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A review Article on: Supercritical Fluid Extraction

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ABSTRACT: Basically, supercritical fluid extraction (SCFE) is an approach that uses a liquid phase that has characteristics midway between gas and liquid properties to induce solubilization of solutes in the matrix. The extraction could be selectively tuned to some extent because the solvation performance (which is density controlled) of the SCFE can be varied over a wide range by varying the pressure, temperature, or both. Compared to traditional organic liquids, which have higher diffusivity and lower viscosity, SCFE provides significantly better mass transfer of solutes from sample matrices. The review summarizes studies performed using supercritical fluid extraction of high-value compounds from natural products that have previously been used in the food, pharmaceutical, agricultural, dairy industries, etc. It discusses processing parameters optimized on a pilot scale to upgrade to an industrial set-up.

Keywords: Constituents, extraction, herbals, medicinal plant, supercritical, technology.

I. INTRODUCTION:

Research is being carried out worldwide to evaluate the effectiveness of several new non-thermal technologies in food processing to reduce the harmful impacts of traditional thermal methods such as pulsed electric field[1]. Supercritical fluids have been utilized for extracting natural products since the late 1970s, with a focus on a small number of applications for a prolonged period of time. Currently, industries are becoming increasingly interested in supercritical techniques as they start to see the results of advancements in processes and equipment. The global expansion of potential uses for supercritical fluid extraction (SFE) is evidenced by the rise in patents filed in recent years. Its usage is already integrated into the current landscape, driven mainly by the increasing demand for high-quality products and the globalization of the economy. Furthermore, it excels in its application in the trade of pharmaceuticals, food, chemicals, and cosmetic ingredients. The rise in the use of this technology in industry is primarily because of its selectivity, ease, and ability to separate a wide range of organic compounds. Many of these compounds are either impossible or not practical to extract using traditional methods, or require expensive high-resolution columns for purification, which may not be readily available in the national market, leading to high costs. The widespread use of organic solvents in various industrial activities, such as extracting fats and oils, obtaining bioactive compounds, removing heavy metals, processing polymers, and producing fuels, is a globally debated issue because of the damage it causes to the environment. Considering this image, the Montreal Protocol was implemented in 1987, followed by the Kyoto Protocol in 1997, with the primary goal of limiting or eradicating the manufacture and use of substances harmful to the ozone layer[3].

The idea of suprcritical fluid technology involves harnessing the unique characteristics of solvents when they are in their supercritical state. The compound will transition between states depending on the specific combination of pressure and temperature. The three fundamental states are solid, liquid, and gaseous states. In thermodynamics, a phase diagram is a visual illustration showing the various physical states of a substance based on different temperature and pressure conditions[4]. Introducing supercritical fluid extraction (SFE) marks a significant achievement in this monumental journey. Over the last two decades, SFE has transitioned from being conducted on a small scale in laboratories to being implemented on a larger, industrial scale. The development of green chemistry in extraction is driven by the goal of decreasing energy usage and substituting typical solvents with more environmentally friendly options. Ultrasound-assisted extraction, microwave-assisted extraction, supercritical fluid extraction, mechanical pressing, and détente instantanée contrôlée (DIC) are among the green technologies utilized in herbal extraction. The SFE involves using carbon dioxide at critical temperature and pressure to separate or extract chemical compounds from a matrix. Even though xenon (Xe) and sulfur hexafluoride (SF6) have low critical temperature and pressure values like other SCFs, their commercial use is limited due to their expensive manufacturing process. Despite having low critical values, the use of gases such as nitrous oxide (N2O) or ethane is restricted due to safety concerns[7].

TERMINOLOGY:

Supercritical: The term “supercritical” refers to a substance in a non-condensing and single-phase fluidwhen brought above its critical temperature (Tc) andcritical pressure (Pc). Beyond this point, there is asupercritical region where the substance shows sometypical physicochemical properties of gases or liquids,such as high density, intermediate diffusivity and low viscosity and surface tension[8].

