Solubility of Organic Biocides in Supercritical CO_2 and CO_2 + Cosolvent Mixtures†

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Solubilities of four organic biocides in supercritical carbon dioxide were measured using a dynamic flow apparatus over a pressure range of (10 to 30) MPa and a temperature range of (35 to 80) °C. The biocides studied were Amical-48 (diiodomethyl *p*-tolyl sulfone), chlorothalonil (tetrachloroisophthalonitrile), TCMTB (2-(thiocyanomethylthio) benzothiazole), and tebuconazole (α-[2-(4-chlorophenyl)ethyl]-α- (1,1-dimethyl-ethyl)-1*H*-1,2,4-triazole-1-ethanol). Data represented the effects of temperature and pressure on biocide solubility. Measured solubilities were correlated with the density of pure solvent. The effects of methanol and acetone as cosolvents on the solubility of TCMTB and tebuconazole were determined at (50 and 65) °C and at selected pressures between (10 and 30) MPa. The introduction of 3 mol % acetone or methanol increased the solubilities of tebuconazole by a factor of 3 to 7. The cosolvent effect decreased with increase in pressure. At (5 to 10) mol % of cosolvent, the solubility of either biocide increased with the amount of cosolvent; however, the increase was more significant for tebuconazole than for TCMTB.

Introduction

Supercritical carbon dioxide (sc-CO_2) has liquidlike solvating strength and gaslike transport properties which allow it to be a unique medium for extractions, chemical reactions, or depositions of particles within porous solids. There has been increased interest in the use of sc-CO_2 in the past few years. sc-CO_2 has shown to be a potential cleanup solvent because of its capabilities to extract toxic chemicals from soil and other contaminated solids such as wood chips.[1−7]

Some of the reasons for increased interest in sc-CO_2 include environmental problems associated with liquid solvents, the increasing cost of energy-intensive separation techniques in the newly emerging food, pharmaceutical, and biotechnology industries, and the inability of the traditional techniques to design new materials with specific characteristics (foams, aerogels, powders, fibers, microcapsules, liposomes) or to improve classical materials (impregnation, coating, coloring, striping, monodispersed crystallization).[8−10]

The solubility of biocides in sc-CO_2 is one of the most useful thermophysical properties that must be fully understood and modeled in order to develop a process for sc-CO_2 extraction or impregnation of biocides. Solubilities of a solute in sc-CO_2 are determined mainly by the solute vapor pressure and solvent−solute interaction. A qualitative measure for the solvating power of the sc-CO_2 is the Hildebrand solubility parameter, δ, which is the square root of the cohesive energy molar density. On a log−log scale, the solubility of organics increases approximately linearly with the density of sc-CO_2 with all isotherms collapsing to a line.

Equilibrium solubility data for the various biocides studied are required for the purpose of cleanup techniques, for development of analytical methods for solid environmental samples, or for other sc-CO_2 technologies such as deposition into semiporous solids. Most of the chemicals in this work are new fungicides in the agriculture and wood-preserving industries. The incentive of the present study was the scarcity of appropriate thermodynamic data for screening and designing of processes that involve these chemicals. This paper reports the equilibrium solubility data for selected biocides in pure sc-CO_2 and with a selected cosolvent.

Experimental Procedure

Materials. Four organic biocides were selected for initial screening based upon considerations such as large production volume, inclusion of a variety of organic classes in the screening, and reasonable safety in laboratory handling. The biocides selected for laboratory testing were Amical-48 (diiodomethyl *p*-tolyl sulfone), chlorothalonil (tetrachloroisophthalonitrile), TCMTB (2-(thiocyanomethylthio) benzothiazole), and tebuconazole *(*α-[2-(4-chlorophenyl)ethyl]-α-(1,1-dimethylethyl)-1*H*-1,2,4-triazole-1-ethanol. TCMTB was supplied by Buckman Laboratories, Inc., and tebuconazole by Mobay Corp., and the other two were obtained from Sigma Chemical Co. The physical properties, purities, and molecular structures of these chemicals are listed in Table 1. These biocides were used without further purification. Most of these chemicals used in these studies can be toxic to humans. For anyone who wants to reproduce or continue this work, care must be taken to handle these chemicals as recommended by the material safety data sheets.

Apparatus and Procedures. The equipment used to measure solubility of the biocides was a modified dual-pump Isco Series 2200 SFE (Isco, Inc., Lincoln, NE) system which consisted primarily of two syringe pumps, a heating

† Experimental data collection for this work was conducted at Oregon State University, Chemical Engineering Department.

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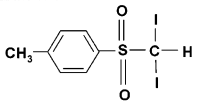
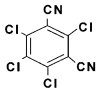
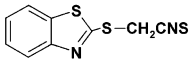
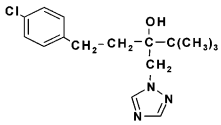
Table 1. Biocides Tested for Solubility

biocide	structure	mol mass	P^{vap} (20 °C) Pa	boiling point °C	melting point °C	δ^a $(J\cdot cm^{-3})^{1/2}$	purity mass %
Amical-48		417	NA	NA	180	24.32	96
chlorothalonil		266	NA	NA	250	42.71	95
TCMTB		238	5.39×10^{-3}	80	35	23.4	99
tebuconazole		308	5.5×10^{-3}	140	103	29.4	95

[a] Evaluated using the atomic and group contribution method of Fedros (ref 38).

coil, an equilibrium cell, a metering valve, and a cold trap for sample collection. The operational concept was to measure the amount of biocide required to create a saturated solution with a known amount of sc-CO_2.

