Supercritical Fluid Extraction of Nutraceuticals and Bioactive Compounds

Edited by

Jose L. Martínez

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Supercritical Fluid Extraction of Nutraceuticals and Bioactive Compounds

Dedication

To Marlene and Alejandro

Preface

In the last decade new trends in the food industry have emerged, enhanced concern over the quality and safety of food products, increased preference for natural products, and stricter regulations related to the residual levels of solvents. Additionally, the nutraceutical and functional food sector represents one of the fastest growing areas in a consumer-driven trend market. These trends have driven supercritical fluid (SCF) technology to be a primary alternative to traditional solvents for extraction, fractionation, and isolation of active ingredients. The aim of this book is to present the current state of the art in extracting and fractionating bioactive ingredients by SCFs.

This book contains twelve chapters that primarily focus on implemented industrial processes and trends of the technology. The content of the chapters includes a review of the major active components in the target material, including chemical, physical, nutritional, and pharmaceutical properties; an analysis of the specific SCF process used; a comparison of traditional processing methods versus SCF technology; and a set of conclusions with supporting data and insight. A review of the fundamentals of the technology and an examination of SCF extraction systems and process economics are also included.

The contributing authors are international experts on the topics covered, and I would like to thank them for their thoughtful and well-written contributions. This book is addressed to food scientists, technologists, and engineers as well as other professionals interested in the nutraceutical and functional food sector. Additionally, I hope that this book will serve to stimulate academia and industry to search for new process and product developments as well as their industrial implementation.

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1 Fundamentals of Supercritical Fluid Technology

Selva Pereda, Susana B. Bottini, and Esteban A. Brignole

CONTENTS

1.1 INTRODUCTION

Solvents are used in large amounts in the chemical, pharmaceutical, food, and natural-product industries. In the search for environmentally friendly solvents, increasing attention is being paid to supercritical fluids (SCFs) for a wide variety of applications. For instance, supercritical solvents are used in extractions, material processing, micronization, chemical reactions, cleaning, and drying, among other applications. SCFs and near-critical fluids add a new dimension to conventional (liquid) solvents: *their density-dependent solvent power.* The density of SCFs can be easily tuned to the process needs, with changes in temperature, pressure, and/or composition. Other important properties of SCFs are their very low surface tensions, low viscosities, and moderately high diffusion coefficients.

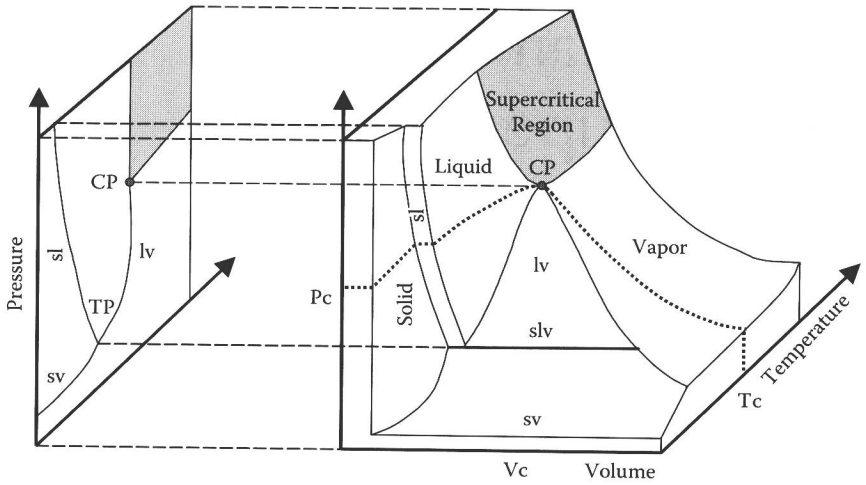

FIGURE 1.1 PVT diagram of a pure substance and its projection on the PT plane.

The design of processes using supercritical solvents is strongly dependent on the phase equilibrium scenario, which is highly sensitive to changes in operating conditions. Therefore, phase equilibrium engineering plays a key role in the synthesis and design of these processes.

