



Solubilization of the neutral and charged forms of 2,4,6-trichlorophenol by β -cyclodextrin, methyl- β -cyclodextrin and hydroxypropyl- β -cyclodextrin in water

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Received 30 September 2002; received in revised form 21 February 2003; accepted 25 February 2003

Abstract

The solubilities of the neutral and charged forms of 2,4,6-trichlorophenol (TCP) in β -cyclodextrin (β -CD) and two of its most used derivatives: methyl- β -cyclodextrin (MCD) and hydroxypropyl- β -cyclodextrin (HPCD) solutions were investigated. The three cyclodextrins were found to form 1:1 inclusion complexes. Binding constants estimated from an enhancement solubility method revealed that the stability of the complexes was dependent on the polarity of the compound and on the cyclodextrin used.

In general, weaker binding constants were observed for TCP with β -CD than with HPCD or MCD. The solubilization efficiencies towards TCP can be ranked in the following order: MCD > HPCD > β -CD. For all cyclodextrins, the stability constant of neutral TCP ($\log K_{ow} = 3.85$) was larger than that of charged TCP ($\log K_{ow} = 1.4$).

A precipitation occurred in TCP/ β -CD solution (around 10 g/l β -CD concentration) at pH 3. However, this phenomenon is not observed for TCP/ β -CD solution at pH 8.8.

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Keywords: Solubilization; 2,4,6-Trichlorophenol (TCP); β -Cyclodextrin (β -CD); Methyl- β -cyclodextrin (MCD); Hydroxypropyl- β -cyclodextrin (HPCD)

1. Introduction

Chlorophenols such as trichlorophenol (TCP) have been mainly used as wood preservatives and as pre-harvest pesticides [1]. Chlorophenol contamination has been observed

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in industrial wastewater effluents, waters in treatment lagoons and surface soils from drying areas near wood treatment areas [2]. Consequently, trichlorophenol is a widespread environmental contaminant of soils, surface waters, and groundwater.

TCP is a weak acid ($pK_a = 6.1$). The uncharged protonated molecules (at $pH < pK_a$) are relatively hydrophobic and electrostatically inert, while the negatively charged deprotonated molecules are more influenced by electrostatic interactions. The ionized species, owing to its higher ability to be solvated by water, has a higher solubility than does the protonated species [3,4].

Wightman and Fein [5] reported that the measured TCP concentration follows a 10-fold increase for every pH unit increment above 6 and is constant for pH values below 5 (300 mg/l). This relation is typical for acid equilibrium above and below their pK_a . Some authors [6,7] found no difference in the aqueous solubility between two ionic strengths (0.001 and 0.1 M NaCl) at pH 6. However, as the pH increased above the pK_a , the solubility increased with ionic strength. The octanol–water partition coefficient (K_{ow}) of TCP varies also with the pH, decreasing as pH increases. The ionic strength of the aqueous solution also affects the $\log K_{ow}$ values positively as ionic strength increases [4].

Cyclodextrins (CDs) are cyclic oligosaccharides formed from enzymatic degradation of starch by bacteria. The peculiar molecular structure of these compounds confers on them a hydrophilic shell and a relatively apolar cavity. Cyclodextrins are known to solubilize many low-polarity organic compounds through the formation of water-soluble inclusion complexes [8,9]. The driving forces leading to complexation are important in CD chemistry. The driving forces have been attributed to several factors including Van Der Waals forces, hydrophobic effects and dipole–dipole interactions [10,11].

Agents such as an organic cosolvent or micelle-forming surfactants are being used for chemically enhancing the removal of pollutants. The surfactants have a large solubilization power, but may form highly viscous emulsions that are difficult to remove [12,13]. Several published works point out the potential use of CDs chemical enhancement agents for sub-surface remediation [12–15]. The transport of low-polarity organic compounds through soil can be enhanced by CD and consequently, the bioremediation could be improved [16,17].

The relative resistance of TCP to biological degradation, the reason for its use as a preservative, creates a pollution problem when it enters the environment. The increase of aqueous solubility of hydrophobic organic compounds by CD can favour their biodegradation [16,17].

No reports have appeared concerning the removal of TCP by CDs.

The objective of this paper is to evaluate the ability of three types of CD (β -cyclodextrin (β -CD), methyl- β -cyclodextrin (MCD) and hydroxypropyl- β -cyclodextrin (HPCD)) to increase the apparent solubility of TCP. The solubilities of TCP at pH 3 and 8.8 in water and in CDs solutions were measured in order to estimate the removal efficiency of TCP from soil.