The biocides were ground and charged to the saturator with glass beads (1.5 mm o.d.) to increase the porosity of the packed bed, to facilitate efficient fluid−solid contact, and to minimize channeling. To ensure establishment of equilibrium and to check the mass transfer limits on measured solubility, the expanded CO_2 gas flow rate was increased from (70 to 500) mL·min^{-1} for the different substrates at 50 °C and 30 MPa. Measured solubilities changed less than 1.3% for flow rates less than 300 mL·min^{-1}, which indicated that equilibrium was achieved at the exit of the saturator. Higher flow rates can result in unsaturated flow or entrainment of the solute. Therefore, a solvent flow rate of 200 mL·min^{-1} at atmospheric pressure was used in all experiments. This flow rate was found to be low enough to ensure that measured solubilities were independent of solvent flow rates. Glass wool and metal frits (1 μm) were used at the inlet and outlet of the saturator to prevent entrainment of biocide. At the beginning of each run, the saturator was allowed 20 min to attain thermal equilibrium.

A schematic of the solubility measuring system is shown Figure 1. Liquid CO_2 was drawn through a dip tube from a supply cylinder by syringe pump A (ISCO 260), which has a pressure range of (1 to 51.7) MPa and a maximum achievable flow rate of 107 mL·min^{-1}. The pump cylinder-jacket temperature was kept at 4 °C within an accuracy of ±0.1 °C using a chiller (VWR 1156). After each refill stroke, the CO_2 was allowed to thermally equilibrate for about 30 min, after which it was compressed to the desired pressure. The system was purged with CO_2 at low pressure before being brought to the required temperature and pressure.

When a cosolvent was used with CO_2, the cosolvent was introduced by using another syringe pump (pump B, Isco model 100D) which had delivery rates between 0.1 and 25.0 cm^3/min and pressure up to 689.7 bar. Liquid CO_2 and cosolvent were mixed and then compressed past the critical pressure of the mixture. The temperature of the mixture was raised by using a preheater to the desired value above the supercritical temperature of the mixture. The compressed fluid was then passed through a saturator packed with biocide. The preheater and the saturator were contained in an oven. The temperature of the oven was maintained within ±1 °C. In this study, the equilibrium cell consisted of the saturator, which was a 10 cm^3 stainless steel tube and a Jurguson view cell (Jurguson model 12-T-40 with a volume of 33.92 cm^3).

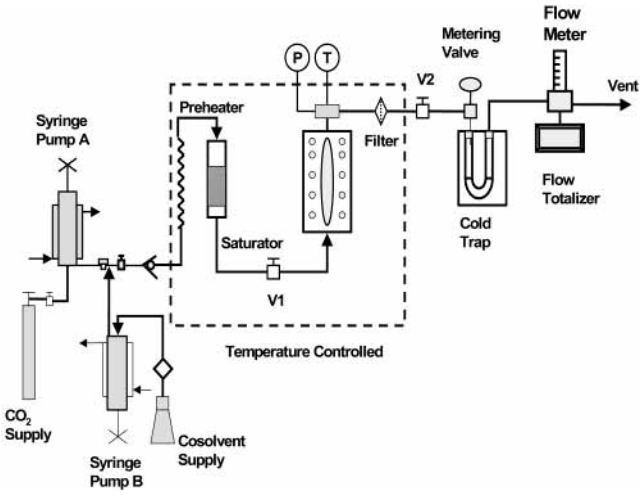


Figure 1. Schematic of flow apparatus for measuring biocide solubility in supercritical fluids.

For biocides that are liquid above the critical point of the solvent, a view cell (Jerguson gauge 12-T-40) was connected in series with the saturator. The sight gauge (40 mL) ensured that the sampling was taken from the gaseous phase and no liquid was entrained. The system was filled to half of the sight gauge with the solute of interest, and it was brought to the required pressure and temperature. It was then allowed to thermally equilibrate and reach steady-state conditions by continuously flowing the sc-CO_2 at about 200 mL·min^{-1} for 2 to 3 h.

The flow rate was controlled using a micrometering valve (Autoclave model 10VRMM2812). The difficulty in this system was that precipitation of solute between the saturator and the trap inlet can lead to significant errors. The micrometering valve and the connecting tubing were heated to about (15 to 20) °C above the melting point of the solid solute to minimize clogging by solid biocide precipitate and to compensate for the Joule−Thompson effect upon depressurization of the CO_2. Excessive heating of the tubing between the saturator and the micrometering

valve, however, may lead to retrograde precipitation at lower pressures,[11] which can cause similar errors.

The amount of biocide dissolved was determined using two methods. Gravimetric analysis of the solute in the collection trap gave accurate results when no cosolvent was used. A high-pressure liquid chromatographic method was employed for the solubility of TCMTB in the CO_2 + cosolvent system to avoid potential errors in the gravimetric method due to TCMTB's higher vapor pressure (as compared to that of tebuconazole). The collected sample inside the trap was diluted in methanol to a total volume of 50 mL, and 10 μL of this was injected into an HPLC (Shimadzu, SCL6A). For tebuconazole, the sampling procedure was modified by flushing the tube between the valve V2 and the micrometering valve with (20 to 25) mL of methanol into a weighed beaker (Figure 1). The drying tube and the beaker were then left in the fume hood for at least 72 h before reweighing.