1.2 SUPERCRITICAL FLUIDS

The different physical states of a pure substance can be visualized in a three-dimensional pressure–volume–temperature (PVT) diagram, as shown in Figure 1.1. The surfaces represent the different states—solid, liquid, or vapor—that correspond to particular values of pressure and temperature. According to the phase rule, the two-phase (solid–liquid, solid–vapor, and liquid–vapor) regions of a pure substance have only one degree of freedom. Therefore, the equilibrium pressure in each case is a function of temperature. The PT projections of the solid–liquid, solid–vapor, and liquid–vapor equilibrium lines are shown on the left of Figure 1.1. In particular, the vapor–liquid line represents the vapor pressure curve that starts at the triple point (TP) of solid–liquid–vapor coexistence and ends at the critical point (CP). The nature of the CP can be understood following the changes of the fluid properties along the vapor pressure curve. With increasing values of temperature, the density of the liquid phase diminishes and the vapor density increases due to the higher vapor pressure. Eventually, both densities converge at the CP and differentiating the liquid or the vapor state is no longer possible above the critical temperature. When both temperature and pressure are above the critical values (Figure 1.1), the system is considered to be in the supercritical region.

Within a region close to the critical conditions, the system properties are highly sensitive to pressure and temperature; this region is considered near-critical. Usually, the SCF solvent is applied at a temperature close to its critical value and at a pressure high enough for its density to become greater than the fluid critical density. A

TABLE 1.1
Critical Properties of Fluids of Interest in Supercritical Processes

Fluid	Critical Temperature Tc/K	Critical Pressure Pc/bar	Critical Volume Vc/cm^3·mol^{-1}
CO_2	304.12	73.7	94.07
Ethane	305.3	48.7	145.5
Propane	369.8	42.5	200.0
Water	647.1	220.6	55.95
Ammonia	405.4	113.5	72.47
n-Hexane	507.5	30.2	368.0
Methanol	512.6	80.9	118.0

list of fluids that have been proposed as SCF solvents is shown in Table 1.1. These fluids can be classified as a) low-critical temperature (low-Tc) and b) high-critical temperature (high-Tc) solvents. Some condensable gases, like carbon dioxide (CO_2), ethane, and propane, are considered low-Tc solvents, whereas the higher alkanes, methanol, and water can be considered high-Tc solvents. Strong differences in solvent power and selectivity characterize the low-Tc and high-Tc solvents.

Francis [1] made a significant contribution on the subject of CO_2 solvent properties by studying its behavior with a large number of solutes. Liquid CO_2 is miscible with alkanes up to approximately carbon number 10, while the range of miscibility increases for ethane up to 20, and propane up to 35. Therefore, these solvents show selectivity for relatively low-molecular-weight material. Stahl and Quirin [2] have reported the extractability of a wide range of natural products using CO_2; they showed that: "1) hydrocarbons and other lipophilic organic compounds of relatively low molecular mass and polarity are easily extractable; 2) the introduction of polar functional groups, hydroxyl or carboxyl groups render the extraction more difficult or impossible; 3) sugars and amino acids cannot be extracted; 4) fractionation effects are possible if there are marked differences in mass, vapor pressure or polarity of the constituents of a mixture."

Regarding the use of high-Tc solvents, such as toluene or water, the extraction is carried out at temperatures from 500 to 700 K, where even a mild pyrolysis of high-molecular-weight material takes place. The solvent power of high-Tc fluids is much higher than that of low-Tc solvents, and high-Tc solvents are proper solvents for high molecular weight materials. However, they have low selectivity and the severe operating conditions, on the other hand, degrade thermally labile materials. A good feature of low-Tc solvents, as compared with conventional liquid solvents, is that they operate at moderate temperature and have low solvent power. Therefore, by carefully choosing the pressure and temperature of operation, selective fractions can be extracted from vegetable matrices, such as essential oils, alkaloids, lipids, or oleoresins. These are the preferred solvents for the pharmaceutical and natural-product industries. A key advantage of low-Tc solvents is that they are easily separated from the extract.

