

D-Pinitol Solubility in Supercritical CO₂: Experimental Data and Correlation

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Measurements of D-pinitol solubility in supercritical CO₂ in the temperature range (313 to 333) K and pressures ranging from 10 to 40 MPa are reported for the first time in this work. Two different thermodynamic models are applied to correlate the experimental D-pinitol solubilities: a cubic-type equation of state (the Soave–Redlich–Kong, SRK) and a model based on the group contribution approach (the Group Contribution Equation of State, GC-EoS). Both models demonstrate high capability to describe the solid–gas-phase equilibria of this system. In addition, values for the thermophysical properties, sublimation pressure, and solid molar volume of D-pinitol are also given.

Introduction

There is a growing interest in the use of D-pinitol (D-3-O-methyl-chiro-inositol) as a food supplement because of its reported effectiveness in lowering blood glucose levels^{1–6} and because of its additional effects such as a decrease of the cholesterol levels and cardiovascular risk factors⁷ and anti-inflammatory action.⁸

The importance of D-pinitol for human health and the increasing interest in drugs obtained from natural sources are an impetus for the extraction of this compound from vegetable raw materials. D-Pinitol can be found in several vegetable sources such as carob pods, soybean leaves, *Bougainvillea* flowers, etc., but its recovery, as well as the recovery of various other cyclitols from plants, is generally accomplished by laborious separation processes. For example, isolation of inositols and polyhydric alcohols has been attempted by partition chromatography with ion-exchange resins^{9–12} and by thin-layer chromatography. However, these processes produced low yields and recoveries and are very expensive. Thus, interest has been directed to implementing an alternative process to isolate D-pinitol from vegetable raw material such as supercritical fluid extraction (SFE), which is a green process with great potential. To design the SFE process, the solubility of the D-pinitol in the supercritical fluid phase must be known.

This paper is devoted to the experimental measurement and thermodynamic correlation of D-pinitol solubility in supercritical CO₂ (SC-CO₂), which, to the best of our knowledge, has not been reported in the literature till the present. Measurements were carried out in the temperature range (313 to 333) K and at pressures ranging from 10 to 40 MPa. Despite the five hydroxyl groups present in the chemical structure of this compound (see Figure 1), in the preliminary experiments that were carried out its solubility in a polar solvent (ethanol) was found to be so low that it either could not be measured or was within the experimental error. Thus, the possible addition of ethanol to CO₂ as a modifier was rejected.

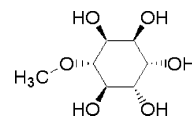


Figure 1. D-Pinitol chemical structure.

Two different thermodynamic models were applied to calculate the solubility of D-pinitol—the GC-EoS,¹³ with predictive and extrapolation potential, and the SRK-EoS,¹⁴ which demonstrates a high correlative capability. In addition, values for the thermophysical properties, sublimation pressure, and solid molar volume of D-pinitol are also given.

Experimental Section

Chemicals. D-Pinitol (> 99 mass %) was generously supplied by Carob General Applications (CGA). Water from Nanopure was used as a solvent to collect the extract. The reagents were used without further purification. High-purity CO₂ (more than 99.9 vol % purity, SFC grade) supplied by Air Liquide was used as received. Silica extra pure (more than 99.8 mass %) from Sigma Chemical Co. Inc. was utilized as a support of the products.

Equipment and Procedure. The solubilities were measured with an SFX 3560 extractor with two syringe pumps (model 260D) manufactured by ISCO (Lincoln, NE). With the proper plumbing, a two-pump system can deliver modified supercritical fluid or a continuous flow of supercritical fluid. The cylinder capacity of the pump is 266 mL, and a maximum pressure of 51 MPa can be attained. The temperature can range from (313.2 to 423.2) K, and supercritical fluid flow rate is between 0.5 and 5 mL·min⁻¹. A detailed description of the equipment was presented in a previous paper¹⁵ and will not be given here.