A precision balance (Mettler AE 200) which was accurate to 0.05 mg was used for the weighing. The flow was measured with digital flow meter (McMillan Co., 310-3) connected to a flow totalizer (Kessler-Ellis Co., INT-69). The measurement method was validated by measuring the solubilities of naphthalene and phenol and comparing the results with those of the literature.[12,13] The differences in solubility at (35 and 45) °C using our flow method and the two literature data values did not exceed 5%. The temperature was measured by thermocouples with an accuracy of 0.1 °C, and the system temperature was controlled within ±0.1 °C. The pressure was measured by a Heise bourdon-tube gauge with accuracy of 0.05 MPa, and the pressure fluctuation was controlled within ±0.1 MPa.

The solubility of phenol in sc-CO_2 was determined at 60 °C for selected pressures from 170 to 230 bar, to verify the reliability and efficiency of the solubility apparatus and the technique employed in this study. The results from our work are in agreement with the data of Van Leer and Paulaitis[13] within 5%. This confirms the reliability of the apparatus and procedure used in this work.

Results and Discussion

Solubility of Biocides in sc-CO_2. The average measured solubility values of the four biocides are given in Tables 2 and 3. Each reported data value was the average of four or five replicate samples. The reproducibility of the measurements was generally within 4%, although the variation of measurements at lower pressures was higher. The data precision was measured using relative standard detection (RSD), which is given by

$$RSD_k = \frac{S_k}{Y_k} \times 100 \qquad (1)$$

where S_k is the standard deviation for the replicate measurements at the sampling event k, and Y_k is the mean of five measurements at sampling events k (1, 2, 3, 4, and 5).

The solubilities of the biocides varied over a range of 1 to 2 orders of magnitude. The results demonstrated that volatility of a solute was the predominant factor that determined its solubility in sc-CO_2. Solutes with lower vapor pressures or higher melting and boiling points showed lower solubilities. For example, TCMTB was 5 times more soluble than chlorothalonil at 65 °C and 30 MPa. Heavy molecular mass biocides, such as Amical-48, showed very low solubilities (Table 2). The relative solubilities of these biocides were consistent with the findings of other workers, that an increase in polarity and high molecular mass or a decrease in vapor pressure of the solute inhibits its solubility in CO_2.[14,15]

Table 2. Solubility Data for Amical-48 and Chlorothalonil in sc-CO_2

			Amical-48		chlorothalonil	
t/°C	P/MPa	CO_2 reduced density, ρ_{1R}	mole fraction $\times 10^{-5}$	RSD_k/%	mole fraction $\times 10^{-5}$	RSD_k/%
45	10	1.065	1.22	11.0	1.32	10.2
	15	1.593			4.81	8.6
	17	1.666	3.80	9.0	8.49	4.3
	20	1.745	3.90	9.2	13.2	6.5
	22.5	1.799	5.81	4.3	12.1	4.2
	25	1.841	6.20	3.2	13.2	4.5
	30	1.913	7.26	4.3	15.6	3.2
55	10	0.698			0.53	6.5
	12.5	1.163			4.62	5.5
	15	1.403			6.09	6.2
	17	1.514			7.99	4.5
	20	1.620	6.38	5.2	9.93	3.2
	22.5	1.686	7.07	4.3	12.2	2.3
	25	1.741	8.98	4.5	14.1	2.1
	30	1.826	8.66	3.2	18.0	1.5
65	10	0.571	0.63	10.5	0.64	7.2
	11	0.688				
	12.5	0.892	2.43	5.5	1.06	5.6
	15	0.892	3.67	6.5	2.17	4.5
	17	1.339	5.60	4.6	5.43	3.2
	20	1.484	8.45	5.6	13.7	4.9
	22.5	1.569	8.29	4.3	15.4	5.5
	25	1.636	9.63	5.5	19.2	3.2
	30	1.737	11.5	3.2	26.8	2.2

Table 3. Solubility Data for TCMTB and Tebuconazole in sc-CO_2

			TCMTB		tebuconazole	
t/°C	P/MPa	CO_2 reduced density, ρ_{1R}	mole fraction $\times 10^{-5}$	RSD_k/%	mole fraction $\times 10^{-5}$	RSD_k/%
50	10	1.083	0.8	2.0	0.63	11.6
	11	1.323	3.8	4.1	1.34	10.3
	12.5	1.508	10.7	3.1	4.78	4.5
	15	1.686	25.6	5.6	16.50	2.9
	20	1.793	59.0	0.4	33.43	10.3
	30	1.870	111.5	1.4	64.21	4.4
65	10	0.570	0.2	9.0	0.35	15.8
	11	0.688	0.6	11.6	0.57	5.5
	12.5	0.895	2.3	3.7	1.80	16.7
	15	1.195	11.1	1.64	8.08	6.7
	20	1.490	62.1	4.25	48.38	15.1
	30	1.738	139.6	4.33	185.71	5.8

Biocide solubilities increased significantly with pressure between (10 and 30) MPa, but additional pressure produced only minimal increase in solubilities. As pressure increases, CO_2 density increases and the intermolecular mean distance of molecules decreases, thereby increasing the specific interaction between the solute and solvent molecules. Solvent temperature affects solute vapor pressure, solvent density, and intermolecular interactions in the fluid phase. The effect of temperature on the solubility of chlorothalonil is given in Table 2. At pressures below 20 MPa, the effect of higher temperature on decreasing the solvent density was more dominant than its effect on increasing the solute vapor pressure. Therefore, solubilities decreased with increasing temperatures (retrograde vaporization). Above 20 MPa, temperature effects on solute vapor pressure were more dominant on solubility than changes in density. Similar phenomena have been documented.[16] A better representation of solubility data may be obtained by plotting solubility isotherms against solvent density[16−18] as shown in Figures 2 to 5.