TABLE 1.2
Comparison of the Physical Properties of Gas, Liquid, and Supercritical Fluids

Physical Property	Gas ($T_{ambient}$)	SCF (Tc, Pc)	Liquid ($T_{ambient}$)
Density ρ (kg m^{-3})	0.6–2	200–500	600–1600
Dynamic viscosity μ (mPa.s)	0.01–0.3	0.01–0.03	0.2–3
Kinematic viscosity η[a] (10^6 m^2s^{-1})	5–500	0.2–0.1	0.1–5
Thermal conductivity λ (W/mK)	0.01–0.025	Maximum[b]	0.1–0.2
Diffusion coefficient D (10^6 m^2s^{-1})	10–40	0.07	0.0002–0.002
Surface tension σ (dyn/cm^2)	—	—	20–40

[a] Kinematic viscosity defined as $\eta = \mu/\rho$

[b] Thermal conductivity presents maximum values in the near-critical region, highly dependent on temperature

SCF-solute interactions in the liquid phase may originate a second liquid phase (gas salting out effect), improving process selectivity and making it possible, for instance, to separate chemical reaction products in situ [3]. A better understanding of supercritical solvent properties will be obtained after considering the phase equilibrium behavior of binary systems that show a different degree of asymmetry in size or intermolecular interactions.

1.2.1 Physical Properties of Supercritical Fluids

The physical properties of SCFs are in-between those of a gaseous and liquid states. Typical values of different physical properties for each fluid state are listed in Table 1.2.

Density and viscosity of SCFs are lower than those of liquids; however, diffusivities are higher. Thermal conductivities are relatively high in the supercritical state and have very large values near the CP because, in principle, the heat capacity of a fluid tends to infinity at the CP. Interfacial tension is close to zero in the critical region. In general, the physical properties in the critical region enhance mass and heat transfer processes.

1.3 PHASE EQUILIBRIUM WITH SUPERCRITICAL FLUIDS

1.3.1 Solid Solubilities

The conditions of phase equilibrium between a SCF (1) and a solid component (2) are formulated on the basis of the isofugacity criterion. If the solid phase is assumed to be a pure component (2), the solubility in the gas phase can be directly obtained as:

$$y_2 = E\frac{p_2^s}{P} \tag{1.1}$$

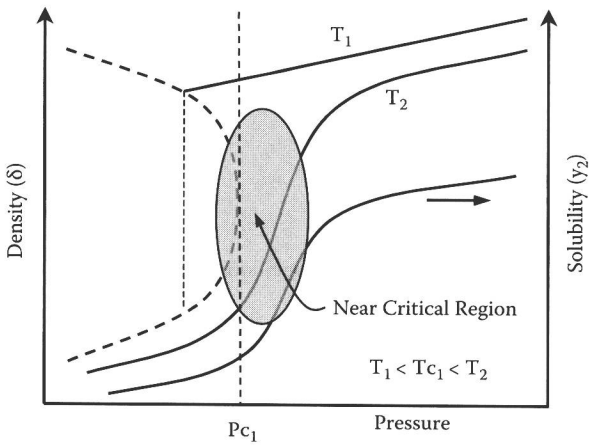

FIGURE 1.2 Density (δ) and solid solubility in fluid phase (y_2) as a function of pressure.

where E is the enhancement factor over the ideal solubility and p_2^s is the sublimation pressure of the solute (2). For a low-volatility, incompressible solid solute, the enhancement factor can be calculated as follows:

$$E = \frac{\exp\left(\dfrac{(P - p_2^S)v_2^{sol}}{RT}\right)}{\Phi_2} \tag{1.2}$$

where Φ_2 is the fugacity coefficient of the solid solute in the gas phase and v_2^{sol} is the solid molar volume. Φ_2 is strongly dependent on the SCF density. Figure 1.2 shows the region of SCF extraction. This region is characterized by a strong variation of fluid density with pressure, at temperatures close to the SCF critical temperature. For a given isotherm, the increase in solubility closely follows the increase in density, as indicated in Figure 1.2. The drastic increase in solubility in the vicinity of the critical region can be of several orders of magnitude and is mainly due to a sharp decrease of the solute fugacity coefficient Φ_2 in the fluid phase. This is the classical enhancement effect at the near-critical region.

The influence of temperature on the solid solubility is the result of two competing effects: the increase of solid volatility and the decrease of solvent density with temperature rise. Near the critical pressure, the effect of fluid density is predominant. Therefore, a moderate increase in temperature leads to a large decrease in fluid density and a consequent reduction in solute solubility. However, at higher pressures, the increase of solid sublimation pressure with temperature exceeds the density reduction effect, and the solubility increases with temperature. This behavior leads to a region of retrograde behavior of the solid solubility, as illustrated in Figure 1.3. At pressures well above the SCF critical pressure, the isotherms exhibit a maximum in solubility. This maximum is usually observed in the range of 30 to 100 MPa.