
“AN OVERVIEW ON SUPERCRITICAL FLUID EXTRACTION FOR HERBAL DRUGS”

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Summary

A wide range of technologies are available for the extraction of active components and essential oils from the medicinal and aromatic plants. The choice of appropriate technique is depends on the economic feasibility and suitability of the process to the particular situation. The supercritical fluid extraction processes for production of medicinal, aromatic plants extracts and essential oils are tried to review in this article. The main issues related to supercritical fluid extraction of medicinal and aromatic plants is discussed in view of the development of this separation technique at industrial scale. After an introduction to supercritical fluid extraction, the roles of thermodynamics and mass transfer properties are emphasized, and the effects of the main operating variables on product recovery are briefly examined. Fundamental concepts about the equipment needed and basic technology are presented, including economical evaluation. Finally, a short survey of successful supercritical extraction processes of medicinal and aromatic plants is reported and a future outlook is given with few important and latest application, advantages and the disadvantages of the supercritical fluid extraction.

Key words: Extraction, Supercritical fluid, Herbal Drugs, CO₂, Phase diagram, Extractor, Separator, aromatic plant extract etc.

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1.0 Introduction To Supercritical Fluid Extraction

In the second half of last century, an increasing interest has been paid to supercritical fluids as alternate solvents for the extraction of natural bioactive molecules from plants. The main reason for the interest in supercritical fluid extraction (SFE) was the possibility of carrying out extractions at temperature near to ambient, thus preventing the substance of interest from incurring in thermal denaturation. A thorough review of the results achieved up to the early 1980s is presented in a book by Stahl *et al.*, published in 1986. Clearly, by that time, the fundamentals of this new extraction process were already understood, even though the technical-economical assessment and the design criteria for large-scale application of SFE were still missing. After twenty years of research and development, it is now possible to say that such achievements are at hand, so SFE is currently a well-established unit operation for extraction and separation. Moreover, its design and operating criteria are fully understood, so that it can profitably be applied in the extraction of medicinal and aromatic plants (MAPs).

1.1 Supercritical Fluids:-

A fluid at supercritical condition, also referred to as a dense gas, is a fluid above its critical temperature (T_C) and critical pressure (P_C) to a certain extent: to be supercritical, the reduced temperature Tr (i.e. T/T_C) must not exceed 1.2 or 1.3, whereas the reduced pressure Pr (i.e. P/P_C) may be as high as allowed by technological limits. At suitable conditions, any fluid can reach its supercritical state. However, only those having a critical temperature not far from ambient temperature can be used as alternative solvents for the extraction of MAPs. Carbon dioxide (CO_2), with $T_C=31.06^\circ C$ and $P_C=73.81$ bar, is the most attractive solvent, because of its properties regarding toxicity, flammability and cost. The possibility of using supercritical fluids (SFs) as extraction solvents is directly linked to their density. In fact, according to an empirical correlation proposed by Chrastil in 1982,

$$s = \rho^a \exp \left(\frac{b}{T} + c \right) \quad (1)$$

Where, s is the solute solubility, ρ is the solvent density and T is the absolute temperature; a , b and c are correlation parameters to be adjusted to experimental solubility data in supercritical CO_2 .

When a fluid approaches the critical conditions, its density gets closer and closer to that of the liquid state. This can be seen, for CO_2 , in Figure 3, where density isotherms are plotted against the reduced pressure. For example, at $T = 35^\circ C$ and $P = 200$ bar, $\rho = 866$ kg/m³.

It is also clear from Figure 3 that, close to the critical point, both the compressibility and expansion coefficient of the fluid are high, so slight changes in the operating conditions can significantly modify the density, i.e. the supercritical fluid solvent power. The importance of the Chrastil equation (Eq. 1) lies in the fact that solvent density is identified as the key factor in a successful SFE process.

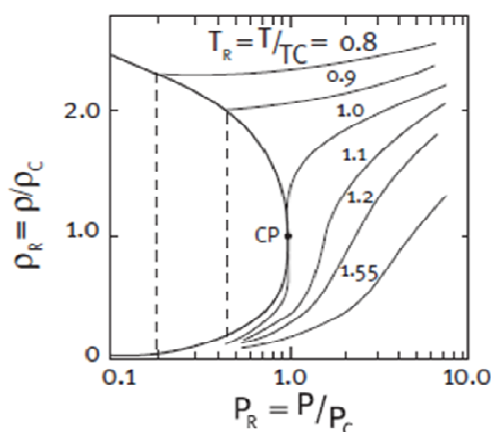


Fig. (1)-Density vs. pressure diagram for carbon dioxide

When plotted against solvent density, solubility data for supercritical CO₂ always display a regular trend such as that in Figure 4a, whereas a more complex behavior is seen when pressure is improperly used as the independent process variable (Figure 4b).

Coming back to Eq. 1, is important to point out that it is not theoretically correct and must be applied within restricted temperature ranges only.

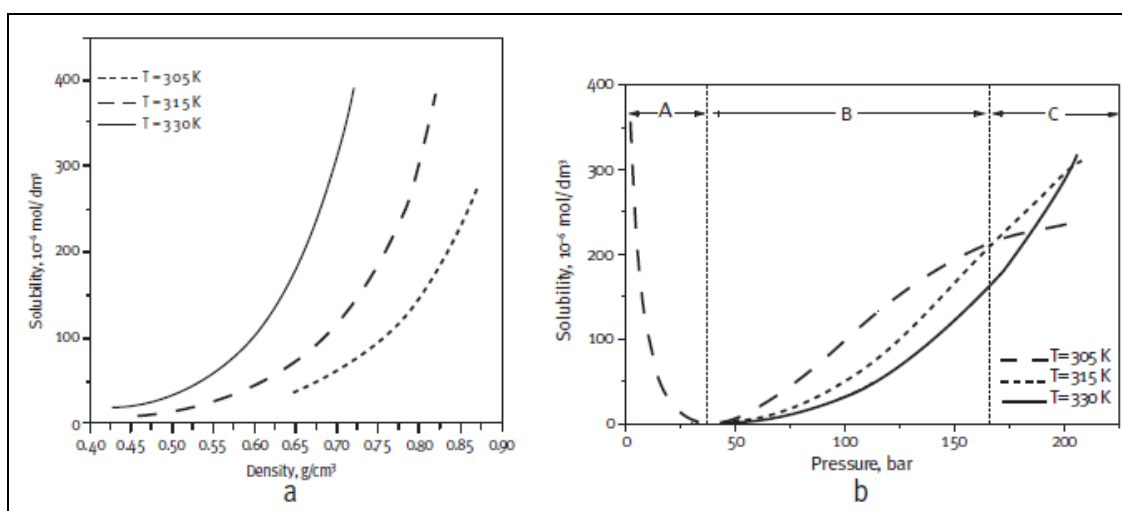


Fig. (2) Solubility of 1, 4-bis-(n-propylamino)-9,10-anthraquinone in supercritical CO₂: as a function of solvent density (4a) and of pressure (4b)

More importantly, the exponential form of Eq. 1 does not guarantee that the solubility of a solute in SF is high. The solubility depends on parameters a , b and c ; in fact, in the case of CO₂, the solubility of a solute of interest for MAP applications is at best in the range of 1 to 1000 by weight or often 1 to 10,000 (Figure 4a illustrates this). This is because CO₂ is a poor solvent, even at supercritical conditions. In addition, this holds for non-polar substances only, as supercritical CO₂ does not dissolve polar molecules at all. Actually, CO₂ is a good solvent only for low molecular weight solutes.