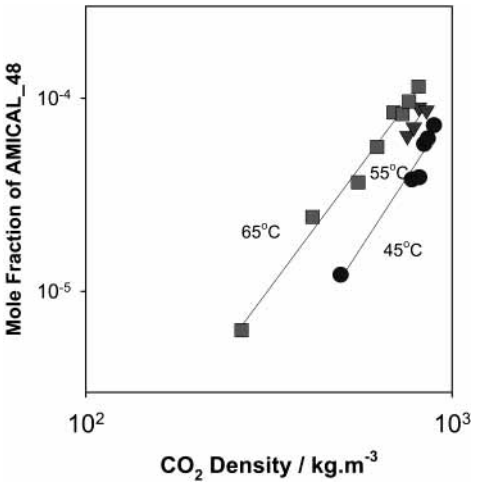


Figure 2. Solubility isotherms of Amical-48 vs density of CO_2; lines represent best fits for the three temperatures tested.

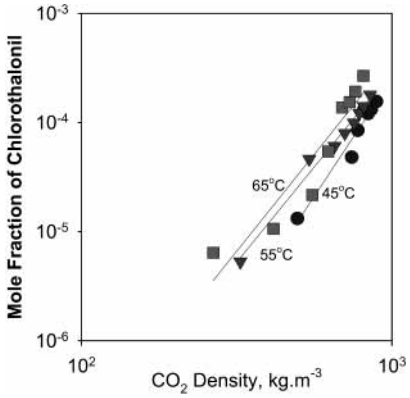


Figure 3. Solubility isotherms of chlorothalonil vs density of CO_2; lines represent best fits for the three temperatures tested.

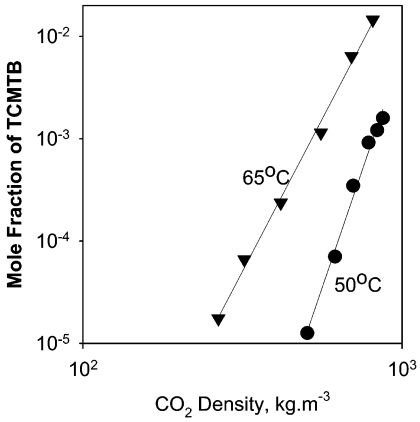


Figure 4. Solubility isotherms of TCMTB vs density of CO_2; lines represent best fits for the two temperatures tested.

Data Correlation. Correlating solute concentration with solvent density was derived by Chrastil.[18] The analysis was based on the assumption that for an equilibrium system, a solute molecule associates with k molecules of the solvent to form a solvato complex. Using the approximation of the Clausius−Clapeyron equation which estimates the vapor concentration of the solute, the following theoretical equation was derived:

$$\ln y = (k - 1) \ln \rho_1 + \frac{a}{T} + b \qquad (2)$$

where y is the mole fraction of a solute in the sc-CO_2, p is the density of the SCF (kg·m^{-3}), a is $\Delta H/R$, ΔH is $\Delta H_{\text{solvation}} + \Delta H_{\text{vaporization}}$, $b = q + (1 - k) \ln M_1 + \ln(M_2 + kM_1)/M_2$, q = constant, and M_1 and, M_2 are the molecular masses of the solvent and solute, respectively.

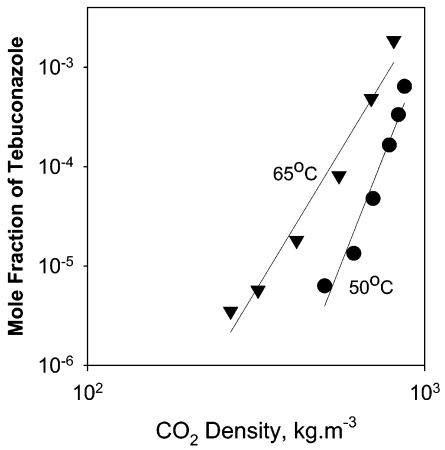


Figure 5. Solubility isotherms of tebuconazole vs density of CO_2; lines represent best fits for the two temperatures tested.

Table 4. Number of Solvent Molecules in the Solvato Complex as Determined from the ln(y) vs ln(ρ) Relationship, Equation 2

solute	t/°C	molecules in solvato complex	regression coefficient
Amical-48	35	3.91	0.95
	45	3.84	0.96
	55	3.55	0.99
chlorothalonil	45	5.33	0.95
	55	4.64	0.99
	65	4.50	0.97
TCMTB	50	7.12	0.95
	65	6.96	1.00
tebuconazole	50	6.96	1.00
	65	6.62	1.00

Logarithms of the solubilities of the four biocides were plotted as a function of the logarithm of CO_2 densities (Figures 2, 3, 4, and 5). The slopes of the solubility isotherms indicate the number of molecules causing clustering of molecules and resulting in larger solvato complexes.[18] The slopes of these plots and the regression coefficients are given in Table 4. The association constant, k, was found to range between 3 and 8, which was in the range reported earlier.[19] Isotherms for the same solute were not exactly parallel. Better fitting can be obtained by making k a function of density and at the expense of adding two additional parameters.[20] Although a density-based correlation is simple, it requires no physical data as other models do; for example, equations-of-state-based models require solute vapor pressure as function of temperature. However, attempts by the authors to relate k to physical properties of the solutes such as reduced solubility parameters (i.e., the ratio of the solubility parameters of the solute and the solvent) were only partly successful.[21]

