# D. ORGANIC SOLVENT-WATER PARTITIONING; BIOCONCENTRATION

ILLUSTRATIVE EXAMPLES

Estimating the Activity Coefficients of Organic Compounds in Organic Phases
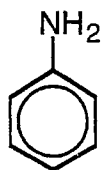
Problem

Calculate the activity coefficients for naphthalene and aniline in water-saturated hexane (γ_h), in water-saturated octanol (γ_o), and in water (γ_w) at 25°C using the data given below. Compare and discuss the results.
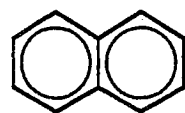
	mw	128.2 g·mol^{-1}
	T_m	80.6°C
	$C_w^{sat}(25°C)$	2.5 x 10^{-4} mol·L^{-1}
	$K_{hw}(25°C)$	2.1 x 10^3
naphthalene	$K_{ow}(25°C)$	2.3 x 10^3

NH$_2$	mw	93.1 g·mol^{-1}
	T_m	- 6.3°C
	$C_w^{sat}(25°C)$	3.9 x 10^{-1} mol·L^{-1}
	$K_{hw}(25°C)$	7.0 x 10^{-1}
aniline	$K_{ow}(25°C)$	7.9

Answer

Since immiscible phases partition organic chemicals according to the relative incompatibilities of those chemicals in each phase, partition constants simply reflect the ratios of the corresponding activity coefficients and molar volumes in dilute solution:

$$K_{sw} = \frac{C_s}{C_w} \simeq \frac{\gamma_w V_w}{\gamma_s V_s} \qquad (7\text{-}4)$$

Thus one may solve for the activity coefficients of solutes in *water-saturated organic media* if K_{sw} is known:

$$\gamma_s = \gamma_w \cdot \frac{1}{K_{sw}} \cdot \frac{V_w}{V_s} \qquad (D\text{-}1)$$

As a first approximation, γ_w may be expressed by γ_w^{sat} which is related to the aqueous solubility of the liquid compound (see *Eqs. 5-8* and *5-9*):

$$\gamma_w \simeq \gamma_w^{sat} = \frac{1}{C_w^{sat}(1L) \cdot V_w} \qquad (D\text{-}2)$$

Since naphthalene is a solid at 25°C, its liquid aqueous solubility may be estimated from its melting point (*Eqs. 5-8, 5-9,* and *4-21*):

$$C_w^{sat}(L) = C_w^{sat}(s) \cdot e^{+(6.8)(\frac{T_m}{T}-1)} \qquad (D\text{-}3)$$

Hence, a $C_w^{sat}(L)$ value of 8.9×10^{-4} mol·L^{-1} is calculated from Eq. D-3 for naphthalene. Inserting the liquid aqueous solubilities of the two compounds into Eq. D-2 yields:

$$\gamma_w^{sat} \text{ (naphthalene)} = 62,500$$
$$\gamma_w^{sat} \text{ (aniline)} = 140$$

Consider now whether γ_w at dilute solution is equal to γ_w^{sat}. Assuming a liquid density of approximately 1 g·mL^{-1} for naphthalene, the volume fraction, f_v, occupied by the compound in the water at saturation is about

$$f_v \simeq (2.5 \times 10^{-4} \, mol \cdot L_w^{-1})(128.2 \, g \cdot mol^{-1})(1 \times 10^{-3} \, L_n \cdot g^{-1})$$

$$\simeq 3.2 \times 10^{-5} \, L_n \cdot L_w^{-1} \simeq 0.003 \, \%$$

Hence, the nonpolar naphthalene is sufficiently diluted even at saturation, and, therefore, it can be assumed that $\gamma_w \simeq \gamma_w^{sat}$. Note that some organic chemicals, for example, surface active compounds, may still self-associate significantly, though present at quite low volume fractions; an example is oleic acid *(Jung et al., 1987)*.

In the case of aniline (density $\simeq 1 \, g \cdot mL^{-1}$), the calculated volume fraction is substantially higher:

$$f_v \simeq (3.9 \times 10^{-1} \, mol \cdot L_w^{-1}) \, (93.1 \, g \cdot mol^{-1})(1 \times 10^{-3} \, L_a \cdot g^{-1})$$

$$\simeq 3.6 \times 10^{-2} \simeq 3.6\%$$

Hence, for aniline and other compounds that may self-associate by hydrogen bonding, one cannot *a priori* assume that $\gamma_w = \gamma_w^{sat}$. This has been demonstrated by *Schwarzenbach et al. (1988)* who found self-association of 4-nitrophenols at even lower concentrations. Nevertheless, for the following calculations, neglect the error introduced by the assumption made in Eq. D-2.

