

Photochemical conversion of triclosan to 2,8-dichlorodibenzo-*p*-dioxin in aqueous solution[†]

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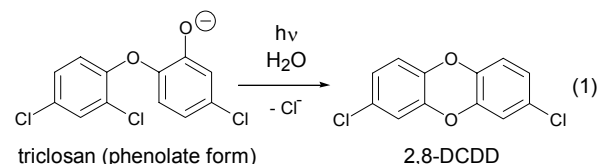
Triclosan undergoes a photochemical cyclization reaction in aqueous solution to yield 2,8-dichlorodibenzo-*p*-dioxin (2,8-DCDD).

Triclosan (5-chloro-2-(2,4-dichlorophenoxy)phenol) is a widely employed antimicrobial that has been found as a contaminant of rivers and lakes.¹⁻⁸ In a recent reconnaissance for a suite of 95 pharmaceuticals, hormones and other organic wastewater contaminants, triclosan was one of the most frequently detected pollutants, being found in 57.6 % of the 139 tested US streams and rivers.³ An early set of studies in the Pawtuxet and Providence Rivers detected triclosan along with structurally related compounds, including 2,8-dichlorodibenzo-*p*-dioxin (2,8-DCDD), which were hypothesized to be derived from the synthesis of triclosan.⁷⁻⁹ Because of general concern about dioxins in the environment, we have become interested in the possibility that triclosan is a dioxin precursor and can be converted to 2,8-DCDD by an intramolecular photochemical substitution reaction. This hypothesis is supported by numerous examples of photochemical nucleophilic aromatic substitution.¹⁰⁻¹³

The thermal cyclization of triclosan and other polychlorophenoxyphenols to polychlorodibenzo-*p*-dioxins is established and occurs readily for triclosan above 300 °C.¹³⁻¹⁶ Previous work on the *photochemical* cyclization has led to conflicting results. It has been reported that triclosan is relatively unique among the polychlorophenoxyphenols in that it does not undergo cyclization to its corresponding dioxin in methanol solution.^{13,17} More recent studies have shown that when irradiated by UV light in the solid state¹⁴ or in aqueous solution,¹⁸ triclosan does convert to 2,8-DCDD. Due to the potentially important environmental and human health implications of this reaction, we have clarified the photochemical behavior of triclosan in aqueous solutions.

Aerated aqueous solutions of triclosan (3.5 to 76 μM) in quartz bottles were irradiated with filtered light (>280, >290 (Pyrex) or >320 nm) from a medium pressure Hg-vapor lamp. Ring closure to 2,8-DCDD was observed in aqueous solutions buffered at pH 8 or above (eq 1).

The presence of dioxin in the irradiated samples was confirmed by GC-MS, HPLC (UV absorbance and mass spectrometric detection), and NMR spectroscopy through comparison with an authentic standard (NeoSyn Laboratories).



There have been previous reports of false detection of dioxins by GC due to thermal cyclization reactions in the heated inlet¹⁹ and of contamination of commercial triclosan with 2,8-DCDD.²⁰ These potential complications were controlled by combining GC with other analysis methods and analyzing the triclosan starting material for 2,8-DCDD (none was detected). Reverse-phase HPLC chromatograms of the photolyzed samples show a well

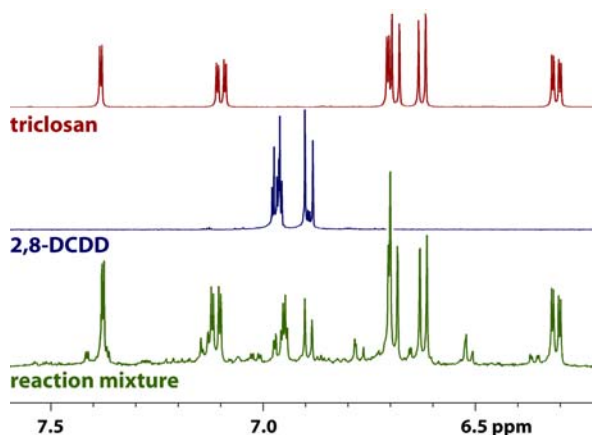


Figure 1. Downfield region of the ¹H NMR spectra (500 MHz) of triclosan (top, CD₃OD/NaOD), 2,8-DCDD (middle, CD₃OD), and a mixture resulting from the photolysis of triclosan in water (bottom, CD₃OD/NaOD). The sample corresponding to the bottom spectrum was obtained by hexanes extraction of the aqueous photosylate. Small differences in the chemical shifts are due to their pH sensitivity.