Solubility of Biocides in CO_2−Cosolvent Systems. The weak solvent power of sc-CO_2 for polar organic compounds is a limitation for its application to reactions, depositions, or extraction processes. In some cases, small amounts of polar cosolvent can dramatically affect the solubilities of compounds in sc-CO_2 + cosolvent mixtures. The experimental parameters for determining the solubility of biocides in a CO_2 and cosolvent mixture were at supercritical conditions which were above the critical loci of methanol + CO_2 and acetone−CO_2 systems.[22,23] The solubility data of TCMTB in sc-CO_2 in the presence of 3

Table 5. Effects of Pressure on the Solubility of TCMTB in sc-CO_2 with Either 3 mol % Methanol or 1.68 mol % Acetone at 50 °C and 65 °C

	sc-CO_2 with 3 mol % methanol			sc-CO_2 with 1.68 mol % acetone		
P/MPa	mole fraction $\times 10^{-5}$	RSD_k/%	cosolvent effect[a]	mole fraction $\times 10^{-5}$	RSD_k/%	cosolvent effect[a]
			$t = 50$ °C			
10	0.63	14.2	0.74	0.48	13.5	0.57
12.5	9.63	3.6	0.89			
15	25.69	1.9	1.00	25.39	6.0	0.99
20	69.81	1.8	1.18	87.73	3.6	1.49
30	128.58	2.0	1.15	162.30	2.7	1.46
			$t = 65$ °C			
10	1.49	5.6	0.65	0.06	23.2	0.33
12.5				0.89	8.26	0.39
15	9.02	7.6	0.81			
20	59.7	6.8	0.96	44.61	1.3	0.71
30	132.5	3.1	0.93	115.50	6.1	0.81

[a] Cosolvent effect is defined as the ratio of solute solubility in sc-CO_2−cosolvent to the solute solubility of the solute in sc-CO_2.

Table 6. Effects of Pressure on the Solubility of Tebuconazole in sc-CO_2 with Either 3 mol % Methanol or 3.0 mol % Acetone at 50 °C and 65 °C

	sc-CO_2 with 3 mol % methanol			sc-CO_2 with 3% mol % acetone		
P/MPa	mole fraction $\times 10^{-5}$	RSD_k/%	cosolvent effect[a]	mole fraction $\times 10^{-5}$	RSD_k/%	cosolvent effect[a]
			$t = 50$ °C			
10	0.72	7.3	1.14	1.94	3.2	3.08
11	3.17	2.1	2.37	9.59	2.1	7.15
12.5	15.83	5.0	3.32	17.86	3.2	3.74
15	57.21	1.7	3.48	44.83	0.43	2.72
20	115.32	0.4	3.48	88.56	2.9	2.67
30	292.8	1.8	4.59	169.10	1.4	2.64
			$t = 65$ °C			
10	0.35	7.4	1.00	0.86	2.5	2.45
11	0.73	2.2	1.28	1.68	3.3	2.99
12.5	2.44	10.1	1.35	4.55	0.9	2.52
15	14.71	4.2	1.82	19.33	1.9	2.39
20	93.84	0.86	1.94	91.07	0.1	1.89
30	370.71	0.63	2.00	246.89	0.3	1.34

[a] Cosolvent effect is defined as the ratio of solubility in cosolvent−sc-CO_2 to the solubility of the solute in sc-CO_2.

mol % methanol and 1.68 mol % acetone at (50 and 65) °C are given in Table 5. The solubilities of tebuconazole in sc-CO_2 with 3 mol % methanol and 3 mol % acetone are similarly shown in Table 6. Biocides in sc-CO_2 + cosolvent mixtures exhibited similar "crossover point" behavior to that seen in pure CO_2. Our experimental data also showed ternary crossover pressures to be higher than those of binary systems. The crossover pressures of tebuconazole in 3 mol % methanol or 3 mol % acetone were (23.2 and 20.7) MPa, compared to 18.2 MPa for sc-CO_2 alone. Similarly, the crossover pressure of TCMTB in 3 mol % methanol was 24.5 MPa compared to 19.6 MPa for sc-CO_2 alone. In 1.68 mol % acetone, the crossover point was shifted to a pressure higher than 30.0 MPa. Similar shifts of the crossover pressure have been observed by other researchers.[22,24]

Addition of 3 mol % methanol to sc-CO_2 increased TCMTB solubility at higher pressures (>15 MPa); however, the effect of methanol was minimal at pressures lower than 15 MPa. For tebuconazole, the presence of acetone helped to increase solubility at all pressures. The solubility enhancement as a result of a cosolvent was measured using the "cosolvent effect" factor, defined as the ratio of the

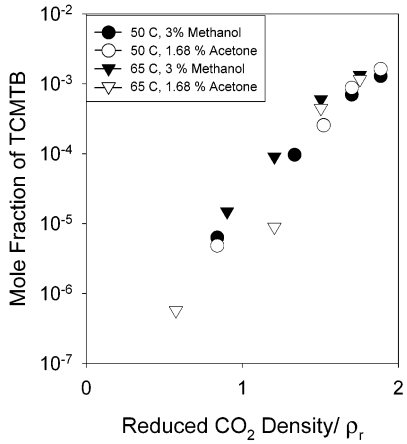


Figure 6. Solubility isotherms of TCMTB in sc-CO_2 with 3 mol % methanol or 1.68 mol % acetone as a function of pressure.