Using $V_h \simeq 0.13 \, L \cdot mol^{-1}$ and $V_o \simeq 0.13 \, L \cdot mol^{-1}$ for the water-saturated molar volumes of hexane and octanol, respectively, calculate now the γ_s values using Eq. D-1 with $\gamma_w \simeq \gamma_w^{sat}$. The resulting values are

γ_h (naphthalene)	$\simeq 4$	γ_o (naphthalene)	$\simeq 3.8$
γ_h (aniline)	$\simeq 28$	γ_o (aniline)	$\simeq 2.5$

A comparison of these results shows that the nonpolar compound, naphthalene, is accommodated similarly well in both solvents, while the more polar compound, aniline, is much more incompatible with hexane as compared to octanol (note that the hexane molecules cannot hydrogen

bond with polar groups such as the amino group of aniline). Finally, the results also demonstrate again the ability of octanol to accommodate both nonpolar as well as polar solutes (see also *Fig. 7.2*).

Estimating K_{ow} by Various Methods

Problem

Estimate the octanol-water partition constants of naphthalene and aniline from (a) their aqueous solubilities, (b) their hexane-water partition constants, and (c) structural group contributions.

Answer (a)

Use the linear free-energy relationship (LFER) *Eq. 7-14* to calculate log K_{ow}:

$$\log K_{ow} = -a \cdot \log C_w^{sat} (l,L) + b \qquad (7\text{-}14)$$

For naphthalene, take the a and b values given in *Table 7.2* for polycyclic aromatic hydrocarbons (with $C_w^{sat} (l,L) = 8.9 \times 10^{-4}$ mol·L^{-1}, see above):

$$\log K_{ow} = -0.87 \log (8.9 \times 10^{-4}) + 0.68$$

$$= 3.33$$

Hence,

$$K_{ow} \text{ (naphthalene)} = 2.2 \times 10^3$$

which compares very well with the experimental value of 2.3×10^3.

For aniline, use the a and b values for substituted benzenes including polar substitutents:

$$\log K_{ow} = -0.72 \log (3.9 \times 10^{-1}) + 1.18$$

$$= 1.47$$

and, therefore,

$$K_{ow} \text{ (aniline)} = 30$$

This is not a very good estimate (K_{ow}(exp) = 7.9), which may not be too surprising when considering the rather poor correlation coefficient ($R^2 = 0.87$) for this equation.

Answer (b)
Use the LFER given in *Figure 7.6* for nonpolar compounds to estimate K_{ow} of naphthalene from its K_{hw} value:

$$\log K_{ow} = \frac{\log K_{hw} + 0.76}{1.28} \qquad (D\text{-}4)$$

Insertion of the K_{hw} value given above into Eq. D-4 yields

$$\log K_{ow} = \frac{\log (2.1 \times 10^3) + 0.76}{1.28}$$

$$= 3.19$$

or

$$K_{ow} \text{ (naphthalene)} = 1.5 \times 10^3$$

This result is somewhat worse than the estimate using the aqueous solubility of liquid naphthalene (see above), but the value obtained is still quite reasonable.

As can be seen from *Figure 7.6*, for the more polar compound aniline, an even greater discrepancy between predicted and experimental value has to be expected and is also found. Here, the LFER including polar compounds has to be used:

$$\log K_{ow} = \frac{\log K_{hw} + 2.26}{1.66} \qquad (D\text{-}5)$$

Using the K_{hw} value of aniline given above, a K_{ow} value of

$$K_{ow} \text{ (aniline)} = 18.5$$

is obtained.