2. Experimental section

The solubilities of natural CDs in water are different based on the number of glucose units (6, 7 or 8, respectively, for α -, β -, or γ -CD). β -Cyclodextrin is the least expensive, but, unfortunately, has a low limited water solubility (18 g/l). Thus, β -cyclodextrin is often chemically

modified to enhance its water solubility. Two of its derivatives, methyl- β -cyclodextrin and hydroxypropyl- β -cyclodextrin were found to be very water-soluble. The average molecular weights of β -CD, MCD and HPCD are 1135, 1303 and 1365 g/mol, respectively.

2.1. Chemicals and instruments

β -Cyclodextrin, methyl- β -cyclodextrin and hydroxypropyl- β -cyclodextrin were purchased from Sigma–Aldrich and used without further purification. 2,4,6-Trichlorophenol was obtained from Sigma–Aldrich (99% pure). The water content of the CDs used was measured by TG analysis using a Setaram (LABSYS) calorimeter. UV-Vis spectrophotometer (Shimadzu) was used to follow TCP concentration.

2.2. Solubilization experiments

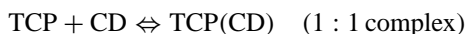
For the solubility measurements, 30 ml of solution containing varying concentrations of CD in appropriate buffer, were poured in 60 ml bottles and the solid TCP was then added to each bottle in quantities in excess of the solubility limit. Triplicate bottles were prepared for each CD concentration. Blanks were prepared in an identical manner with the exception that no CD was added. All samples were equilibrated on a reciprocating shaker for at least 2 days at 24 ± 1 °C. After equilibration, liquid samples were extracted from the bottles by syringe and filtered through a 0.22 μ m glass fibre filter to remove solid TCP. An aliquot of the final filtered sample was withdrawn and diluted with 50:50 methanol/water solution in volumetric flasks. Samples were then analyzed by UV-Vis spectrophotometry. The wavelengths (nm) used for UV detection were 290 for TCP at pH 3, and 315 for TCP at pH 8.8. The role of methanol is to decompose the CD-solute complexes, thereby keeping the UV spectrum unchanged.

This procedure was carried out at pH 3 to ensure that all of the TCP was unionized and at pH 8.8 where the ionized form is predominant. The pH values were adjusted using a citrate/phosphate buffer. The ionic strength was fixed at 0.1 M.

3. Results and discussion

3.1. Equilibrium equation

The solubilization of solutes by cyclodextrin may be regarded as the partition of solutes from water into the cyclodextrin cavity, and the stability constants of CD-solute can be considered as partition coefficient K_{CD} . An equilibrium equation can be used to describe the interaction between TCP and CD:



The relationship between relative aqueous-phase concentration and the concentration of the CD (kg/l) can be given:

$$S_r = \frac{S_a}{S_w} = 1 + K_{CD}[\text{CD}] \quad (1)$$

where S_r is the relative aqueous-phase concentration; S_a the total aqueous-phase concentration includes both free and complexed species, and is called apparent solubility; S_w the concentration of free solute which can be regarded as the aqueous solubility of the compound; K_{CD} (l/kg) the partition coefficient of the compound between the CD and water. Eq. (1) suggests the linear relationship between S_r and [CD]. This phenomenon can be attributed to the formation of 1:1 inclusion complex [15–17].

3.2. Solubilization of TCP in CD/water solutions

3.2.1. β -CD experiments

The relative aqueous-phase concentrations S_r of the TCP are plotted against the β -CD concentration in Figs. 1 and 2 for pH 3 and 8.8, respectively.

At pH 3, the S_a/S_w ratio of TCP initially increase with increasing β -CD concentration up to maximum value and then decrease. The initial increase of S_r is linear as described by Eq. (1) ($R^2 = 0.99$) supporting the existence of 1:1 β -CD/TCP complex. The slope of this linear section of the $S_r = f(\beta\text{-CD})$ curves gives the equilibrium constant.

The break point of the curves is correlated with the beginning of a precipitation phenomenon in the solution. It probably indicates the solubility limit of the β -CD/TCP complex at the experimental conditions (pH 3, ionic strength 0.1 M). The complex seems to be less soluble in water than the free β -cyclodextrin.

This phenomenon has also been observed by Cao et al. [18] during the solubilization experiments of substituted indole compounds by β -cyclodextrin in pure water where the formation of insoluble aggregates at higher β -CD concentration (above 9 g/l) is observed.