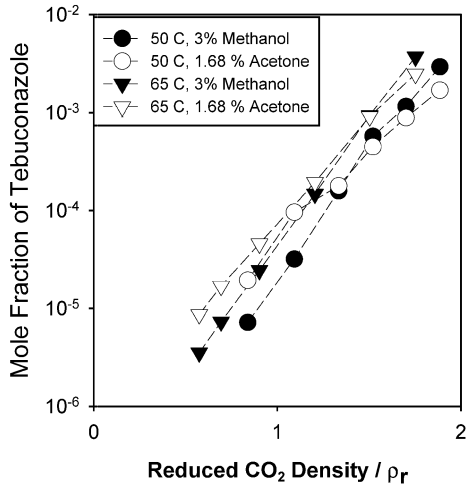


Figure 7. Solubility isotherms of tebuconazole in sc-CO_2 with 3 mol % methanol or 3 mol % acetone as a function of pressure.

solubility obtained with a cosolvent to that obtained without a cosolvent. Both cosolvents resulted in increased solubility of tebuconazole, but neither had a very significant effect for TCMTB. For TCMTB in methanol + sc-CO_2 and acetone−sc-CO_2, the cosolvent effect increased slightly with pressure (Table 5). However, for the 3 mol % methanol−sc-CO_2 mixture, the cosolvent effect on tebuconazole increased monotonically with an increase in pressure at (50 and 65) °C (Table 6). The solubilities of TCMTB and tebuconazole as a function of reduced density, $\rho_r = \rho/\rho_c$, for the different temperatures and types of cosolvents are shown in Figures 6 and 7, respectively. The cosolvent effect exhibited a maximum at about 11 MPa in the acetone−sc-CO_2 mixture for tebuconazole at both temperatures. The cosolvent effect is lower at higher temperatures because the increase in vapor pressure improves the solubility in pure sc-CO_2 more than in the sc-CO_2 + cosolvent mixture, where chemical interactions become an important factor affecting solubility.

The addition of a cosolvent increases the bulk density of the fluid mixture; this generally contributes to solubility enhancements. This effect is higher near the critical point where the isothermal compressibility is high. However, at pressures and temperatures further away from this region, where the fluid is less compressible, the increase in bulk density is not very significant.

This can be used to explain the change in cosolvent effect with system pressure as for the naproxen + methanol−

CO_2 system.[25] This effect has been explained using UV−visible or fluorescence spectroscopy study of the nature of the solute−cosolvent interaction under different conditions.[26−30] The region near the solute molecule was enriched with cosolvent molecules so that the local concentration of cosolvent near a solute molecule was several times higher than the bulk concentration. Such local ordering of the cosolvent molecules, however, decreased with increasing pressure, and at high enough pressures, the concentration of the cosolvent around the solute approached the bulk concentration. While the local composition enhancement decreases with pressure, the absolute local concentration of cosolvent around the solute increases with increasing pressure, due to the increase in density. Goldman et al.[31] also used equations of state and Monte Carlo simulations to describe this effect as the change in the solute−solvent and solvent−cosolvent interactions with pressure. At lower pressures (and thus density), a higher number of solvent/cosolvent molecules interact favorably with solute, increasing the solubility.

At a low cosolvent concentration, the cosolvent effect depends predominantly on the absolute concentration of cosolvent around the solute. As pressure increases, the absolute concentration increase causes the cosolvent effect to increase. At high cosolvent concentration, the effect of local composition enhancement becomes significant. The local composition enhancement is maximum in the region of high compressibility (near P_c); therefore, it is possible that a decrease in local composition enhancement with increasing system pressure would lead to the observed decrease in the cosolvent effect.

The polarity and H-bonding ability of both solute and cosolvent also might play important roles to enhance the cosolvent effect. A comprehensive Kamlet and Taft's scale was used to correlate linear free energies to explain the effects of cosolvents.[32] For polar solutes, the cosolvent effect is a strong function of cosolvent polarity, while for nonpolar solutes, in modified sc-CO_2, both methanol and acetone showed little effect at low concentrations. However, the cosolvent effect increased significantly as the amount of cosolvent increased above 1 mol % (4 mol % of methanol and 2.5 mol % of acetone).[33]

For tebuconazole, there are two possible mechanisms to explain the cosolvent effects. First, the polarity of tebuconazole plays an important role in the cosolvent effect because acetone, which has a higher polarity than methanol, gave a higher cosolvent effect. Second, because tebuconazole contains the −OH group, H-bonding could be important. The small amount of methanol added to CO_2 increases the mixture basicity much higher than that of pure sc-CO_2, which exhibits only slight basicity. This increases the hydrogen-bonding interaction of polar biocides.[32] Therefore, tebuconazole can be assumed to be an H-bond donor whose solubility increases when an H-bond acceptor like acetone is used as a cosolvent. Since methanol is a strong H-bond donor, it would not be a suitable cosolvent for tebuconazole, based on H-bonding effects. If solubility enhancement is due to H-bonding, raising the system temperature should result in a decrease in the observed cosolvent effect. The cosolvent effect of tebuconazole at a temperature of 65 °C was much less than at 50 °C, which supports the proposed tebuconazole−acetone H-bonding mechanism. The existence of this mechanism was proven using dipole moment[33] and data for the degree of intermolecular H-bonding between solutes and cosolvents obtained at these conditions using an oscillator circuit for capacitance measurements, adapted to measure dipole moment, and Fourier transform infrared spectroscopy, respectively.[35]