Answer (c)

Since both naphthalene and aniline are quite simple molecules with no complicated intramolecular interactions (no F-values have to be applied), reasonably good results can be expected when estimating K_{ow} from structural group contributions. For naphthalene, the fragment contributions include (*Table 7.3*)

$$\log K_{ow} \text{ (naphthalene)} = \sum_i f_i \text{ (naphthalene)}$$
$$= 8\, f_{c,arom} + 2f_{c,arom.between\ rings} + 8\, f_H^{\phi}$$
$$= 8(0.13) + 2(0.23) + 8(0.23)$$
$$= 3.34$$

and, hence,

$$K_{ow} \text{ (naphthalene)} = 2.2 \times 10^3$$

In the case of aniline, take benzene ($\log K_{ow} = 2.13$, see *Appendix*) as a starting point:

$$\log K_{ow} \text{ (aniline)} = \log K_{ow} \text{ (benzene)} - f_H^{\phi} + f_{NH_2}^{\phi}$$
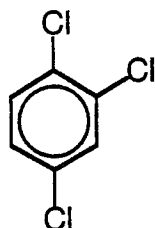$$= 2.13 - 0.23 - 1.00$$
$$= 0.90$$

or,

$$K_{ow} \text{ (aniline)} = 7.9$$

which, in this case, exactly matches the experimental value.

Estimating Bioconcentration from K_{ow}

Problem
Estimate the maximum concentration of 1,2,4-trichlorobenzene (1,2,4-TCB) in a rainbow trout swimming in water exhibiting a 1,2,4-TCB concentration, C_w, of 10 nM.

mw	181.5 g·mol^{-1}
K_{ow} (25°C)	$10^{4.0}$

1,2,4-TCB

Answer
It has long been recognized (*Neely et al., 1974*) that nonpolar organic compounds accumulate in organisms to an extent that is directly related to the chemical's incompatibility with water (i.e., γ_w). Since γ_w values for chemicals are also related to organic solvent-water partition coefficients (particularly when using solvents that mimic well the lipids present in organism, such as is the case for n-octanol, see *Chiou, 1985*), it may not be too surprising to find that the extent of bioaccumulation for any particular compound is also related to the compound's K_{ow}. *Veith et al. (1979)* give a correlation that relates the bioconcentration factor (BCF), defined as the concentration in fish divided by the concentration in the water, to octanol-water partition constants based on tests on fathead minnows, rainbow trouts, and bluegills:

$$\log \text{BCF} \left(\frac{\text{mol/g wet fish}}{\text{mol/mL water}} \right) = 0.85 \log K_{ow} - 0.70$$

$$\text{(D-6)}$$

$$n = 59, R^2 = 0.90$$

Because it is thought that most of the accumulated organic contaminant is localized in fatty tissues and cellular components (e.g., membranes), *Chiou (1985)* has normalized the fish concentrations to the lipid content of the individual type of fish tested and observed:

$$\log \text{BCF} \left(\frac{\text{mol/g fish lipid}}{\text{mol/mL water}} \right) = 0.89 \log K_{ow} + 0.61$$

$$(D\text{-}7)$$

$$n = 18, R^2 = 0.90$$

These correlations, and others available in the literature, are fundamentally the same but differ in how fish concentrations are normalized. Comparison of Eqs. D-6 and D-7 indicates that the lipid content of a fish is about 5% of its wet weight (the intercepts differ by about 1.3). *Note that such correlations are limited to cases in which metabolism of the contaminant is slow or nonexistent.*

Thus, to estimate the 1,2,4-TCB concentration in a trout exposed to 10 nM of this compound in water, first estimate the BCF using Eq. D-6:

$$\log \text{BCF} = 0.85 \log (10^4) - 0.7 = 2.7$$

or

$$\text{BCF} = 500 \text{ mL water/g wet fish}$$

Note that if the BCF had been calculated based on the lipid content of the fish (Eq. D-7), the BCF would have had an about ten times larger value. Hence, the concentration in the fish can be calculated by

$$\text{concentration in trout} = \text{BCF} \cdot C_w$$

$$= 500 \frac{\text{mL water}}{\text{g wet fish}} \cdot (10 \times 10^{-12}) \frac{\text{mol}}{\text{mL water}}$$

$$= 5 \times 10^{-9} \text{ mol/g wet fish}$$

$$\text{or about 1 ppm}$$

PROBLEMS

● D-1 Extraction of Organic Pollutants from Water Samples

For analyzing organic pollutants in water, the compounds are commonly preconcentrated either by adsorption, stripping, or extraction with an organic solvent. You have the job to determine 1,2,4-trichlorobenzene (1,2,4-TCB, see above) in a contaminated groundwater. You decide to extract a 1 L sample of this water with hexane and you wonder how much hexane you should use. Calculate the volume of hexane that you need at minimum, if you want to extract at least 95% of the total 1,2,4-TCB present in the water sample. How could you improve the extraction efficiency? If you wanted to extract 2-chlorophenol from the same water sample, would you also use hexane as a solvent? If not, what other solvent would you suggest and what precautions would you have to take?
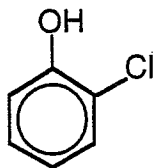

K_{ow} (25°C) $\simeq$ 150
(other solvent water partition constants for 2-chlorophenol can be found in *Hansch and Leo, 1979*).