Supercritical Fluid: Supercritical fluids are highly compressed gases which combine properties of gases and liquids in an intriguing manner. Fluids such as supercritical xenon, ethane and carbon dioxide offer a range of unusual chemical possibilities in both synthetic and analytical chemistry[9].

Supercritical Fluid Extraction (SFE): Supercritical fluid extraction (SFE) involves using supercritical fluids as the extracting solvent to separate one component (the extractant) from another (the matrix). Extraction typically involves removing substances from a solid source, though it can also involve extracting from liquids. SFE can serve as a means of preparing samples for analysis or be employed on a larger scale to remove unwanted substances from a product (such as decaffeination) or extract a specific product (like essential oils). These indispensable oils may contain limonene and other linear solvents. Supercritical carbon dioxide (CO2) is frequently utilized, occasionally with added co-solvents like ethanol or methanol. Supercritical carbon dioxide is extracted under conditions where the temperature is above 31 °C and the pressure is above 74 bar. Adding modifiers may lead to a slight alteration in this. The upcoming discussion will mainly focus on CO2 extraction, unless stated otherwise[6].

Figure 1 illustrates a basic process-scale SFE system, with a standard batch extraction sequence outlined. Raw materials are placed into the extraction tank, which is fitted with temperature controllers and pressure valves at both ends in order to maintain the desired extraction conditions. Pumps are required to pressurize the extraction tank with the fluid and circulate it within the system. The fluid and solubilized components move from the tank to the separator, where the fluid's solvation ability is reduced by raising the temperature or lowering the system's pressure. Product retrieval is done through a valve situated in the lower section of the separator(s)[10].

The solubility of the target compound in the chosen solvent is what drives any extraction process, and this depends on the interactions between the solvent and solute. Supercritical fluid extraction (SFE) is now seen as a better alternative method for extracting bioactive compounds from natural sources. This is due to its shorter extraction time, lower use of organic solvents, compatibility with heat-sensitive materials, delivery of purer extracts, and environmental friendliness[12]. The curve delineates the areas that correspond to gas, liquid, and solid phases. The critical point signifies the termination of the vapor liquid coexistence curve. There is no phase transition above the critical temperature because the fluid cannot change into a liquid phase, no matter how much pressure is applied. In the supercritical state, there is only one phase that is not classified as a gas or a liquid, having properties that fall between those of a pure liquid and gas[13].

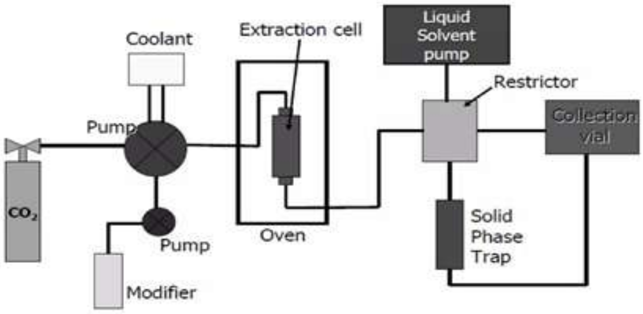

Fig: 1 Supercritical fluid Extraction[11].

Component Of SFE:

1. Fluid reservoir.
2. Pump.
3. Extraction cell/ column.
4. Restrictor
5. Collector.
6. Detectors[11].

Method development for SFE:

Table 1- Method development for supercritical fluid extraction[11].

Sample type	Intermediate volatility	Involatile non-polar	Involatile non-polar, higher MW	Involatile polar
Pressure or density	Low	Intermediate	High	High with polar modifiers
Temperature	Low near critical temperature	Low near critical temperature	Increase temperature	Increase temperature >modifier boiling point
Time	Generally short but will vary on sample matrix	Short, longer with less soluble analytes	Increase time as solubility decrease	Increase time as solubility decrease
Flow rate	Low	Increase to improve diffusion	Increase to improve diffusion	Low, allow interaction of modifier

Supercritical fluid as solvent:

Rapid Expansion of Supercritical Solution (RESS):

RESS involves using supercritical fluid for extraction and drug encapsulation in a conventional manner. Depressurizing the saturated supercritical fluid with solid substrate quickly (moving from the supercritical region to ambient conditions) results in rapid expansion of the supercritical fluid, leading to a quick decrease in solvation power as it enters a low-pressure chamber through a heated capillary or laser-drilled nozzle. Because the solvation power decreases, the solvent quickly becomes super-saturated, leading to super fluid nucleation and particle formation. Variables that can be changed include the solubility of solute in a supercritical fluid (often SC-carbon dioxide), temperature, pressure, capillary design angle and the effect of the capillary jet hitting the surface. This technique results in dry particles that do not need additional processing steps[14].