Table 7. Solubility of TCMTB and Cosolvent Effects with Increasing Amounts of Cosolvents in sc-CO_2 at 15 MPa and 65 °C

mole percent	mole fraction × 10^{-5}	cosolvent effect
	sc-CO_2 + Methanol	
1.0	8.6	0.77
5.0	17.8	1.59
10.0	43.5	3.90
	sc-CO_2 + Acetone	
1.0	10.3	0.92
3.5	24.5	2.21
5.0	42.7	3.66

Table 8. Solubility of Tebuconazole and Cosolvent Effects with Increasing Amounts of Cosolvents in sc-CO_2 at 15 MPa and 65 °C

mole percent	mole fraction × 10^{-5}	cosolvent effect
	sc-CO_2 + Methanol	
1.0	10.56	1.31
5.0	14.66	1.82
10.0	33.60	4.17
	sc-CO_2 + Acetone	
1.0	8.80	1.09
3.5	19.33	2.39
5.0	42.91	5.32

As discussed previously, the shape of the plot of the cosolvent effect versus pressure can change from monotonically increasing to monotonically decreasing as more cosolvent is used.[25,36] At constant temperature and pressure, an increase in the concentration of either cosolvent increased the cosolvent effect for TCMTB and tebuconazole (Tables 7 and 8). This suggests that higher cosolvent concentrations modify the bulk properties of the fluid significantly.[37]

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Literature Cited

(1) Knopf, F. C.; Dooley, K. M. Extraction of Pesticides from Solid Matrices Using Supercritical Fluids. In *Supercritical Fluid Extraction and Chromatography*: *Techniques and Applications*; Charpentier, B. A., Sevenants, M. R., Eds.; ACS Symposium Series No. 366; American Chemical Society: Washington, DC, 1988; pp 143−150.

(2) Yocklovich, S. G.; Levy, E. J.; Geiser, F. D.; Guthrie, J. W.; Lurcott, S. M. Supercritical Fluid Extraction and Chromatography of Pesticide. In *Supercritical Fluid Extraction and Chromatography*: *Techniques and Applications*; Charpentier, B. A., Sevenants, M. R., Eds.; ACS Symposium Series No. 366; American Chemical Society: Washington, DC, 1988; pp 162−169.

(3) DeRoos, F. L.; Bicking, M. K. L. Supercritical Fluid Extraction for the Determination of PCDDs and PCDFs in Soil. *Chemosphere* **1990**, *20*, 1355−1361.

(4) Ghonasgi, D.; Gupta, S.; Dooley, K. M.; Knopf, F. C. Supercritical CO_2 Extraction of Organic Contaminants from Aqueous Streams. *AIChE J.* **1991**, *37*, 944−950.

(5) Sahle-Demessie, E.; Yi, J. S.; Levien, K. L.; Morrell, J. J. Supercritical Carbon Dioxide Extraction of Pentachlorophenol from Pressure Treated Wood. *Sep. Sci. Technol.* **1997**, *32*, 1067−1085.

(6) King, J. W.; Zhang, Z. Y. Selective Extraction of Pesticides from Lipid-containing Matrix Using Supercritical Binary Gas Mixture. *Anal. Chem.* **1998**, *70*, 1431−1436.

(7) Yang, J. S.; Kim, D. W.; Kim, D. W.; Lee, D. H.; Chang, Y. S. Effect of solvent on extraction of polychlorinated biphenyls and polychlorinated dibenzodioxins from charcoal. *J. Liq. Chromatogr. Relat. Technol.* **2001**, *24*, 2293−2301.

(8) Akgerman, A.; Roop, R. K.; Hess, R. K.; Yeo, S. Supercritical Extraction in Environmental Control. In *Supercirtical Fluid Technology*: *Reviews in Modern Theory and Applications*; Bruno, T. J., Ely, J. F., Eds; CRC Press: Ann Arbor, MI, 1991.

