can cause loss of PCBs. Although PCBs have low vapor pressures and high boiling points, volatilization, adsorption to glass or plastic, and differential extraction and clean-up could be potential sources of serious analytical error. Losses due to the analytical procedure were not found (see Materials and Methods). To investigate the losses other than biodegradation in the chemostat, an experiment was done with an organism not able to grow on biphenyl, P. fluorescens NCTC10038. This is a Gram-negative, aerobic rod, capable of metabolizing benzoate aerobically, similar to Alcaligenes strain JB1. The results of this experiment were used to calculate abiotic disappearance rate constants \( k_b \). All these disappearance rate constants, except one, were not significantly (t-test, α = 5%) different from zero (Table 2). A very low value of \( k_b \) was found for 2,2',6,6'-TCB; however, this was much lower than its \( k_a \) value.

Discussion

The results of the experiments described in this work show that a range of tetra-, penta-, and hexachlorobiphenyls is degraded in chemostat cultures of Alcaligenes sp. strain JB1. The cultures removed between 92 and 99.5% of the PCBs to which they were exposed in the medium influent (Table 1 and Figure 2). The lack of significant degradation of these PCBs (except for a slight reduction in concentration of 2,2',6,6'-TCB) in a culture of P. fluorescens NCTC10038 demonstrates that the removal was due to biodegradation and not to physical—chemical losses. The rates of biodegradation may be expressed as specific consumption rates \( (\mu) \). However, these rates are a function of the concentrations of the compounds (see eq 3). From these experiments, two different specific consumption rates for the same PCB congener may be calculated. For example, the high influent concentration experiment yields for 2,2',3,3'-TCB \( q = 0.7 \mu g (g \ dw)^{-1} h^{-1} \), whereas the low influent concentration experiment yields \( q = 0.08 \mu g (g \ dw)^{-1} h^{-1} \). Therefore, a better comparison of biodegradation rates would be in terms of Michaelis—Menten parameters or as rate constants. One of the biggest advantages of chemostat cultures for kinetic studies is that their constant biomass concentrations simplifies the kinetics of degradation. In the case of this study, where the concentrations of the PCBs were much lower than their likely \( K_m \) values, pseudo-first-order kinetics described the degradation reasonably well. This is indicated by the comparable values of the pseudo-first-order biodegradation rate constants \( (k_a) \) in cultures exposed to different concentrations of PCBs (Table 2). The pseudo-first-order biodegradation rate constants were between 7.8 h\(^{-1}\) for 2,2',3,3'-TCB and 0.44 h\(^{-1}\) for 2,2',5,5'-TCB. These rate constants correspond to half-lives of 0.09 and 1.58 h, respectively. Division of \( k_a \) by the biomass concentration (0.6 ± 0.06 g dw/L in these cultures) gives second-order biodegradation rate constants.

The order of the biodegradation rate constants of the PCBs in this study is as follows: 2,2',3,3'-TCB > 2,2',3,3',6,6'-HCB > 2,2',4,4',6-PnCB > 2,2',3,3',6,6'-PnCB > 2,2',3,3',4,4',6-PnCB > 2,2',3,3',6,6'-HCB > 2,2',4,4',6'-PnCB > 2,2',3,3',6,6'-PnCB > 2,2',6,6'-TCB > 2,2',5,5'-TCB. The major aerobic microbial degradation pathway of PCBs starts with 2,3-dioxygenation of the less substituted aromatic ring (Figure 3, route A), followed by ring cleavage and further degradation to (chloro) benzoates (3). The most highly chlorinated phenyl ring is presumed to be the nonreacting ring. The higher biodegradation rates of certain HCBs and PnCBs than those of TCBs may be caused by the influence of the nonreacting ring. However, from these results, it is not clear whether the lowest chlorinated ring is indeed always the reacting ring. The remarkable fact that the degradation rate constant of 2,2',3,3',6,6'-HCB is higher than that of 2,2',6,6'-TCB suggests that in this case an extra chlorine substituent has a stimulating effect on degradation. Bedard et al. also reported faster degradation of 2,2',3,3',6,6'-HCB than 2,2',6,6'-TCB in case of Alcaligenes eutrophus H850 (14). Further investigation of the relationships between substitution patterns of PCBs and their biodegradation rates may give more insight into these results. A preliminary investigation of such relationships showed that the biodegradation rate constants measured in this study correlate with both electronic and hydrophobic effects of chlorine substituents. The electronic effects of increasing chlorine substitution reduce biodegradation rate constants. On the other hand, the increase in hydrophobicity as a result of increasing chlorine substitution stimulates biodegradation (15).

The penta- and hexachlorobiphenyl degrading strains Pseudomonas sp. LB400 and Alcaligenes eutrophus H850, are thought to possess both 3,4- (Figure 3, route B) and 2,3-biphenyl dioxygenase activities (16). 3,4-Dioxygenase activity is thought to be stimulated by PCBs having a 2,5-chlorophenyl ring. The relatively slow degradation of 2,5-chlorophenyl rings by Alcaligenes sp. JB1 may be an indication that 3,4-dioxygenase activity is not present in this strain. Assuming 2,3-dioxygenase attack by strain JB1 on the 5.6-position, 2,2',3,3',6,6'-HCB must be oxidatively dehalogenated in the first reaction steps, as shown in Figure 3, route A. The oxidative dehalogenation of PCBs has been reported earlier (17, 18), although the elimination of chlorine is usually thought to be a fortuitous event that occurs in the later metabolic steps.

After studying the degradation spectra of eight PCB-degrading strains, a four-class division of such strains was
We are grateful to J. M. D. van der Steen and F. W. van der Wielen for their technical assistance.

Acknowledgments

We are grateful to J. M. D. van der Steen and F. W. van der Wielen for their technical assistance.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCB</td>
<td>polychlorinated biphenyl</td>
</tr>
<tr>
<td>TCB</td>
<td>tetrachlorobiphenyl</td>
</tr>
<tr>
<td>PnCB</td>
<td>pentachlorobiphenyl</td>
</tr>
<tr>
<td>HCB</td>
<td>hexachlorobiphenyl</td>
</tr>
<tr>
<td>D</td>
<td>dilution rate (h⁻¹)</td>
</tr>
<tr>
<td>Cₘ</td>
<td>PCB concentration in the medium (µg L⁻¹)</td>
</tr>
<tr>
<td>Cₙ</td>
<td>PCB concentration in the culture (µg L⁻¹)</td>
</tr>
<tr>
<td>q</td>
<td>specific substrate consumption rate (µg (g dw)⁻¹ (h⁻¹)</td>
</tr>
<tr>
<td>X</td>
<td>biomass concentration (g dw L⁻¹)</td>
</tr>
<tr>
<td>qₘₐₓ</td>
<td>maximum specific substrate consumption rate (µg (g dw)⁻¹ (h⁻¹)</td>
</tr>
<tr>
<td>Kₘ</td>
<td>affinity constant of the enzymes for the substrate (µg L⁻¹)</td>
</tr>
<tr>
<td>kₙ</td>
<td>pseudo-first-order biodegradation rate constant (h⁻¹)</td>
</tr>
<tr>
<td>kₐ</td>
<td>first-order abiotic disappearance rate constant (h⁻¹)</td>
</tr>
</tbody>
</table>

Literature Cited


Received for review April 7, 1995. Accepted July 31, 1995.*

ES940371D