The limit on solubility is dictated by thermodynamics. According to the iso-fugacity criterion applied to the substance to be extracted, between the two phases at equilibrium (the condensed one – either solid or liquid – and the supercritical one), we have:

$$y_i = \frac{P^{sat}}{P} E_i \quad (2)$$

$$E_i = \frac{\Phi_i^{o,v}}{\Phi_i^v} \exp\left(v^{s/L} \frac{P - P^{sat}}{RT}\right) \quad (3)$$

Where, y_i is the mole fraction of i in the supercritical phase, $\Phi_i^{o,v}$ and Φ_i^v are the fugacity coefficients of i in the standard state and in the mixture, respectively, at the process conditions, P^{sat} is the solute saturation (or sublimation) partial pressure (i.e. the component volatility), and $v^{s/L}$ is the molar volume of the condensed phase (either solid or liquid). T is the absolute temperature and R is the universal gas constant. E_i is the so-called enhancement factor, which accounts for the increasing solubility due to system non-idealities with respect of the ideal behavior (given by Eq.2).

According to Eq. 2, the solubility of i in the SF can be calculated at the process condition, provided that the fugacity coefficients Φ_i can be evaluated accurately by means of an equation of state. However, the substance vapor pressure directly influences the solubility when P^{sat} is as usual for MAPs, very low. Only an equally low value of the fugacity coefficient, i.e. a high system non-ideality, can partially counteract the lack of volatility of the pure component.

Regardless of the way its value has been obtained, i.e. from Eq. 1 or Eqs. 2-3, the solubility is only one of two fundamental pieces of information that must be known in order to assess the feasibility of an SFE process for MAPs. The second one is selectivity, which is defined as the ratio of the solubility of the substance i of interest with respect to a reference substance j :

$$\alpha_{ij} = \frac{S_i}{S_j} \quad (4)$$

If on one hand high solubility is desirable, to reduce the solvent consumption per unit product extracted, on the other hand selectivity must be as far as possible from 1, to ensure that the substance of interest is extracted as pure rather than in mixture with other components. In summary, to develop a successful SFE process for MAPs, both solubility and selectivity issues must be fulfilled properly.

Coming back to CO_2 , it must be kept in mind that this solvent is rather non-selective: when it is able to dissolve a group of similar substances (for example, in terms of carbon atoms), all of them are extracted to a similar extent, provided they have similar polarities.

Therefore, it can be stated that CO_2 alone is not as selective as a good and pure solvent. It is also noteworthy that CO_2 capacity and selectivity may be improved by using an organic solvent as the entrainer, also called the co-solvent, with the function of modifying chemical interactions between CO_2 and the substance to be dissolved in it.

But by doing this, the SFE process becomes more complicated, as an extra chemical component needs to be introduced into the process. However, the co-solvent can be easily separated from the product downstream, due to the high selectivity displayed by supercritical CO_2 in this respect.

2.0 Supercritical Fluid Extraction process

2.1 SFE Processes:-

An SFE process for extracting MAPs is basically composed of two main sections (Figure 5a). The feed, containing the substance of interest, indicated by A, comes in contact with supercritical CO_2 , at suitable temperature and pressure, in an extraction device. In this simple scheme, component A is selectively extracted and must be recovered from the supercritical solution, which is usually a dilute one for the reason explained in the previous section. Product recovery occurs in the separation

section, whose temperature and pressure can be adjusted in order to optimize the amount of A produced.

Note that, due to the low solubility in supercritical CO₂, after recovery of the product of interest the solvent must be recycled and pumped back to the extractor, in order to minimize operating costs. It is also noteworthy that the separator can be operated either at the same temperature or at the same pressure of the extractor, the best condition resulting from an economical analysis of the overall production costs.

If the temperature is kept constant, product separation is achieved by depressurization (Figure 5a), and mechanical energy has to be provided to the system to raise the CO₂ pressure from the separator to the extractor conditions. On the other hand, extracted products can be separated from CO₂ by increasing the temperature, and thermal energy must be supplied in this case (Figure 5b), where the circulation of the solvent can be done at nearly isobaric conditions. Of course, the way the separation of products from CO₂ is achieved can be more complex: for instance, both temperature and pressure can be varied when passing from the extractor to the separator sectors, or a solid can be used to promote separation by adsorption.

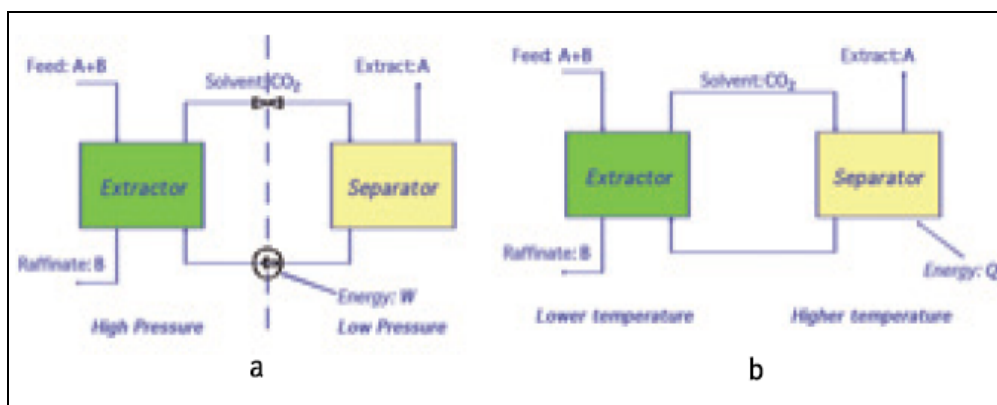


Fig. (5): Block flow diagrams of simple SFE processes: with separation obtained by pressure change (a) and by temperature change (b)

If, as it often occurs, many substances are extracted by CO₂ at the extraction conditions because of lower CO₂ selectivity, their fractionation can also be achieved in the separation section, by simply using more than one separator, operated at different conditions. As shown in Figure 6, multiple fractions with different properties can be recovered from the same extraction.

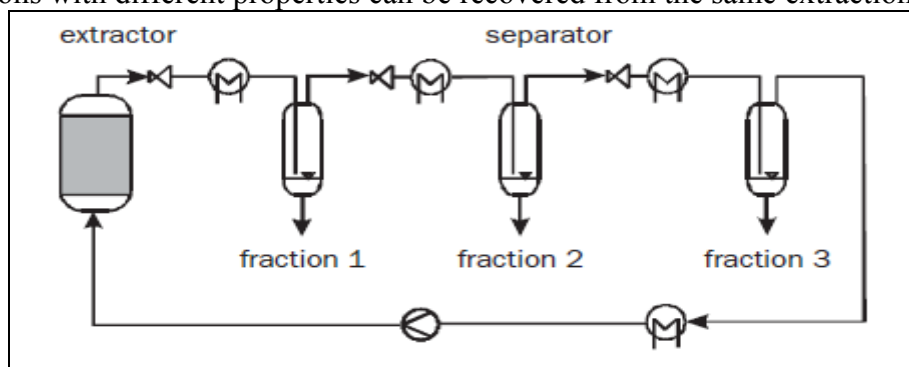


Fig.(6): Single extractor, multiple separator scheme

Finally, a multiple extractor scheme can also be envisaged, as represented in Figure 5 with only one separation step, for sake of clarity. This configuration is particularly useful when, as in the case of SFE of MAPs, the substances to be extracted are embedded in a solid matrix, which is initially loaded in the extraction vessel as a fixed bed. In this case, the extractors can be connected either in parallel or in series, depending on specific requirements.