The extractor measured the amount of supercritical CO₂ used during the extraction. The flow rate of the supercritical fluid used for all experiments was 0.5 mL·min⁻¹, which ensured that saturation of the supercritical phase was achieved in a reasonable time. Water was used to trap the D-pinitol extracted. After that, the extract was transferred to 10 mL calibrated flasks and diluted with water. In some cases, a higher dilution might be necessary to achieve a concentration level adequate for determination by UV spectrometry. A detailed explanation of the experimental sample preparation is given elsewhere.^{15,16} A 8453 Hewlett-

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Table 1. D-Pinitol (1) Solubility in Pure Supercritical Carbon Dioxide (2) from $T = 313.15$ K to 333.15 K

p/MPa	$y_1 \cdot 10^5$		
	$T = 313.15$ K	$T = 323.15$ K	$T = 333.15$ K
10	1.190	0.835	0.565
20	15.200	3.080	1.080
30	44.400	7.910	4.560
40	83.200	19.300	9.390

Packard diode array UV–Vis spectrophotometer was used to determine the amount of D-pinitol in the extract, after calibration with gravimetrically prepared standard solutions.

Solubility is obtained as the value of the slope of the linear representation of the amount of D-pinitol extracted versus the amount of solvent used, on a molar basis, at different extraction times (five values at least). The uncertainty associated with D-pinitol solubility in pure SC-CO₂, expressed in absolute deviation of the mole fractions reported, varied within the following range $1.6 \cdot 10^{-5}$ for the highest to $4.7 \cdot 10^{-7}$ for the lowest measured solubility.

Results and Discussion

Experimental Solubility Data. The results of the solubility measurements obtained in this work are listed in Table 1. In the pressure and temperature ranges explored, as expected, D-pinitol solubility in SC-CO₂ increases with pressure and decreases with temperature.

Solubility Data Correlation. For solid–gas-phase equilibria, the general equilibrium relation is

$$f_s^{\text{solid}} = f_s^{\text{G}} \quad (1)$$

where the subscript s stands for the solid solute, f_s^{G} is the fugacity of component s in the gas (supercritical fluid phase), and f_s^{solid} is that in the solid phase.

The fugacity of the solute in the supercritical phase is

$$f_s^{\text{G}} = y_s P \varphi_s^{\text{G}} \quad (2)$$

where P is the pressure, φ_s^{G} is the fugacity coefficient, and y_s is the solubility (mole fraction) of the solute in the supercritical fluid. For phase equilibrium between a solid compound and a supercritical fluid, the following three assumptions can be introduced:¹⁷ (1) the solid solute remains pure since the size and the shape of solute and solvent molecules are ordinarily sufficiently different and hence solid solutions do not form; (2) the molar volume of the solid solute can be treated as a constant with respect to pressure; and (3) the saturated vapor of the pure solid solute at sublimation behaves as an ideal gas.

Since the solid phase is pure (assumption 1), the fugacity of the solute in the solid state is equal to the pure solid fugacity; hence, the following holds:

$$f_s^{\text{solid}} = P_s^{\text{sub}} \varphi_s^{\text{sub}} \exp \int_{P_s^{\text{sub}}}^P \frac{v_s^{\text{solid}} dP}{RT} \quad (3)$$

where P_s^{sub} is the sublimation (vapor) pressure of the pure solid, φ_s^{sub} is the fugacity coefficient at sublimation pressure, and v_s^{solid} is the molar volume of the solid, all at temperature T .

Then, applying assumption 2 and the thermodynamic equilibrium condition (eq 1), the mole fraction of the solid component in the supercritical phase can be expressed as

$$y_s = \frac{P_s^{\text{sub}}}{P} E \quad (4)$$

Table 2. D-Pinitol Physical Properties Estimated in This Work

physical property	
triple point pressure/MPa	$1.69 \cdot 10^{-6}$
sublimation enthalpy/ $\text{J} \cdot \text{mol}^{-1}$	91 408.69
critical temperature, T_c/K	856.78
critical pressure, P_c/MPa	3.81
acentric factor	0.772
solid volume, $v_s^{\text{solid}}/\text{m}^3 \cdot \text{mol}^{-1}$	$136.58 \cdot 10^{-6}$
sublimation pressure, $P_s^{\text{sub}}/\text{MPa}$	$2.97 \cdot 10^{-11}$ at $T = 313.15$ K
	$8.76 \cdot 10^{-11}$ at $T = 323.15$ K
	$2.10 \cdot 10^{-10}$ at $T = 333.15$ K