separated peak for the hydrophobic 2,8-DCDD at longer retention times than triclosan and the other photolysis products. A sample for NMR analysis was prepared by extraction of a photolyzed sample with hexanes. Both one-dimensional ¹H (Figure 1) and two-dimensional ¹H/¹³C HMQC experiments demonstrated that the extract was primarily comprised of triclosan and 2,8-DCDD.

Kinetic measurements were performed to assess the quantum yield for triclosan degradation (Φ_T) and 2,8-DCDD formation (Φ_D) under a variety of conditions (entries 1-13, Table 1). Quantum yields were determined by comparison with the pyridine-*p*-nitroacetophenone actinometer.²¹ Both Φ_T and Φ_D are sensitive to pH inflecting at the pK_a of triclosan (7.9), suggesting that the phenolate form is the photoreactive species. This is in agreement with the observation by Lindström, *et al.* that the phenolate form of triclosan is photoreactive, while triclosan and its methyl ether are photostable.¹

Conversion yields (Φ_D/Φ_T) vary with pH and irradiation wavelength, but are in the range of 1-12 % (at pH 8 or above). This indicates that conversion to 2,8-DCDD is a significant loss process, but not the dominant one.

Freeman and Srinivasa have noted that the photochemical cyclization of 3,4,5,6-tetrachloro-2-(pentachlorophenoxy)phenol, the perchlorinated analogue of triclosan, to octachlorodibenzo-*p*-dioxin is facilitated by triplet sensitizers.²²⁻²⁴ In the case of triclosan, the opposite behavior is observed. Performing the photochemical reaction in 10 % acetone or in the presence of *m*-methoxyacetophenone (0.35 mM), resulted in slower conversion due to light screening by the sensitizers. The presence of triplet quenchers oxygen (entries 9 and 10, Table 1) or isoprene had no effect on the conversion rate or yield. The results of these

Table 1. Reaction conditions, quantum yields, and conversion yields for triclosan decay (Φ_T) and 2,8-dichlorodibenzo-p-dioxin (2,8-DCDD) formation (Φ_D) and decay (Φ_{D^*}).

triclosan						
	[triclosan] _i μM	pH	conditions	Φ_T^a	Φ_D^a	% yld Φ_D/Φ_T
1	21.0	11.5	Pyrex ^b	0.32	3.9×10^{-2}	12
2	76.0	8.0	Pyrex	0.84	3.9×10^{-2}	4.6
3	32.5	8.0	Pyrex	0.84	2.7×10^{-2}	3.2
4	18.4	8.0	Pyrex	0.74	3.0×10^{-2}	4.1
5	3.4	8.0	Pyrex	0.73	3.0×10^{-2}	4.1
6	13.5	7.2	Pyrex	0.36	ND ^c	ND
7	15.3	6.3	Pyrex	0.04	ND	ND
8	16.1	3.9	Pyrex	0.02	ND	ND
9	19.9	11.5	280 nm ^d	0.54	9.3×10^{-3}	1.7
10	19.9	11.5	280 nm ^e	0.56	8.4×10^{-3}	1.5
11	15.6	8.0	280 nm	0.85	1.5×10^{-2}	1.8
12	16.3	11.6	320 nm	0.47	1.0×10^{-2}	2.2
13	16.5	8.2	320 nm ^f	0.70	3.0×10^{-2}	4.2
14	16.2	9.1	Pyrex, MR ^g	0.54	2.0×10^{-2}	3.7
15	15.1	7.8	280 nm, MR	0.93	1.3×10^{-2}	1.4
16	14.7	8.0	320 nm, MR	0.34	4.0×10^{-3}	1.2
2,8-dichlorodibenzo-p-dioxin (2,8-DCDD)						
	[2,8-DCDD] _i μM	pH	conditions	$\Phi_{D^*}^a$		
17	1.3	11	280 nm	4.4×10^{-3}		
18	0.73	8	280 nm	5.9×10^{-3}		
19	1.3	8	320 nm	1.4×10^{-3}		