More details on the development of SFE processes are provided in a book by Brunner listed in the bibliography. SFE of solids is a semibatch operation, which can also be operated in a simulated moving bed configuration to obtain a continuous production.

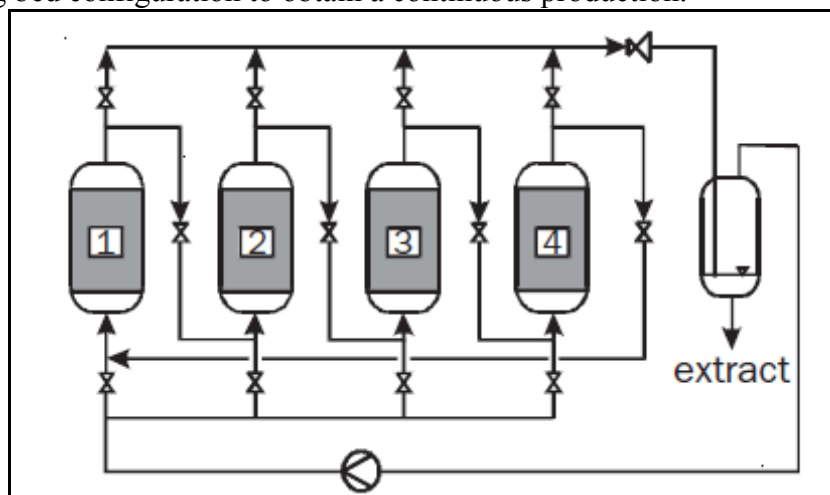


Fig.(7): Multiple extractor, single separator scheme

Typical extraction profiles from solid materials (single vessel) are shown in Figure 8 where the extractor yield, i.e. the amount of substance of interest extracted with respect to the total amount initially contained in the solid, is plotted against extraction time. The profiles, which are steeper if the temperature is higher, have two parts: a straight line corresponding to the extraction of the substance “readily available” to supercritical CO₂, and an asymptotic curve representing the extraction of the part attached to the solid matrix. In the first case, the extraction is limited by solubility; in the second, mass transport (diffusion) properties are important and can be limiting and crucial for the success of SFE.

The effects of operating temperature are also clear in Figure 8. Other important operating variables are pressure, CO₂ flow rate and humidity of the material to be extracted.

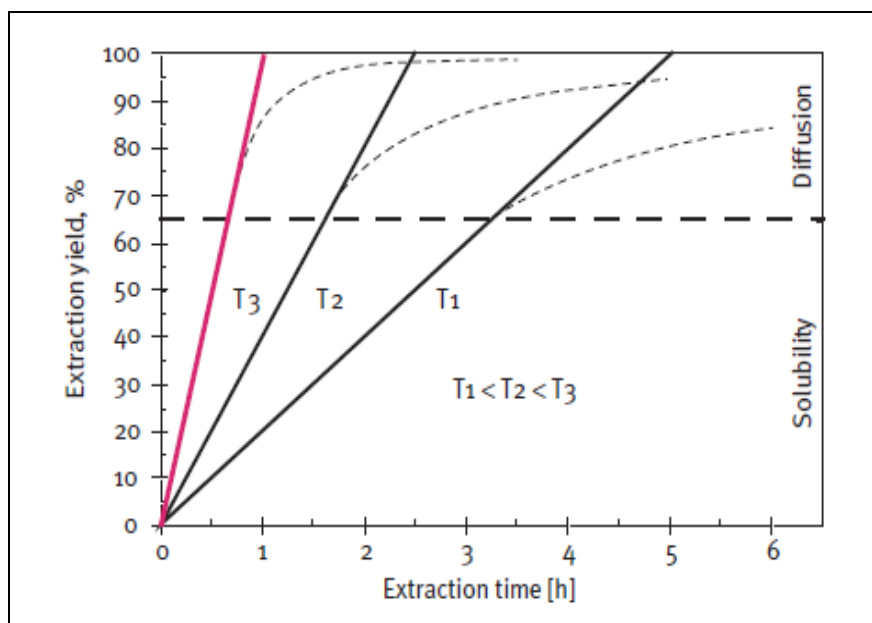


Fig.(8): Extraction yield versus time at different temperatures

2.2 The SFE Process and Equipment Development¹

In order to design and develop an SFE process for MAPs with CO₂ (possibly assisted by ethanol or water as entrainers), we need to know and optimize:

1. The solubility of the substance of interest
2. The selectivity of this substance with respect to others that are extracted simultaneously
3. The extraction profiles (such as those in Figure 8)
4. The way to separate the substance of interest from the total extract

All this information can be obtained by simple measurements performed in a laboratory-scale apparatus of minimum volume such as that illustrated in Figure 9.

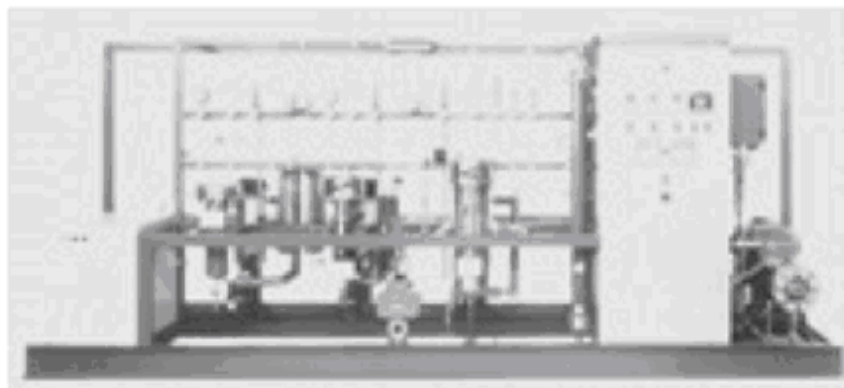


Fig.(9): Laboratory-scale apparatus for SFE process design

To measure extraction profiles, a small pilot-scale apparatus can be used. Extractor and separator volumes do not need to exceed 1 liter each. The analytical system must be suitable to measure the concentration and purity of the products of interest. Basic requirements in terms of equipment are:

- 2.2.1) A liquid CO₂ storage tank
- 2.2.2) A pump for liquid CO₂
- 2.2.3) A cooler to prevent CO₂ from evaporating in the pump

2.2.4) A heat exchanger to control the temperature of CO₂ entering the extractor

2.2.5) An extraction vessel

2.2.6) A heat exchanger to control the CO₂ plus solute mixture entering the separator

2.2.7) A separation vessel

Note that condensing and recycling of CO₂ after separation is not needed at the laboratory-scale developmental level, whereas these are essential requirements at the industrial production level.

All parts of the SFE laboratory-scale plant must be designed in order to resist the maximum operating pressure. If this does not exceed 300-350 bar, the entire equipment (e.g. vessels, valves, fittings) is pretty much of standard type and relatively inexpensive. If, as usual, stainless steel is used, the thickness of any part of the plant can be easily calculated by applying the Von-Mises equation:

$$P_i \frac{k^2}{k^2 - 1} \sqrt{3} < \sigma_{am} \quad (5)$$

with:

$$\sigma_{am} = \frac{\sigma_s}{S_f} \quad (6)$$

where P_i is the internal pressure, k is the external to internal diameter ratio, σ_s is the yield stress, and S_f is a suitable safety factor (usually $S_f=1.5$).