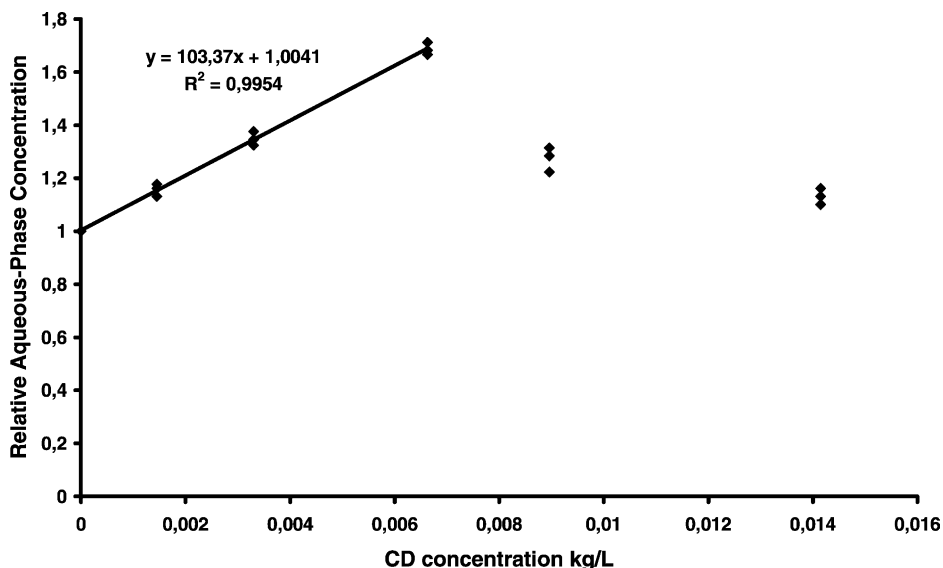


Fig. 1. Relationships between the concentration of β -CD and the relative solubility of TCP; pH 3, $T = 24^\circ\text{C}$.

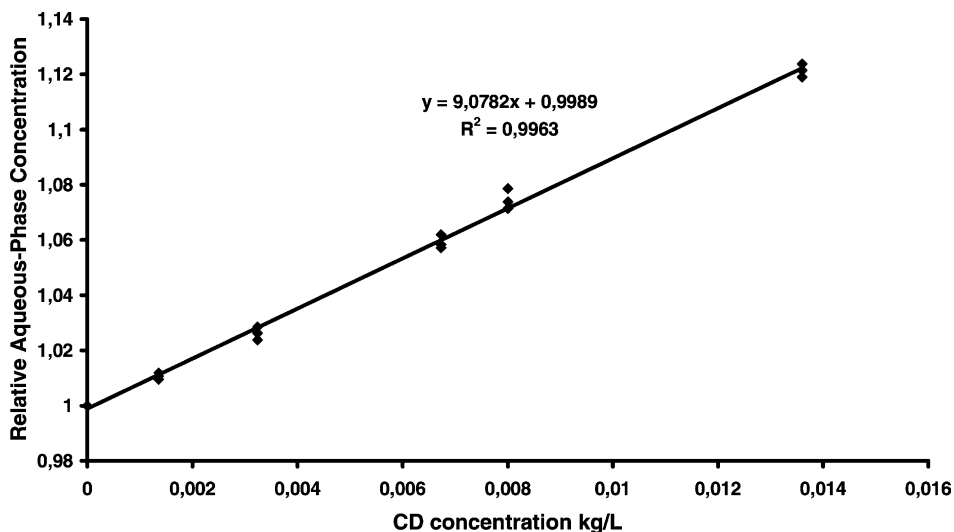


Fig. 2. Relationships between the concentration of β -CD and the relative solubility of TCP; pH 8.8, $T = 24^\circ\text{C}$.

However, in this work, no precipitation was observed at pH 8.8. This may be explained by the higher solubility limit of β -CD/TCP complex in a basic medium. Moreover, at this pH condition, the stability constant of the complex is smaller than that at pH 3, and consequently, the concentration of the complexed species is small.

3.2.2. MCD and HPCD experiments

The relative aqueous-phase concentrations (S_a/S_w) of the TCP are plotted against the CD concentration in Figs. 3 and 4 for pH 3 and 8.8, respectively. Linear regressions were performed for these data following the partition model (Eq. (1)). The regression between S_r and CD concentration exhibits an excellent correlation ($R^2 = 0.99$), supporting the 1:1 stoichiometry of the TCP/CD complex at pH 3 and 8.8. No precipitation phenomenon was observed for either of the pH conditions. This can be explained by the higher solubility of free MCD or HPCD in water. Their complexes are therefore, relatively very water-soluble.