2-chlorophenol

● D-2 Some Additional K_{ow} Estimation Exercises Using Fragment Constants and Intramolecular Interaction Factors
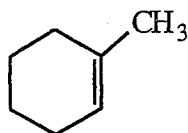
Estimate the K_{ow} values of the four compounds (I-IV) indicated below by using (a) only fragment constants and interaction factors and (b) by starting with the K_{ow} value of a structurally related compound that you choose from the *Appendix*.
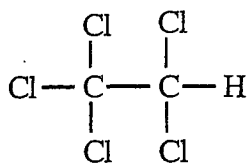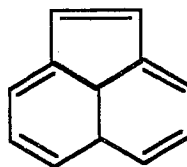
pentachloroethane
I
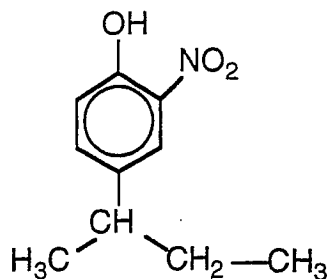
4-s-butyl-2-nitrophenol
II

(log K_{ow} (2-nitrophenol) = 1.89;
see *Schwarzenbach et al., 1988*)

1-methyl-cyclohexene
III

acenaphthylene
IV

## ● *D-3 Correlating Acute Toxicity With Octanol-Water Partitioning - How Well Does it Work?*

In a large number of studies in which fish or Daphnia were used as test organisms, it was found for various compound classes, that the acute toxicities of the compounds correlated quite well with their octanol-water partition constants (see review by *Hermens, 1989*). Using, for example, LC_{50} as a measure of acute toxicity (LC_{50} is the concentration causing 50% mortality after a certain time period), numerous relationships of the general form

$$\log \frac{1}{LC_{50}} = a \cdot \log K_{ow} + b$$

have been reported. Estimate the 14-day LC_{50} of 1,2,4-trichlorobenzene (1,2,4-TCB) and of 2,4-dinitrotoluene (2,4-DNT) for guppies using the data given below, and compare these values with the indicated experimental LC_{50}'s of the two compounds. Plot ($-\log LC_{50}$) versus log K_{ow} and discuss your findings. The LC_{50} (14 days) data for the methyl-

and chlorobenzenes are from *Könemann (1981)*, the data for the nitroaromatic compounds are from *Deneer et al. (1987)*.
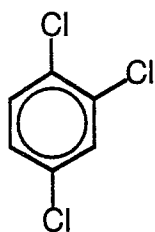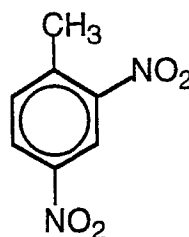
	1,2,4-TCB	2,4-DNT
log K_{ow}	4.00	1.98
LC$_{50}$ (14 day, exp)	1.3×10^{-5} mol·L^{-1}	6.9×10^{-5} mol·L^{-1}

Compound	LC$_{50}$ (14 days, guppies) (μmol·L^{-1})	log K_{ow}
Toluene	740	2.69
1,3-Dimethylbenzene	355	3.15
Chlorobenzene	170	2.92
1,2-Dichlorobenzene	40	3.38
1,4-Dichlorobenzene	27	3.38
1,2,3,4-Tetrachlorobenzene	3.7	4.55
1,2,3,5-Tetrachlorobenzene	3.7	4.65
Pentachlorobenzene	0.70	5.03
Nitrobenzene	500	1.83
2-Nitrotoluene	240	2.30
4-Nitrotoluene	270	2.39
2-Chloronitrobenzene	190	2.26
4-Chloronitrobenzene	38	2.35
3,5-Dichloronitrobenzene	30	3.13
1,2-Dinitrobenzene	7	1.58
1,4-Dinitrobenzene	2.3	1.47