(9) Sahle-Demesie, E.; Levein, K.; Morrell, J. J. Deposition of Chemicals in Porous Solids using Supercritical Fluid Carriers. *CHEMTECH* **1998**, *28* (3), 12−18.
(10) Bustami, R. T.; Chan, H. K.; Dehghani, F.; Foster, N. R. Generation of micro-particles of proteins for aerosol delivery using high-pressure modified carbon dioxide. *Pharm. Res.* **2000**, *17*, 1360−1366.
(11) Tsekhanskaya, Y. V.; Iomtev, M. B.; Mushkina, E. V. Solubility of Diphenylamine and Naphthalene in Carbon Dioxide Under Pressure. *Russ. J. Phys. Chem.* **1962**, *36*, 1177−1181.
(12) Diepen, E. A.; Scheffer, F. E. C. The Solubility of Naphthalene in Supercritical Ethylene. *J. Phys. Chem.* **1953**, *57*, 575−577.
(13) Van Leer, R.; Paulaitis, M. E. Solubility of Phenol and Chlorinated Phenols in Supercritical Carbon Dioxide. *J. Chem. Eng. Data* **1980**, *25*, 257−259.
(14) Stahl, E.; Schilz, W.; Schutz, E.; Willing, E. A. Quick Method for the Microanalytical Evaluation of the Dissolving Power of Supercritical Gases. *Angew. Chem., Int. Ed. Engl.* **1978**, *17*, 731−738.
(15) Dandge, D. K.; Heller, J. P.; Wilson, K. V. Structure Solubility Correlation: Organic compounds and Dense Carbon Dioxide Binary Systems. *Ind. Eng. Chem. Prod. Res. Dev.* **1985**, *24*, 162−166.
(16) Johnston, K. P.; Eckert, C. A. An Analytical Carnahan−Starling−van der Waals Model for Solubility of Hydrocarbon Solids in Supercritical Fluids. *AIChE J.* **1981**, *27*, 773−779.
(17) Kumar, S. K.; Johnston, K. P. Modeling Solubility of Solids in Supercritical Fluids with Density as an Independent Variable. *J. Supercrit. Fluids* **1988**, *1*, 15−22.
(18) Chrastil, J. Solubility of Solids and Liquids in Supercritical Gases. *J. Phys. Chem.* **1982**, *86*, 3016−3021.
(19) Gurdial, G. S.; Wells, P. A.; Foster, N. R.; Chaplin, R. P. The Role of Polarity on Correlations of Soild-Supercritical Fluid Phase Systems. *J. Supercrit. Fluids* **1989**, *2*, 85−96.
(20) Adachi, Y.; Lu, B. Supercritical Fluid Extraction with Carbon Dioxide and Ethylene. *Fluid Phase Equilib.* **1983**, *14*, 147−156.
(21) Sahle-Demessie, E. Deposition of Chemicals in Semi-porous Solids Using Supercritical Fluid Carriers. Ph.D. Dissertation, Oregon State University, Corvallis, OR, 1994.
(22) Gurdial, G. S.; Foster, N. R.; Yun, S. L. J.; Tilly, K. D. Phase Behavior of Supercritical Fluid-Entrainer Systems. *J. Am. Chem. Soc.* **1993**, *115*, 34−45.
(23) Hussien, A.; Levien, K. L.; Morrell, J. J. Phase Behavior of Binary and Ternary Mixtures of Wood Preservatives in Supercritical CO_2 with Cosolvent. ACS Symposium Series No. 608; American Chemical Society: Washington, DC, 1995; pp 402−414.
(24) Dobbs, J. M.; Wong, J. M.; Johnston, K. P. Nonpolar Cosolvents for Solubility Enhancement in Supercritical Fluid Carbon Dioxide. *J. Chem. Eng. Data* **1986**, *31*, 303−308.
(25) Ting, S. S. T.; Macnaughton, S. J.; Tomosko, D. L.; Foster, N. R. Solubility of Naproxen in Supercritical Carbon Dioxide with and without Cosolvents. *Ind. Eng. Chem. Res.* **1993**, *32*, 1471−1481.
(26) Kim, S.; Johnston, K. P. Clustering in Supercritical Fluid Mixtures. *AIChE J.* **1987**, *33*, 1603−1611.
(27) Kim, S.; Johnston, K. P. Molecular Interactions in Dilute Supercritical Fluids Mixtures. *Ind. Eng. Chem. Res.* **1987**, *26*, 1206−1213.
(28) Yunker, C. R.; Smith, R. D. Solvatochromic Behavior of Binary Supercritical Fluids: The Carbon Dioxide/2-Propanol Systems. *J. Phys. Chem.* **1988**, *92*, 2374−2378.
(29) Yunker, C. R.; Smith, R. D. Thermochromic Shifts in Supercritical Fluids. *J. Phys. Chem.* **1989**, *93*, 1261−1263.
(30) Knutson, B. L.; Tomasko, D. L.; Eckert, C. A.; Debenedetti, P. G.; Chialvo, A. A. Local Density Augmentation in Supercritical Solutions. In *Supercritical Fluid Technology*: *Theoretical and Applied Approaches to Analytical Chemistry*; ACS Symposium Series No. 488; American Chemical Society: Washington, DC, 1992; pp 60−72.
(31) Goldman, S.; Gray, C. G.; Li, W.; Tomberli, B.; Joslin, C. G. Predicting Solubilities in Supercritical Fluids. *J. Phys. Chem.* **1996**, *100*, 7246−7249.
(32) Bulgarevich, D. S.; Sako, T.; Sugeta, T.; Oteke, K.; Takebayashi, Y.; Kamizawa, C.; Horikawa, Y.; Kato, M. The Role of General and Hydrogen-Bonding Interactions in the Solvation Process of Organic Compounds by Supercritical CO_2/*n*-Alcohol Mixtures. *Ind. Eng. Chem. Res.* **2002**, *41*, 2074−2081.
(33) Van Alsten, J. G. Structural and Functional Effects in Solutions with Pure and Entrainer-Doped Supercritical Solvents. Ph.D. Thesis, University of Illinois at Urbana-Champaign, 1986.
(34) Bonilla, A.; Vassos, B. A Novel Approach for Dipole Moment Laboratory Experiments. *J. Chem. Educ.* **1977**, *54*, 130−131.
(35) Fulton, J. L.; Yee, G. G.; Smith, R. D. Hydrogen Bonding of Methyl Alcohol-*d* in Supercritical Carbon Dioxide and Supercritical Ethane Solutions. *J. Am. Chem. Soc.* **1991**, *113*, 8327−8334.
(36) Schmitt, W. J.; Reid, R. C. Solubility of Monofunctional Organic Solids in Chemically Diverse Supercritical Fluids. *J. Chem. Eng. Data* **1986**, *31*, 204−212.
(37) Joshi, D. K.; Prausnitz, D. K. Supercritical Fluid Extraction with Mixed Solvents. *AIChE J.* **1984**, *30*, 522−525.
(38) Fedros, R. F. A Method for Estimating Both the Solubility Parameters and Molar Volumes of Liquids. *Polym. Eng. Sci.* **1974**, *14*, 147−154.

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