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Comparison and modelling of rutin solubility in supercritical carbon dioxide and subcritical 1,1,1,2-tetrafluoroethane

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ABSTRACT

Rutin is a common dietary flavonoid that has been widely consumed in pharmaceutical industry. To facilitate the extraction of rutin from plant tissues, we determined the solubility of rutin in supercritical carbon dioxide by dynamic method at 313.2–343.2 K over the pressures range of 9.0–18.0 MPa and in subcritical 1,1,1,2-tetrafluoroethane (R134a) by static method at 313.2–343.2 K over the pressures rang of 7.0–18.0 MPa. The experimental results indicate that the extraction of rutin should be operated by subcritical R134a or supercritical CO$_2$ below or above the transition pressure (the pressure at which the rutin solubilities in subcritical R134a and supercritical CO$_2$ are the same), respectively. Furthermore, the solubility data were satisfactorily correlated by Chrastil model and m-ER & HV model (modified Esmaeilzadeh–Roshanfekr equation of state combined with Huron–Vidal mixing rule), and the thermodynamic consistency of the solubility data was confirmed by the thermodynamic consistency test.

1. Introduction

In recent decades, the plant-derived drugs have increasingly been receiving public interest [1]. Rutin belongs to a kind of flavone glycoside, which is also known as vitamin P. Attributed to the potent antioxidant property, rutin is reported to have pharmacological activities such as anti-inflammation, anti-microbial, anti-tumor and anti-asthma [2–4]. As an important flavonoid in pharmaceutical industry, the demand for natural rutin is in increasing trend [1], so it is crucial to extract them from plant tissues.

Heat reflux extraction is a conventional organic solvent extraction method containing steps of heating, boiling and refluxing [5]. Since the instrumentation required is simple and easy to operate, it is widely used for extraction of plant materials [1]. However, these procedures have distinct drawbacks. First, they are time consuming. For example, the extraction of pharmacologically active compounds from *Salvia officinalis* by conventional methods usually takes between 1 and 2 weeks [6]. Second, the ionization, hydrolysis and oxidation during extraction can result in the loss and degradation of target products [7,8]. Last, they require a large amount of hazardous organic solvents, which may exacerbate the environmental burden.

As an alternative to the traditional extraction by organic solvents, supercritical fluids exhibit particular properties that are suitable for extraction of active compounds from herbs and other plants [9,10]. They have gas like transport properties, such as relatively low viscosity and high diffusivity, and liquid like dissolving capabilities. In supercritical fluid extraction (SFE), quantitative or complete extraction can be obtained by forcing the fresh fluid to flow through the matrices [11]. Moreover, owing to the huge density fluctuation near critical state, the solvation power is tunable, thus enables the selective extraction of desired products by manipulating the operation temperature and pressure [12]. Most importantly, solutes dissolved can be easily separated from solvents by depressurization, and solvents can be recycled or reused to minimize pollution, thus SFE is environmental friendly. Therefore, there is no solvent residue and needs no extra separation or disposal costs. Among all kinds of supercritical fluids, supercritical carbon dioxide (SCCO$_2$) is the most popular one and has been widely used in SFE [13–15] because of the mild critical state (T_c = 304.1 K, P_c = 7.38 MPa), nonflammable, non-explosive, non-toxic and inexpensive properties. However, SCCO$_2$ is not so powerful in dissolving polar solutes due to its non-polarity. To overcome this deficiency, many researchers have focused on the alternative polar solvent 1,1,1,2-tetrafluoroethane (R134a) [16–18]. R134a has zero ozone depletion potential and a slight global warming capability. Moreover, the critical pressure of R134a is 4.06 MPa, which is much lower than that of SCCO$_2$, so it is thought to have better dissolving capacity at low pressure.

Solubility is the key property for the design and optimization of extraction processes and the evaluation of the feasibility of SCCO$_2$ and subcritical R134a to replace organic solvents in traditional extraction [18–20]. To our best knowledge, the solubility of rutin in SCCO$_2$ and

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Nomenclature

A, B, C	Parameters of equation of state [–]
$AARD$	Average absolute relative deviation [%]
A_P, A_φ	Integral area [–]
ΔA	Integral area deviation [–]
E_A	Threshold of integral area deviation [%]
E_y	Absolute relative deviation of solubility [%]
ΔH	Enthalpy change [J mol^{-1}]
k_1, k_2, k_3	Adjustable parameters [–]
K	Equilibrium constant [–]
M	Molecular weight [g mol^{-1}]
n	Number of moles [mol]
P	Pressure [MPa]
R	Universal gas constant [8.314 J mol^{-1} K^{-1}]
S	Mass solubility [g L^{-1}]
T	Temperature [K]
v	Molar volume [cm^3 mol^{-1}]
V_t	Total volume of the system [cm^3]
y	Mole fraction solubility [–]
Z	Compressibility factor [–]