^aQuantum yields are corrected for internal screening of the triclosan, triclosan anion, and Mississippi River water as appropriate. ^bPerformed with a Pyrex borosilicate glass well which blocks wavelengths <290 nm. ^cNo 2,8-DCDD detected. ^dQuartz well with a <280 nm filter. ^eExperiment performed in deoxygenated water. ^fQuartz well with a <320 nm filter. ^gExperiment performed in filtered Mississippi River water.

experiments suggest that cyclization is not occurring through an excited triplet state.

Kinetic traces of the dioxin product, 2,8-DCDD, displayed growth and decay profiles characteristic of intermediate species. Experiments with pure 2,8-DCDD confirmed that it is also photoreactive, with degradation quantum yields (Φ_D) between 2 and 20 times lower than the appearance quantum yields, Φ_D (entries 17-19, Table 1). Dioxins are known to undergo photochemical degradation,^{16,25-32} and the values for Φ_D in this study are comparable to that found for 2,7-DCDD in 60 % acetonitrile/water under similar conditions.²⁶ The decomposition products of 2,8-DCDD have not been identified, but may include dechlorinated congeners or rearranged products.¹⁶

As a test of the environmental significance of these results, Mississippi River water was spiked with triclosan and irradiated with three different cutoff filters (Pyrex, >280, and >320). In each sample, triclosan was photodegraded and 2,8-DCDD was formed (entries 14-16, Table 1 and Figure 2). After correction for internal screening due to naturally occurring chromophores in the river water, the quantum efficiencies for triclosan degradation and 2,8-DCDD formation in Mississippi River water were comparable to those found under similar conditions in buffer solutions prepared with reverse osmosis-purified laboratory water. These results suggest that triclosan is likely converted to 2,8-DCDD in sunlight-irradiated surface waters.

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Notes and references

[†] Electronic supplementary information (ESI) available: full experimental details, kinetic data and HMQC NMR data.

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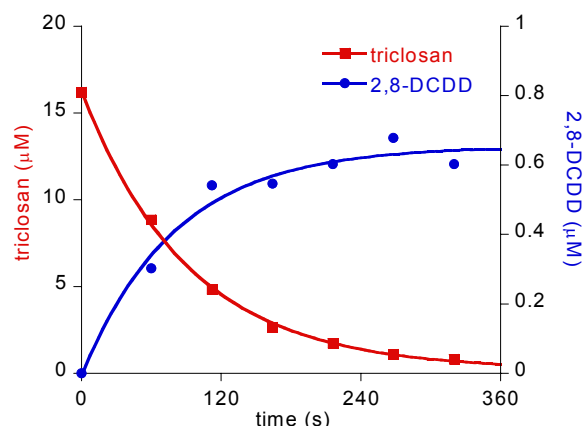


Figure 2. Photochemical conversion of triclosan to 2,8-DCDD in Mississippi River water. These data correspond to entry 14 in Table 1. The solid lines are non-linear least squares fits to exponential growth ($r^2 = 0.9746$) and decay ($r^2 = 0.9991$), and were used to calculate the quantum yields given in Table 1.