From Eq. 5, it can be seen that the thickness of a cylindrical vessel depends on its diameter. Examples are given in Table 1 for a vessel of 0.2 m internal diameter, with both stainless steel and carbon steel construction materials.

P [atm]		50	100	150	200	250	300
s [mm]	SS	3.8	8.1	12.9	18.5	25.0	32.7
	CS	2.2	4.6	7.2	10.0	13.0	16.2

Special care must be paid to closures and seals. SFE of MAPs is mostly an extraction operation from solid materials, which is carried out in batch or semi batch mode. Therefore, extraction vessels need to be pressurized, depressurized, opened, filled, and closed again several times per day. In order to ensure fast and safe operation procedures and reliable seals, gaskets like O-rings are useful and closure devices have been specifically designed. Again, the technology needed is already fully developed. We refer to chapter 4 of the book by Bertuccio and Vetter for details. The book also describes the machinery for moving fluids under pressure, i.e. pumps and compressors. We conclude that setting up a laboratory-scale apparatus with which to perform feasibility studies concerning the possibility of applying SFE to MAPs is not really an issue, and can be done with a relatively small capital cost.

However, this does not mean that SFE of MAPs is in itself an economically convenient operation. An accurate evaluation of production costs, including both capital and utility costs, must be performed before scaling up a process whose technical feasibility has been demonstrated at the laboratory level. Costs are also discussed in the book by Bertuccio and Vetter (chapter 8), but are

only indicative. The reader should remember that capital costs have been steadily decreasing in the last years must be taken into account.

2.3 SUPERCRITICAL FLUID EXTRACTION” Applied to Medicinal and Aromatic Plants

A large number of MAPs has been considered for possible extraction by supercritical CO₂. The most recent developments suitable to have industrial relevance are listed in Table 2. These examples illustrate the great potential of SFE in this field.

Table no. 2: Medicinal and aromatic plants extracted by SFE

Sr. No.	Plant Name	Part Used	Product(S) Extracted
1.	<i>Calendula officinalis</i> ^{2,3}	flowers	Oleoresin
2.	<i>Echinacea purpurea</i> ⁴	whole herb	Alkamides, polyphenolics including chichoric acid, carbohydrates
3.	<i>Eucalyptus</i> spp. ⁵	leaves	Essential oil
4	<i>Ginkgo biloba</i> ⁶	leaves	Flavonol glycosides (flavonoids) and terpenoids
5.	<i>Hypericum Perforatum</i> ⁴	herb	Naphthodianthones, hypericin and pseudohypericin
6.	<i>Levisticum officinale</i> ⁷	dry rhizomes, roots	Essential oil
7.	<i>Matricaria chamomilla</i> ⁸	(fl owers)	Oleoresin
8.	<i>Mentha</i> spp. ⁹	leaves	Essential oil
9.	<i>Origanum</i> spp. ¹⁰	herb	Essential oil
10.	<i>Piper methysticum</i> ⁴	roots, rhizomes	Kava lactones
11.	<i>Piper nigrum</i> ¹¹	fruit	Oleoresin
12.	<i>Saccharum</i> spp. ¹²	crude wax	Long chain n-alcohols
13	<i>Salvia desoleana</i> ⁹	leaves	Essential oil

14.	<i>Serenoa repens</i> ⁴	fruit	Free fatty acids, phytosterols (low concentrations) fatty alcohols and triglycerides
15.	<i>Solanum lycopersicum</i> ¹³	fruit	Carotenoids, tocopherols and sitosterols
Sr.No.	Plant Name	Part Used	Product(S) Extracted
16.	<i>Taxus brevifolia</i> ¹⁴	bark	Taxol
17.	<i>Taxus cuspidate</i> ¹⁵	needles	Paclitaxel and baccatin III
18.	<i>Vitis vinifera</i> ¹⁶	seeds	Procyanidins
19.	<i>Zingiber officinale</i> ¹⁷	rhizome	Oleoresin
20.	Sarawak black pepper ¹⁸		Essential oil
21.	Graviola (<i>Annona Muricata</i>) ¹⁹		Oleoresin
22.	<i>Radix puerariae</i> (<i>GeGen</i>) ²⁰		flavonoids
23.	CATNIP ²¹		OIL
24.	Romanian <i>Mentha</i> hybrids ²²		Z-sabinene hydrate-rich essential oils

2.4 THE SUPERCRITICAL FLUID EXTRACTION AS A NEW ANALYTICAL METHOD:-

SFE is used on a large scale for the extraction of some food grade and essential oils and pharmaceutical products from plants. It is relatively rapid because of the low viscosities and high diffusivities associated with supercritical fluids. The extraction can be selective to some extent by controlling the density of the medium and the extracted material is easily recovered by simply depressurizing, allowing the supercritical fluid to return to gas phase and evaporate leaving no or little solvent residues.²³ However, carbon dioxide is the most common supercritical solvent. Since the end of the 1970s, supercritical fluids has been used to isolate natural products, but for a long time the applications concentrated on only few products. Now the development of processes and equipment is beginning to pay off and industries are getting more and more interested in supercritical techniques.²⁴ In SF the physicochemical properties of a given fluid, such as density, diffusivity, dielectric constant and viscosity can be easily controlled by changing the pressure or the temperature without ever crossing phase boundaries.²³ The phase diagram of a single substance can be seen in Fig. 10.

The dissolving power of a supercritical fluid depends on its density, which unlike that of liquid solvents is highly adjustable by changing pressure or temperature. Especially in the vicinity of the critical point a small isothermal raise in pressure increases the fluid density remarkably while the effect diminishes with increasing distance from the critical values. Thus, the solvent strength of a fluid can be controlled more easily than that of a liquid solvent.²³ Recently, the supercritical fluid has approved higher diffusion coefficient and lower viscosity and surface tension than a liquid solvent, which leads to a more favorable mass transfer.²⁵ The demand for new analytical techniques in food and environmental sciences is strongly related to the higher demand of information on processing, quality control, adulteration, contamination, environmental and food regulations and the need for faster, more powerful, cleaner and cheaper analytical procedures are required by chemists, regulatory agencies and quality control laboratories to meet these demands can be achieved by SFE. Thus, this review paper has been justified.