Greek letters

ε, σ	Constants in equation of state
φ	Fugacity coefficient [–]
ρ	Density [g L^{-1}]

Subscripts

1	Solvent
2	Solute
A	Solute
B	Solvent
i	the ith data point

Superscripts

c	Critical
cal	Calculated solubility
exp	Experimental solubility
s	Solute
sol	Solvation
sub	Sublimation
sup	Super- or subcritical state
vap	Vaporization

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subcritical R134a has not been reported in the literature so far. Hence, this work aimed to determine the solubility of rutin in both SCCO$_2$ and subcritical R134a, assess the solvating capability of the two fluids, and propose the optimal extraction conditions. Furthermore, the solubility data were correlated by Chrastil model [21] and m-ER & HV model (modified Esmaeilzadeh–Roshanfekr equation of state [22] combined with Huron–Vidal mixing rule [23] [24]) and then tested with thermodynamic consistency criteria.

2. Experiment section

2.1. Materials

CO$_2$ (mass purity ≥ 99.9%), R134 (mass purity ≥ 99.9%), and anhydrous ethanol (mass purity ≥ 99.7%) were obtained from Beijing Praxair Industrial Gas Co., Ltd., DuPont Company, and Beijing Chemical Reagent Factory, respectively. The detailed information about rutin is listed in Table 1. All the chemicals were used without further purification.

2.2. Apparatus and procedure for SCCO$_2$ system

The solubility of rutin in SCCO$_2$ was measured by dynamic method, and the schematic diagram of the apparatus is shown in Fig. 1(a). The CO$_2$ from cylinder was pressurized by the compressor and firstly transported into preheating and mixing cell, where CO$_2$ was pre-heated. Then CO$_2$ was transported into the high-pressure cell to fully contact with rutin and reached equilibrium. At last, the mixture was released via the decompression sampling valve, and rutin was collected by two U-shaped tubes. The volume of CO$_2$ consumed in the single measurement was recorded by the wet-gas flow meter. A detailed description of the apparatus and procedures has been described in our previous work [25,26]. For each experiment, about 6 g of rutin was loaded into the 150 mL high-pressure equilibrium cell.
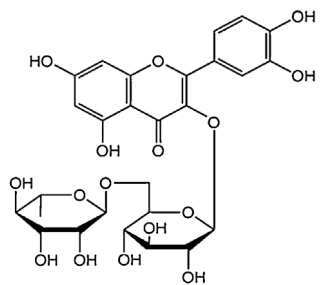
Before we set about measuring the solubility, pre-experiments of determination of CO$_2$ flow rate and equilibrium time need to be done to ensure the experimental reliability. The solubility variation with CO$_2$ flow rate (measured at ambient condition) is depicted in Fig. 2(a). We

can see that there is a platform when CO$_2$ flow rate is between 0.15 and 0.3 L/min; however, when the curve passes through the platform, the measured solubility data decrease with CO$_2$ flow rate. Hence, the CO$_2$ flow rate was set to be 0.25 L/min. On the other hand, the solubility variation with equilibrium time is shown in Fig. 2(b). It can be seen that when the equilibrium time is above 50 min, the solubility remains unchanged, which indicates that the equilibrium is reached. Taking the efficiency into consideration, the equilibrium time was set as 60 min.

2.3. Apparatus and procedure for subcritical R134a system

The schematic of the static method apparatus is shown in Fig. 1(b). The major part of the experimental procedures is similar to the dynamic method, including pressurization, achievement of the equilibrium by contacting, separation of the solute and solvent by the decompression

Table 1
The detailed information of solute.

Compound	Rutin
Chemical structure	
Formula	C$_{27}$H$_{30}$O$_{16}$
Mass purity	≥98.0%[a]
T_m (K)	450.2[b]
ΔH_m (kJ mol^{-1})	82.3[b]
v^s (cm^3 mol^{-1})	334.1[a]
Supplier	Beijing HWRK Chem. Co., Ltd.

[a] Provided by the supplier.
[b] Experimental values taken from NIST.