3.2.3. Comparative analysis of β -CD, MCD and HPCD solubilization efficiencies towards TCP

The β -CD, MCD and HPCD/water partition coefficients ($K_{\beta\text{-CD}}$, K_{MCD} and K_{HPCD} , respectively) for the compound, obtained from linear regression are listed in Table 1. Higher binding constants were found for TCP with methyl- β -cyclodextrin and hydroxypropyl- β -cyclodextrin than with β -cyclodextrin. The solubilization efficiencies towards TCP can be ranked in the following order: MCD > HPCD > β -CD. Thus, the cyclodextrin derivatives were more efficient than natural CD for TCP solubilization. For the modified CDs, it appears that the MCD is more effective than the HPCD. This is in agreement with the results of Boving et al. [19] who found that MCD is more effective than HPCD in enhancing

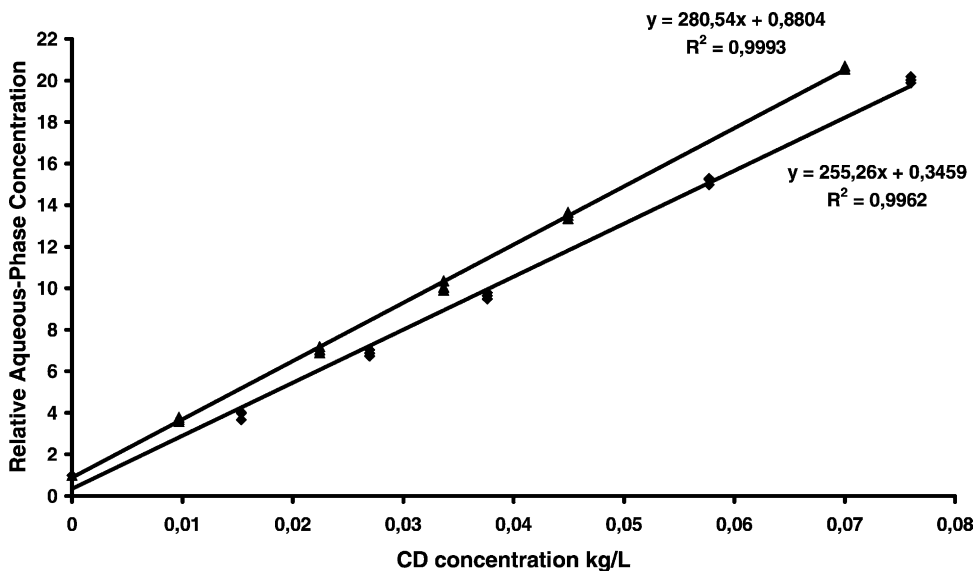


Fig. 3. Relative solubility of TCP vs. CD concentration; pH 3, $T = 24$ °C. (◆) HPCD, (▲) MCD.

solubilization of trichloroethene and tetrachloroethene. This is likely due to the less polar character of MCD.

For all CDs used in this work, the stability constant of neutral TCP is higher than that of charged TCP. Therefore, the neutral TCP is more soluble than the charged TCP in all CD solutions.