- A. Lindström, I. J. Buerge, T. Poiger, P.-A. Bergqvist, M. D. Mueller, and H.-R. Buser, *Environ. Sci. Technol.*, 2002, **36**, 2322.
- M. Adolfsson-Erici, M. Pettersson, J. Parkkonen, and J. Sturve, *Chemosphere*, 2002, **46**, 1485.
- D. W. Kolpin, E. T. Furlong, M. T. Meyer, E. M. Thurman, S. D. Zaugg, L. B. Barber, and H. T. Buxton, *Environ. Sci. Technol.*, 2002, **36**, 1202.
- L. L. P. van Stee, P. E. G. Leonards, R. J. J. Vreuls, and U. A. T. Brinkman, *Analyst*, 1999, **124**, 1547.
- T. Okumura and Y. Nishikawa, *Anal. Chim. Acta*, 1996, **325**, 175.
- N. Paxeus, *Water Res.*, 1996, **30**, 1115.
- V. Lopez-Avila and R. A. Hites, *Environ. Sci. Technol.*, 1980, **14**, 1382.
- G. A. Jungclaus, V. Lopez-Avila, and R. A. Hites, *Environ. Sci. Technol.*, 1978, **12**, 88.
- R. A. Hites and V. Lopez-Avila, *Anal. Chem.*, 1979, **51**, 1452A.
- S. G. Merica and N. J. Bunce, *Can. J. Chem.*, 1995, **73**, 826.
- E. Havinga and J. Cornelisse, *Pure Appl. Chem.*, 1976, **47**, 1.
- J. Cornelisse, G. P. De Gunst, and E. Havinga, *Adv. Phys. Org. Chem.*, 1975, **11**, 225.
- C. A. Nilsson, K. Andersson, C. Rappe, and S. O. Westermark, *J. Chromatogr.*, 1974, **96**, 137.
- A. Kanetoshi, H. Ogawa, E. Katsura, H. Kaneshima, and T. Miura, *J. Chromatogr.*, 1988, **454**, 145.
- A. Kanetoshi, H. Ogawa, E. Katsura, H. Kaneshima, and T. Miura, *J. Chromatogr.*, 1988, **442**, 289.
- G. G. Choudhry and G. R. B. Webster, *Toxicol. Environ. Chem.*, 1987, **14**, 43.
- H. G. Langer, T. P. Brady, and P. R. Briggs, *Environ. Health Perspect.*, 1973, **5**, 3.
- A. Kanetoshi, H. Ogawa, E. Katsura, H. Kaneshima, and T. Miura, *Kankyo Kagaku*, 1992, **2**, 515.
- C. Rappe and C. A. Nilsson, *J. Chromatogr.*, 1972, **67**, 247.
- H. Beck, A. Dross, K. Eckart, W. Mathar, and R. Wittkowski, *Chemosphere*, 1989, **19**, 167.
- A. Leifer, 'The Kinetics of Environmental Aquatic Photochemistry: Theory and Practice', American Chemical Society, 1988.
- P. K. Freeman and R. Srinivasa, *J. Org. Chem.*, 1986, **51**, 3939.
- P. K. Freeman and R. Srinivasa, *J. Agric. Food Chem.*, 1983, **31**, 775.
- P. K. Freeman and R. Srinivasa, *J. Agric. Food Chem.*, 1984, **32**, 1313.
- S. Rayne, P. Wan, M. G. Ikononou, and A. D. Konstantinov, *Environmental Science and Technology*, 2002, **36**, 1995.
- M. Kim and P. W. O'Keefe, *Chemosphere*, 2000, **41**, 793.
- S. Vollmuth and R. Niessner, *Chemosphere*, 1995, **30**, 2317.
- P. K. Freeman and S. A. Hatlevig, *Aquat. Surf. Photochem.*, 1994, 181.
- S. Vollmuth, A. Zajc, and R. Niessner, *Environ. Sci. Technol.*, 1994, **28**, 1145.
- S. Kieatitwong, L. V. Nguyen, V. R. Hebert, M. Hackett, G. C. Miller, M. J. Miille, and R. Mitzel, *Environ. Sci. Technol.*, 1990, **24**, 1575.
- D. G. Crosby and A. S. Wong, *Science*, 1977, **195**, 1337.
- D. G. Crosby, A. S. Wong, J. R. Plimmer, and E. A. Woolson, *Science*, 1971, **173**, 748.