2.5 Properties and fundamentals of supercritical fluids Solvent strength:

The density of a supercritical fluid is extremely sensitive to minor changes in temperature and pressure near the critical point. The densities of the fluids are closer to that of organic liquids but the solubility of solids can be 3-10 orders of magnitude higher. The solvent strength of a fluid can be expressed by the solubility parameter, which is the square root of the cohesive energy density and is defined rigorously

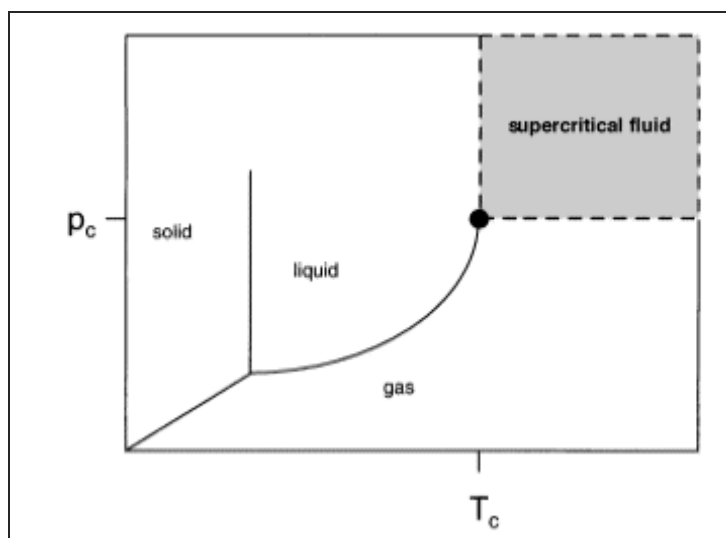


Fig.(10) Phase diagram for a single substance

Where, P_c , critical pressure; T_c , critical temperature⁽¹⁾ Pressure; T_c , critical temperature²³ from first principles. A plot of the solubility parameter for carbon dioxide versus pressure would resemble that a plot of density versus pressure²⁵. This confirms that the solvation strength of a supercritical fluid is directly related to the fluid density. Thus the solubility of a solid can be manipulated by making slight changes in temperatures and pressures. Another attractive feature of supercritical fluids is that the properties lie between that of gases and liquids. A supercritical fluid has densities similar to that of liquids, while the viscosities and diffusivities are closer to that of gases. Thus, a supercritical fluid can diffuse faster in a solid matrix than a liquid, yet possess a solvent strength to extract the solute from the solid matrix.^{26, 24}

2.5.1 Phase behavior:

An understanding of the phase behavior is important since the phase behavior observed in supercritical fluids considerably differ from the behavior observed in liquids. One such behavior is the retrograde region. For an isobaric system, an increase in the temperature of a solution increases the solubility of the solute over certain ranges of pressure (consistent with the typical liquid systems)

but decreases the solute solubility in other pressure ranges. This anomalous behavior wherein the solubility of the solute decreases with a temperature increase is called the retrograde behavior. Thus, the following generalizations may be made regarding the solute solubilities in supercritical fluids. Solute solubilities approach and may exceed that of liquid solvents. Solubilities generally increase with increase in pressure. An increase in the temperature of the supercritical fluid may increase, decrease or have no effect on the solubility of the solute depending upon the pressure.²³ CO₂ is not a very good solvent for high molecular weight and polar compounds. To increase the solubility of such compounds in supercritical carbon dioxide, small amounts (ranging from 0 to 20 mol %) of polar or non-polar co-solvents called modifiers may be added. The co solvent interacts strongly with the solute and significantly increases the solubility.^{23,24}

2.5.2 Co-solvents or modifiers:

A more common practice in SFE is to change the polarity of the supercritical fluid and increase their solvating power towards the analyte of interest by employing polar modifiers (co-solvents).

For example, the addition of relatively small percentages (1-10%) of methanol to carbon dioxide expands its extraction range to include more polar analytes. The modifiers can also reduce the analyte matrix interactions improving their quantitative extraction.²³

There are two main procedures to study with cosolvents or modifiers in SFE are; the first one, and the most common, accounts for a mixing of the modifier with the CO₂ flow while the second mixes the modifier with raw material in the extraction cell. This procedure is always associated to a static extraction step in which the modifier, in intimate contact with the sample matrix, is able to substitute the analyte molecules bound in active centers of the matrix and release them into the supercritical fluid phase.²⁷

2.6 Extraction with supercritical fluids:

Supercritical extraction has been applied to a large number of solid matrices. The desired product can be either the extract or the extracted solid itself. The advantage of using supercritical fluids in extraction is the ease of separation of the extracted solute from the supercritical fluid solvent by simple expansion. In addition, supercritical fluids have liquid like densities but superior mass transfer characteristics compared to liquid solvents due to their high diffusion and very low surface tension that enables easy penetration into the porous structure of the solid matrix to release the solute.^{24,28}

Extraction of soluble species (solutes) from solid matrices takes place through four different mechanisms. If there are no interactions between the solute and the solid phase, the process is simple dissolution of the solute in a suitable solvent that does not dissolve the solid matrix.²⁴ If there are interactions between the solid and the solute, then the extraction process is termed as desorption and the adsorption isotherm of the solute on the solid in presence of the solvent determines the equilibrium. Most solids extraction processes, such as activated carbon regeneration, fall in this category. A third mechanism is swelling of the solid phase by the solvent accompanied by extraction of the entrapped solute through the first two mechanisms, such as extraction of pigments or residual solvents from polymeric matrices. The fourth mechanism is reactive extraction where the insoluble solute reacts with the solvent and the reaction products are soluble hence extractable, such as extraction of lignin from cellulose. Extraction is always followed by another separation process where the extracted solute is separated from the solvent.²⁶

Another important aspect in supercritical extraction relates to solvent/solute interactions. Normally the interactions between the solid and the solute determine the ease of extraction, i.e., the strength of the adsorption isotherm is determined by interactions between the adsorbent and the adsorbate. However, when supercritical fluids are used, interactions between the solvent and the

solute affect the adsorption characteristics due to large negative partial molar volumes and partial molar enthalpies in supercritical fluids.^{26, 28}

The thermodynamic parameters that govern the extraction are found to be temperature, pressure, the adsorption equilibrium constant and the solubility of the organic in supercritical fluid. Similar to the retrograde behavior of solubility in supercritical fluids, the adsorption equilibrium constants can either decrease or increase for an increase in temperature at isobaric conditions. This is primarily due to the large negative partial molar properties of the supercritical fluids. In addition to the above factors, the rate parameters like the external mass transfer resistances, the axial dispersion in the fluid phase, and the effective diffusion of the organics in the pores also play a crucial role in the desorption process. A thorough understanding of these governing parameters is important in the modeling of supercritical fluid extraction process and in the design, development and future scale-up of the process.²⁶

2.7 SFE process:

A simplified process-scale SFE system is shown in Fig. 11 and a typical batch extraction proceeds as follows. Raw material is charged in the extraction tank which is equipped with temperature controllers and pressure valves at both ends to keep desired extraction conditions. The extraction tank is pressurized with the fluid by means of pumps, which are also needed for the circulation of the fluid in the system. From the tank the fluid and the solubilized components are transferred to the separator where the solvation power of the fluid is decreased by increasing the temperature, or more likely, decreasing the pressure of supercritical fluid extractor.²³ The product is then collected via a valve located in the lower part of the separator(s).^{23, 24}