where

$$E \equiv \frac{\varphi_s^{\text{sub}} \exp \int_{P_s^{\text{sub}}}^P \frac{v_s^{\text{solid}} dP}{RT}}{\varphi_s^{\text{G}}} = \frac{\varphi_s^{\text{sub}} \exp \left[\frac{v_s^{\text{solid}} (P - P_s^{\text{sub}})}{RT} \right]}{\varphi_s^{\text{G}}} \quad (5)$$

In most practical cases, the P_s^{sub} value is quite small, and thus φ_s^{sub} is nearly equal to unity. The Poynting correction (exponential term in eq 5) is not negligible, but it generally accounts for an enhancement factor less than 2 or 3. However, the solute fugacity coefficient in the supercritical phase (φ_s^{G}) is significantly different from unity and can produce very large enhancement factors.

According to eqs 4 and 5, information about D-pinitol sublimation pressure and solid molar volume is required in order to calculate its solubility in SC-CO₂. Furthermore, a reliable thermodynamic model is necessary to evaluate φ_s^{G} , which in turn, requires information about pure solute physical properties such as critical temperature and pressure, acentric factor, etc.

For D-pinitol, as for a great majority of solid solutes extracted from vegetable material, there is a very limited amount of thermophysical properties data because they are usually not experimentally accessible. The only data available was D-pinitol melting temperature, namely, $T_m = 179$ – 185 °C (www.sigmaaldrich.com). Thus, the rest of the properties required had to be estimated. To do this, the algorithm discussed in detail in Fornari et al.¹⁸ was followed and hence herewith only a concise summary of the relevant steps is given:

- (i) The sublimation pressure was calculated from the Clapeyron equation, applying the data for the melting properties of D-pinitol, estimated in the present study (see Table 2).
- (ii) The solid volume was estimated applying the method proposed by Goodman et al.¹⁹
- (iii) The critical parameters and acentric factor were estimated applying the method of Cholakov et al.²⁰ and Wakeham et al.²¹

The values obtained for D-pinitol physical properties are shown in Table 2.

The calculation of D-pinitol fugacity coefficients (φ_s^{G}) was carried out by applying two different thermodynamic models: the Soave–Redlich–Kong (SRK) equation and the Group Contribution Equation of State (GC-EoS). The SRK-EoS with the one-fluid van der Waals mixing rules and the following combining rules for the cross-energy parameter:

$$a_{ij} = (a_{ii} a_{jj})^{0.5} (1 - k_{ij}) \quad (6)$$

was applied to correlate the experimental solubility data. The optimum values for the D-pinitol–CO₂ energy binary interaction

Table 3. Optimal SRK Binary Interaction Parameters between D-Pinitol and CO₂

T/K	binary interaction parameter (k_{ij})
313.15	-0.0547
323.15	-0.0498
333.15	-0.0408

parameters k_{ij} were determined for each temperature, applying a standard objective function:

$$F = \sum_{i=1}^{N_{\text{exp}}} \left| \frac{y_s^{\text{exp}} - y_s^{\text{cal}}}{y_s^{\text{exp}}} \right|_i \quad (7)$$

where N_{exp} is the number of data points for a given temperature. The respective k_{ij} values obtained are given in Table 3.

The SRK-EoS demonstrated good capability to correlate the experimental solubility data of D-pinitol in SC-CO₂ (see Figure 2). The usual approach is to compute the solid solubility by locating a mole fraction that satisfies the equi-fugacity criterion, which might lead to numerical pitfalls, as multiple solutions to the equi-fugacity condition could exist. The non-uniqueness is a particular problem, and special care should be taken to determine the correct solubility root. Thus, a stability analysis routine, based on a modified tangent-plane function and a phase identification procedure,²² was employed to determine all roots to the equi-fugacity condition.