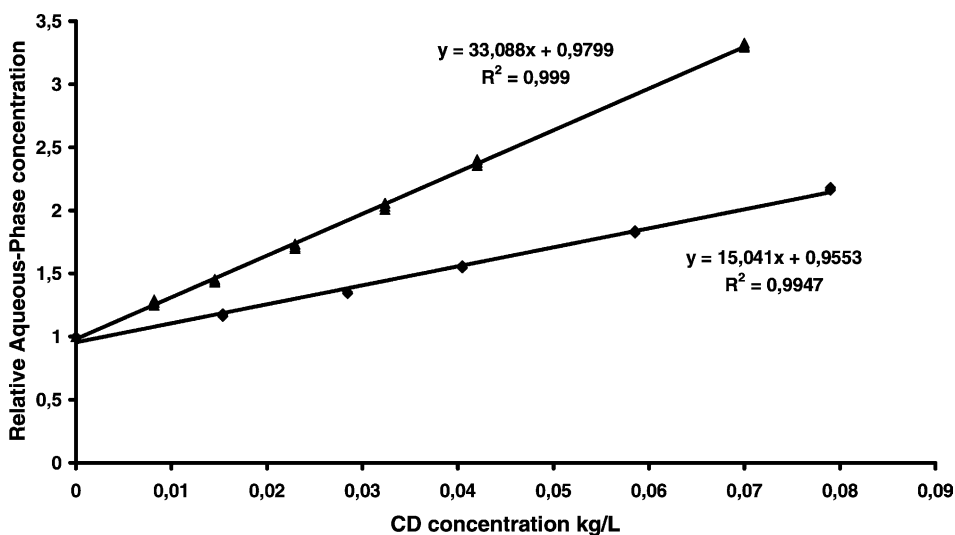


Fig. 4. Relative solubility of TCP vs. CD concentration; pH 8.8, $T = 24$ °C. (◆) HPCD, (▲) MCD.

Table 1
Equilibrium constants for TCP complexes with CDs at 24 °C

| | $K_{\beta\text{-CD}}$ | K_{MCD} | K_{HPCD} | K_{ow}^{a} |
|---------------|-----------------------|------------------|-------------------|----------------------------|
| TCP at pH 3 | 103 | 280 | 255 | 7080 |
| TCP at pH 8.8 | 9 | 33 | 15 | 30 |

K_{CD} (l/kg); K_{ow} : octanol–water partition coefficient.

^a Reference [4].

The octanol–water partition coefficient is a parameter that quantifies the hydrophobicity of an organic molecule [20]. For 2,4,6-trichlorophenol, at 25 °C and 0.1 M ionic strength, the log K_{ow} is 3.84 at pH 3–4 and 1.4 at pH 8–9 [4]. Thus, we can attribute the solubilization effect to the formation of inclusion complexes within the relatively nonpolar cavity of CD and to reduce the interactions between the hydrophobic species and water molecules. This indicates that the hydrophobic interaction is the driving force.

The calculated K_{CD} shown in Table 1, are smaller than the K_{ow} . The CD cavity was estimated to correspond in hydrophobicity to ethanol or 1,4-dioxane, i.e. corresponding to a log $K_{\text{ow}} \sim -0.3$ [21]. This hydrophobicity causes the CD cavity to be less attractive for nonpolar compounds in comparison with octanol.

These results are in agreement with those of Buvari and Barcza [22] where the undissociated or neutral phenol ($K_{\text{ph}} = 129$ l/mol) form a more stable complex with β -CD than the phenolate ion form ($K_{\text{ph}} = 15$ l/mol). The same behavior was observed for benzoic acid, 2-naphthol and 3,5-dinitrobenzoic acid, but not for *p*-nitroaniline and naphthylamine, where the ionized forms lead to more stable complexes than the protonated forms [23].

The results, in this work, are not in agreement with those of Liu et al. [11] who found that the complex α -CD/nitrophenolate was more stable than α -CD/nitrophenol (4-nitrophenolate is much more hydrophilic than 4-nitrophenol). Some authors considered this as a result of stronger dipole-induced dipole interaction for the charged guest molecule [10,11].

Tanada et al. [24] reported that the apparent solubility of the aromatic compounds (benzene, toluene and xylene) did not increase by adding natural CDs but did increase with the addition of HPCD. However, in this work, the apparent solubility of TCP did increase slightly with increasing β -CD concentration. In both works, the solubility in HPCD solution depends on the octanol–water partition coefficient.

It is interesting to note that the TCP is relatively strongly sorbed on soil [25–27]. Further studies should focus on the interaction of CD with TCP sorbed and porous media and on the potential for enhanced transport of TCP in soil. Our next step will be also to investigate the effectiveness of MCD and HPCD in biodegradation of TCP and other chlorophenol compounds. As the application of CD to in situ soil bioremediation could be suitable, we are also looking to see whether increased percolation of complexed pollutants results in increased groundwater pollution and, if how this can be reduced.

4. Conclusion

We have found that: (i) the complex CD/neutral TCP is more stable than the complex CD/charged TCP; this shows that, the driving force leading to the complexation CD/TCP

is the hydrophobic interaction, and in acid condition where the TCP is neutral, the CD can be more capable to TCP removal from the ground. (ii) The MCD and HPCD were more efficient than the β -CD to TCP solubilization. Thus, hydroxypropyl- β -cyclodextrin and methyl- β -cyclodextrin could be suitable for remediation of TCP-polluted soils. (iii) The complex β -CD/TCP precipitated above 9 g/l β -CD concentration and at acid/neutral pH condition. Therefore, β -cyclodextrin could not be suitable for TCP removal at appropriate experimental conditions.

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