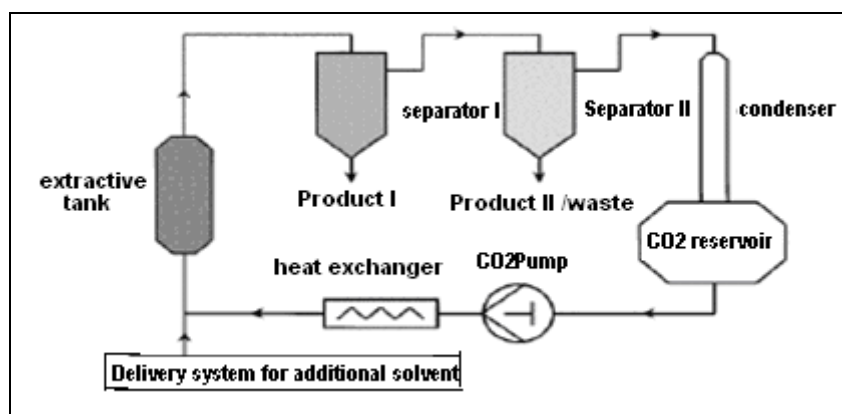


Fig. 11: A simplified drawing of a process-scale

2.8 Advantages and drawbacks of supercritical CO₂ (SC-CO₂):

There are a large number of compounds that can be used as a fluid in supercritical techniques, but by far the most widely used is carbon dioxide. From the viewpoint of pharmaceutical, nutraceutical and food applications it is a good solvent, because it is non-toxic, non-flammable, inexpensive, easy to remove from the product and its critical temperature and pressure are relatively low ($T_c=31.1^\circ\text{C}$, $p_c=72$ bar) make it important for food and natural products sample preparation, is the ability of SFE using CO₂ to be operated at low temperatures using a non-oxidant medium, which allows the extraction of thermally labile or easily oxidized compounds. It is environmental friendly and generally recognized as safe by FDA and EFSA. These properties make it suitable for extracting, for example, thermally labile and non-polar bioactive compounds but, because of its non-polar nature, it cannot be used for dissolving polar molecules. The solubility of polar compounds and the selectivity of the process can be increased by adding small quantities of other solvents, such as

ethanol, in the fluid that named as co-solvent or modifier. On one hand, it decreases the processing times, increases yields and makes it possible to use milder processing conditions, but on the other, it complicates system thermodynamics and increases capital costs.²⁵

The use of high purity SFE-grade CO₂ is not required but impurity and moisture in industrial grade CO₂ can accumulate and may interfere with further analytical operations (gas or liquid chromatography). Thus, an on-line fluid cleanup system may be used to remove trace contaminants. An important drawback of SC-CO₂ and most of the other supercritical fluids is that predominantly, a non-polar extraction fluid, such as CO₂, is used. Therefore, a logical trend to widen the application range of this technique is the study of new methods to decrease analyte polarity to make them more soluble in non-polar supercritical fluids. In this sense, chemical in situ derivatization has been applied to improve the selectivity of the extraction towards a specific group of compounds.^{25, 27}

So the solvent power of SC-CO₂ can be summarized by a few rules:

- It dissolves non-polar or slightly polar compounds.
- The solvent power for low molecular weight compounds is high and decreases with increasing molecular weight.
- SC-CO₂ has high affinity with oxygenated organic compounds of medium molecular weight.
- Free fatty acids and their glycerides exhibit low solubilities .
- Pigments are even less soluble.
- Water has a low solubility (<0.5% w/w) at temperatures below 100°C
- Proteins, polysaccharides, sugars and mineral salts are insoluble and;
- SC-CO₂ is capable of separating compounds that are less volatile, have a higher molecular weight and/or are more polar as pressure increases.²⁴

3.0 APPLICATION

Applications of Supercritical Fluid Extraction process:-

3.1 Some Special applications of supercritical fluids to food processing:-

As mentioned before carbon dioxide is the most common supercritical fluid in the food industry. Due to the non-toxicity and low critical temperature, it can be used to extract thermally labile food components and the product is not contaminated with residual solvent. Further, the extract's color, composition, odor, texture are controllable and extraction by supercritical fluid carbon dioxide retains the aroma of the product.

Supercritical fluid extraction provides a distinct advantage not only in the replacement but also extracts oils that are lower in iron and free fatty acid. Some application of SFE in food is mentioned below:

3.1.1 Removal of fat from foods:

Edible oils and their components has been the target of supercritical fluid processing since the early 70s. Although triacylglycerides are only fairly soluble in SC-CO₂, the advantages of organic solvent-free processing have stimulated research and development in various areas. One of these is the removal of fat from food. The process has been fully designed for commercial application, using the aforementioned standard design. The process has the advantage of producing fat-free or fat-reduced potato chips. According to the expected taste the amount of remaining fat in the potato chips can easily be controlled.^{29, 30}

3.1.2 Enrichment of vitamin E from natural sources:

SFE offers several advantages for the enrichment of tocopherols over conventional techniques such as vacuum distillation, in particular a lower operating temperature. As starting

material one can use various edible oils or their distillates. Most promising as feed materials are CPO) and SODD.³¹ CPO contains several tocotrienols and tocopherols at a total concentration of approximately 500ppm. SODD may contain (after several conventional concentration steps) about 50% tocopherols. Both materials can be used for the production of enriched fractions of tocochromanols.^{30, 31} Although it is possible to recover tocochromanols directly from CPO, it is better to produce esters of the triglycerides in order to be able to more easily separate these compounds from the tocochromanols. In this method, the triglycerides are subject to an esterification with methanol to form fatty acid methyl esters, which are easily extractable with CO₂. That means that the tocochromanols, together with other unsaponifiable matter such as squalene and sterol are enriched in the bottom phase of an extraction column. This attempt is described in more detail by. For a discussion of enriching tocochromanols, phase equilibrium data have to be considered first.³² FFA and tocochromanols exhibit a much higher solubility in CO₂ than the triglycerides. Hence, these components are enriched in the gaseous phase, expressed by a distribution coefficient being higher than one. The distribution coefficient of the triglycerides is smaller than one, whereas that for the carotenes is much smaller than one, meaning that these components stay in the liquid oil phase. Thus, tocochromanols can be extracted as the top phase product in a separation column, whereas carotenes remain in the bottom phase product together with triglycerides. For recovering the carotenes together with the tococromanols the above mentioned esterification to volatile (CO₂ soluble) methyl esters makes possible to recover tocochromanols and carotenes (together with squalene and sterols) as bottom product from this natural source.^{31,32} When the glycerides (in case of the esterification) or the FFAs from deodorizer distillates have been removed, then there is a feed material available for obtaining enriched fractions of tocochromanols and carotenes of much higher concentration. In this feed material, tocochromanols and carotenes (in case of palm oil) are the main components and have to be separated from other unsaponifiable substances present, such as squalene and sterols. Of these compounds, squalene has the highest solubility in SC-CO₂, all phytosterols have a rather low solubility in CO₂ (and remain in the oil phase), and tocochromanols exhibit an intermediate solubility between the two. In a second separation step tocochromanols are separated from phytosterols. A further purification of these compounds is possible, e.g. with adsorptive chromatographic techniques, again using supercritical fluids.³²

3.1.3 Removal of alcohol from wine and beer, and related applications:

De-alcoholized wine or beer is achieved by removing ethanol from water. Distillation is well known for this purpose with the disadvantage that aroma compounds will also be removed. New techniques like membrane separation (pervaporation) emerge, and in between these is SFE with CO₂.³³

Starting from an aqueous solution with about 10% (w/w) ethanol, ethanol can be removed by SC-CO₂ in a stripping column. The rate of ethanol removal depends strongly on temperature. Reducing the alcohol content to values well below 0.5% (w/w) requires about 2.5h at 45°C under non-optimized conditions. Much shorter times for the ethanol removal can be obtained if flow rates and mass transfer equipment are carefully selected. With the information available in the literature, for instance from, a column for dealcoholizing aqueous solutions can be designed. Recovery of aroma compounds is achieved by a side column in which a separation from ethanol is carried out.^{35, 37}