The other thermodynamic model applied in this work is the GC-EoS. Pure group and binary interaction parameters for the

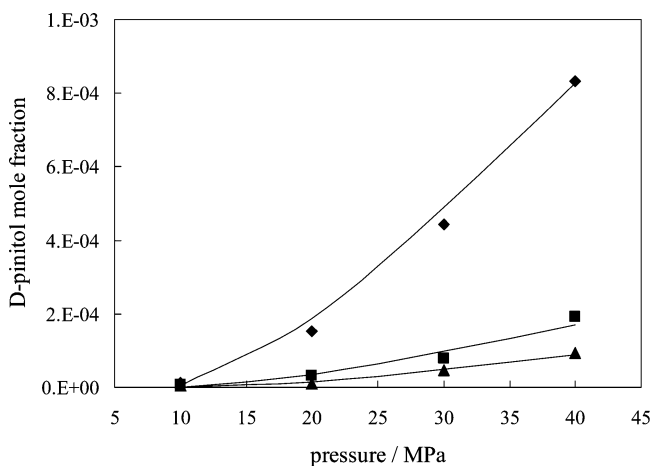


Figure 2. D-Pinitol solubility measured in this work: \blacklozenge , 313.15 K; \blacksquare , 323.15 K; \blacktriangle , 333.15 K; —, SRK-EoS correlation.

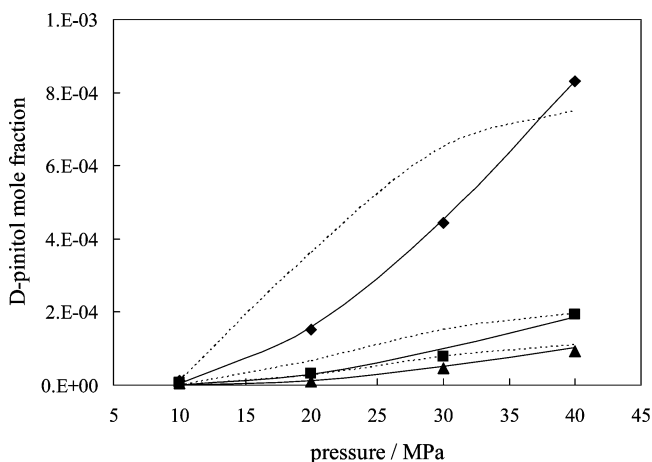


Figure 3. D-Pinitol solubility measured in this work: \blacklozenge , 313.15 K; \blacksquare , 323.15 K; \blacktriangle , 333.15 K; ---, GC-EoS prediction; —, GC-EoS correlation.

D-pinitol + CO₂ mixture constituent groups (ACOH, ACOCH₃, and CO₂) were obtained from the literature.^{23–24} Particularly, the ACOH–CO₂ interaction parameters²⁵ ($k_{ij} = 1.094$ and non-randomness parameters, α_{ij} and α_{ji} , equal to zero) were obtained by fitting experimental vapor–liquid equilibria of the phenol + CO₂ mixture for $T = (348 \text{ to } 423)$ K and pressures up to 5 MPa (i.e., out of the experimental conditions where D-pinitol solubilities were measured). Nevertheless, the GC-EoS solubility predictions are quite reasonable (see Figure 3).

New interaction parameters between the ACOH group and CO₂ ($k_{ij} = 0.927$, $\alpha_{ij} = -0.184$, and $\alpha_{ji} = 0.925$), using eq 7 as an objective function, have lead straightforward to a high quantitative correlation of the experimental data as can be observed in Figure 3.

Conclusions

The solubility of solid D-pinitol in pure SC-CO₂, in the typical temperature and pressure ranges for a supercritical extraction process, is reported for the first time in the present study.

Two different thermodynamic models were applied to correlate the experimental solubility data: the group contribution model GC-EoS and the cubic-type SRK-EoS. Both models were able to correlate the experimental data, but the GC-EoS model demonstrated predictive capability as well. Additionally, estimated values for D-pinitol pure component parameters (such as sublimation pressure, solid volume, critical parameters, and acentric factor) are also given.

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