A related process that can be mentioned is the recovery of absolute alcohol. Many studies were carried out at conditions of complete miscibility of ethanol and CO₂ in order to get a high solubility of ethanol in the vapor phase. At these conditions, anhydrous ethanol cannot be produced. However, ethanol can be concentrated above azeotropic composition whenever the pressure in the ternary mixture CO₂ + ethanol + water is below the critical pressure of the binary mixture

CO₂+ethanol.³⁷

3.1.4 Encapsulation of liquids for engineering solid products:

A liquid product can be entrapped by adsorption onto solid particles (liquid at the outside of solid particles), by agglomeration (liquid in the free volumes between the solid particles), or by impregnation (liquid within the pore system of the solid particles). Microspheres or larger capsules can be formed, totally encapsulating the liquid. The solid material provides a coating for the liquid inside. Such particulate products can be achieved by means of supercritical fluid processing.³³ An example is the so called concentrated powder form-process, wherein CO₂ is mixed (dissolved) in the liquid feed by static mixing. The CO₂-liquid feed mixture is then sprayed into a spray chamber at ambient conditions together with the substrate material. The CO₂ is suddenly released from the liquid, and the liquid forms small droplets. During the spraying process, solid substrate and liquid droplets are intensively mixed and combined to a solid particulate product of the type described above. The product is finally removed from the chamber as a free flowing powder and separated from the outgoing gas stream by a cyclone. With this type of process, a wide variety of solid substrates can be applied to uptake liquids of different kind and up to about 90%.³⁴

As advantages can be claimed the easier handling and storage, prevention of oxidation processes, and easier dosage. Solid products can also be formed under high pressure conditions. As an example for such a type of process, the encapsulation or adsorption of tocopherol acetate on silica gel. Here, about 50% of tocopherol acetate can be incorporated onto the silica gel without apparent change of morphology and flow properties of the powder. The powder with 50% loading is still free flowing. The amount which can be adsorbed at high pressures is comparable to that of normal pressure. Only at very high densities, the equilibrium loading decreases. In the experiments the autoclave was used to saturate the SC-CO₂ current with tocopherol acetate, and the density of the solvent was changed in the nozzle where the loaded SC-CO₂ phase was fed to the absorber. This adsorption at high pressures makes possible the direct product formation in the supercritical fluid, with the advantageous effect that the supercritical solvent can easily be recycled without substantial compression.^{33, 34, 37}

3.1.5 Extraction and characterization of functional compounds:

Nowadays, the growing interest in the so called functional foods has raised the demand of new functional ingredients that can be used by the food industry. These functional ingredients are preferred to have natural origin and to have been obtained using environmentally clean extraction techniques. As expected, the complexity of the natural ingredients with biological activity is very high; this fact has led to the development of new methodologies to extract and characterize them. In order to preserve the activity of such ingredients and to prevent changes in the chemical composition of the functional compounds and/or mixture of compounds, sample preparation techniques based on the use of compressed fluids have been widely developed. SFE has been used to obtain extracts with antioxidant activity from microalgae; by using the combination of SFE and HPLC with both DAD ESIMS³⁷. Several functional compounds were identified corresponding to different carotenoids along with chlorophyll a and some chlorophyll degradation products. These compounds could be associated to the biological activity of such extracts.^{38, 33} Supercritical CO₂ has also been used to extract and characterize antimicrobial compounds and food preservatives from microalgae. Carotenoids are a group of compounds of great importance to human health since they can act, e.g., as potent antioxidants; however, due to their chemical characteristics they are easily degraded by temperature or oxygen, so, the use of SFE has been suggested to minimize risks of activity lost being thus applied to the extraction of carotenoids from different matrices.³⁹ In this application, a vegetable oil was also used as co-solvent showing an improvement in the extraction yield as well as in the stability of the pigment. In both cases, the use of oils as co-extracting agents presents an important

drawback that is the elimination of oil. It helps to improve the extraction but the extract is a mixture of the extracted components of the oil and the “pure” extract.

In general terms, the use of SFE allows the analysis of essential oil preserving its integrity, without the formation of off flavors that could interfere in the characterization of the sample. As it was told before in order to widen the range of application of SFE to relatively polar compounds, small amounts of modifiers ($\leq 15\%$) are added to carbon dioxide allowing the extraction of more polar substances.³³

Other examples of the extraction of valuable compounds from foods using SFE are the isolation of cholesterol from cattle brains and fat-soluble vitamins from parmigiano regiano cheese. The main problem with cattle brains, as well as many other raw food matrices is its high content in water. Water can interfere in the extraction process in two ways: lixiviation or acting as co-solvent thus interfering in the reproducibility of the extraction procedure. In order to avoid this situation, the most common strategy is drying or freeze drying the sample prior to extraction although some authors prefer to mix the sample with a water absorbent inside the extraction cell, for example ,magnesium sulphate.^{40,41}

Another problem related to the extraction of real food samples is their variable fat content which can also interfere in the extraction of the target compounds due to a coextraction of the fat at the selected extraction conditions. Two main approaches have been used to overcome this problem, the first one uses a fat retainer, mainly basic alumina, neutral alumina, florisil or silica, placed in a separate chamber downstream the extraction thimble, while the other one uses the fat retainer inside the extraction cell.⁴¹

3.1.6 Application of SFE in food safety:

At present, food safety includes many different issues such as detection of frauds, adulterations and contaminations. Among these topics, detection of food pollutants is important not only for consumers but also for administrations, control laboratories, and regulatory agencies. In order to protect consumers’ health, regulations establish strict limits to the presence of pollutants in foods that must be carefully observed and determined. Generally, the analysis of food pollutants is linked to long extraction and cleanup procedures commonly based on the use of, e.g., soxhlet and/or saponification. These procedures are laborious and time consuming and, besides, usually employ large volumes of toxic organic solvents. With the objective of reducing both, the sample preparation time and the massive use of organic solvents, techniques based on compressed fluids such as SFE have been developed. One of the main areas of application of SFE in the last few years has been in food pollutants analysis, mainly pesticide residues and environmental pollutants.⁴² Several methods has been developed for the analysis of multiple pesticides (organochlorine, organophosphorus, organonitrogen and pyrethroid) in potatoes, tomatoes, apples, lettuces and honey with a single cleanup step using supercritical CO₂ modified with 10% of acetonitrile. Similar study have been carried out for the analysis of multiresidues of pesticides, using SFE as a cleanup step, in cereals, fish muscle, vegetable canned soups, vegetables or infant and diet foods.^{41,42}

A common characteristic of these study is the extremely high selectivity of SFE in the isolation of the low polarity pesticides; this fact makes SFE probably the technique of choice to isolate pesticides from low fat food. As mentioned in the introduction, to correctly asses the concentration of an analyte in a food sample, a quantitative recovery should be obtained that will mostly depend on the recovery of the analytes and not on the extraction itself. To improve the recovery of the pollutants, a common strategy is the use of solid traps.

These traps consist on a solid phase compatible with the analyte and are flushed away with a compatible solvent.

The trapping step is very important in SFE method development not only because its effect in

the quantitative recovery of the analytes but also because an extra selectivity can easily be introduced, especially in the case of solid-phase trapping, avoiding the use of further post-extraction clean up. Supercritical carbon dioxide extraction can advantageously be used to extract non-polar pollutants, such as PAH from foods.

Different extraction and cleanup methods have been used, but the extracting conditions turned to be very similar (around 300 bar and 100°C) to optimize the PAH extraction.⁴¹

3.2 SFE and analytical uses:

SC-CO₂ has been utilized in multiple methods of analysis. It is used as either an extraction medium, as in rapid analyses for fat content, or as a mobile phase, as in supercritical fluid chromatography. Accordingly, the use of supercritical fluids in the detection of fat content, pesticide residues, and supercritical fluid chromatography as well as some analytical applications are highlighted below:

3.2.1 Rapid analysis for fat content:

SFE have been used to determine the fat content of numerous products ranging from beef to oil seeds and vegetables. For the analysis of fats content in soybeans, sunflower, safflower, cottonseed, rapeseed and ground beef, it was found that supercritical fluid extraction yielded higher recoveries than those obtained by the AOCS approved methods. The use of an in-line piezoelectric detector is able to measure the change in weight of the sample during the extraction process. This allows for more accurate determination of the final weight of the sample after all of the fat has been extracted (total fat). In addition, it can allow for more rapid determination of the total fat by determining the point when the steady state mass has been reached without having to re-extract the sample multiple times to confirm that the steady state mass has been reached.⁴²

3.2.3 Rapid analysis for pesticides in foods:

Pesticide residues are a concern among consumers throughout the United States and other countries. Currently the methods of analyzing food products and other substances such as contaminated soil and water involve the use of organic solvents such as hexane and dichloromethane to extract the pesticides from the sample matrix. Once the pesticides have been extracted from the sample matrix, the samples must be “cleaned” to remove any unwanted compounds, such as lipids, which may interfere GC analysis of the sample for any pesticides present.⁴³ The most common method for cleaning is solid phase extraction. Supercritical fluid extraction provides an alternative to using organic solvents for the extraction of pesticides from their sample matrix. Some of the advantages which supercritical fluid extraction provides over the traditional methods of pesticide extraction are that the extraction can be performed in less time, and utilizes less solvent volume. In addition, supercritical fluid extraction can be tailored to the solute of interest by changing the temperature and pressure of the extraction process. Supercritical fluid extraction can also be tailored for pesticides that contain more polar groups by the addition of polar modifiers to the CO₂ such as methanol.^{42,43}

3.2.4 New applications Supercritical particle formation:

In the 1970s and 1980s, supercritical processes were mainly focused on extraction and separation but, within the last 10 years, interest in supercritical fluid processing has also arisen in other areas. Here some of the new applications of SFE are mentioned

3.2.5 Nanoparticle formation using supercritical fluids:

SFE were used in a number of different circumstances for the preparation of micro-nanodispersed organic systems. Of industrial use are their special solvent properties and the technical feasibility of large temperature gradients.⁴⁴ The generation of a sufficiently high super saturation for the initiation of a precipitation reaction with conventional solvents is on the one hand limited by the generally low dependency of the solubility on temperature, on the other by the difficulty to realize

technically the necessary rapid heat exchange. With this in mind one process in which liquid CO₂ is used as cooling agent deserves attention. In this so-called contact cooling process the active compound solution at -78 °C is sprayed into a CO₂ stream and particle formation is induced in the spray droplets by crystallization. From the viewpoint of toxicological acceptability, the non-combustibility, and the favorable critical data of CO₂ (pc=74 bar, Tc=31°C) the so-called RESS process (rapid expansion of supercritical solutions) appears particularly attractive, especially because extra process steps to remove residual solvent may no longer be required. However, SF-CO₂ can act as an oxidizing agent with oxidationsensitive compounds such as β-carotene and is thus ruled out as a precipitation medium. Both in the GAS process (gas antisolvent process) and in the PCA process, SF-CO₂ instead of water serves as the precipitation medium from organic solvents. In the physically related SEDS the organic active-compound solution and the SF-CO₂ are brought into contact in a coaxial mixing nozzle, and thus a rapid extraction of the solvent (e.g. acetone) is possible. However, to date there have only been reports of particle formation in the micrometer range.^{44,45}

3.2.6 Supercritical drying:

Supercritical drying goes beyond the critical point of the working fluid in order to avoid the direct liquid-gas transition seen in ordinary drying. It is a process to remove liquid in a precisely controlled way, similar to freeze drying. It is commonly used in the production of aero gel and in the preparation of biological specimens for scanning electron microscopy.

As a substance crosses the boundary from liquid to gas (phase diagram), the substance volatilizes and so the volume of the liquid decreases. As this happens, surface tension at the solid-liquid interface pulls against any structures that the liquid is attached to. Delicate structures, like cell walls, the dendrites in silica gel and the tiny machinery of microelectromechanical devices, tend to be broken apart by this surface tension as the interface moves by. To avoid this, the sample can be brought from the liquid phase to the gas phase without crossing the liquid-gas boundary on the phase diagram; in freeze-drying, this means going around to the left (low temperature, low pressure). However, some structures are disrupted even by the solid-gas boundary.

Supercritical drying, on the other hand, goes around the line to the right, on the high-temperature, high-pressure side. This route from liquid to gas does not cross any phase boundary, instead passing through the supercritical region, where the distinction between gas and liquid ceases to apply.

Fluids suitable for supercritical drying include carbon dioxide and freon. Nitrous oxide has similar physical behavior to carbon dioxide, but is a powerful oxidizer in its supercritical state. Supercritical water is also a powerful oxidizer, partly because its critical point occurs at such a high temperature (374 °C) and pressure (647°K and 22.064 Mpa. therefore, SFE has been suggested as the method of choice for thermo labile compounds extraction. It has been used for developing an ever-expanding niche in the food industry whether it is used as a solvent for extraction or analyses. Now a day, SFE is really needed as advance method which can provide fast, reliable, clean and cheap methods for routine analysis.

4.0 Future prospectus

With the newer invention of the herbal drugs and it's utilization in the treatment of various disease and disorders the preparations which are mostly preferable are the herbal drugs therefore it is most important for the chemist and scientist to develop the newer and easier as well as effective extraction technique for the extraction of the chemical constituents from the various parts of the medicinal and aromatic plants. The supercritical fluids like CO₂ under increased pressure can be able to provide the fruit efficient, effective, and suitable technique for the extraction of the herbal drugs in the future without losing the potency and activity of a herbal drugs.

5.0 CONCLUSION

SFE with CO₂ is a technically and possible and economically valid technique to extract bioactive components from Medicinal and aromatic plants. Organic solvent-free products can be obtained and the low operating temperature makes it possible to preserve all their natural properties. The feasibility study on specific products can be performed rather easily at laboratory scale. However, accurate evaluation of production costs, including both capital and operating ones, must be done in order to exploit SFE at the industrial level. Hence the supercritical fluid extraction is the most preferable process for the extraction of the bioactive chemical from the medicinal and aromatic plants.

List of abbreviations

MAPs	:	Medicinal and Aromatic plants
ICS-UNIDO	:	International Centre for Science and High Technology United Nations Industrial Development Organization
CCE	:	Counter-current extraction
SFE	:	Supercritical fluid extraction
SFs	:	Supercritical fluids
SC-CO ₂	:	Supercritical carbon dioxide
HFC	:	Hydrofluorocarbon
T _C	:	Critical temperature
P _C	:	Critical pressure
T	:	Absolute temperature
P	:	Pressure
P ^{sat}	:	Solute saturation or sublimation
R	:	Universal gas constant

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