Rapid Expansion of a Supercritical Solution into a Liquid Solvent (RESOLV):

The RESOLV technique, a variation of traditional RESS, involves quickly introducing a supercritical solution into a liquid solvent to reduce the formation of aggregates in particle manufacturing. This technique includes releasing or expanding supercritical fluids with solid material into a collection chamber with room temperature aqueous solution through a laser-drilled opening. Furthermore, various water-soluble polymers or surfactants are added to the aqueous solution in order to function as a stabilizing agent[15].

Supercritical fluid AS AN ANTI-SOLVENT:

Gas Anti-Solvent Recrystallization (GAS):

In this technique, a supercritical fluid acts as an anti-solvent. Initially, the solute is dissolved in an appropriate organic solvent. The organic solvent evaporates as the supercritical fluid is introduced into it. Therefore, the organic solvent's ability to dissolve substances decreases, making it an ineffective solvent for the solute. The general procedure supports the beginning of nucleation, leading to the formation of the solute. For optimal results using this method, it is best for the solute to have low solubility in the supercritical fluid and for the supercritical fluid to be mixable with the organic solvent[16].

Aerosolized Solvent Extraction System (ASES):

ASES has a strong connection with SAS. ASES utilizes SCFs as an antisolvent and can be handled by spraying the solution and antisolvent. The SCF entering the liquid droplets results in a significant increase in volume and a decrease in solvent power, leading to a sudden increase in supersaturation within the liquid mixture and the formation of small, uniform particles. A high-pressure pump is used to disperse the SCF into the high-pressure container. Once the system reaches a stable condition, the substance in liquid form is added to the container using a specific-sized opening. Getting small liquid droplets requires pumping the solution at a pressure higher than the vessel's operational pressure. The particles gather on the filter surface attached to the vessel's bottom[17].

Adventages of SFE:

1.The penetration power of supercritical fluid into porous solid materials is higher than liquid solvent due to its low viscosity and high diffusivity.
2. A complete extraction is possible in SFE as a fresh fluid is continuously forced to flow through the samples.
3. The solvation power of the supercritical fluid can be adjusted according to requirement by varying temperature and pressure resulting in high selectivity.
4. Suitable for thermo labile material.
5. It can be associated with various compounds detecting tool like gas chromatography and mass spectroscopy, which is useful in direct quantification in addition toextraction.
6. Extraction of natural raw material with supercritical CO2, allows the obtaining of extracts which flavour and taste are perfectly respected and reproducible.
7. The majority of the easily evaporated substances lost during hydrodistillation are found in the supercritical extracts, leading to a favoredflavor and taste among taste testers[18].
8. Elimination of organic solvents i.e. reduces the risk of storage.
9. Rapid (due to fast back-diffusion of analytes in the SCF reduces the extraction time since the complete extraction step is performed in about 20 min).
10. Suitable for extraction and purification of compounds having low volatility present in solid or liquid.
11. Susceptible to thermal degradation (low operating conditions).
12. Complete separation of solvent from extract and raffinate[11].

Disadventages of SFE:

1.Although using Supercritical fluid extraction is time and organic solvent saving, but there is a lack of universal method that works for different types of matrices and analytes.
2. The Supercritical fluid extraction technique requires an experienced analyst to develop the method and run the sample. It requires the analyst to understand the mechanism and working mechanism and it’s not a day-to-day routine analysis[19].
3. Carbon dioxide could be an excellent solvent for non-polar analytes. However, it’s polarity might not be suitable to extract polar compounds due to the insufficient solubility of polar analytes in Sc-carbon dioxide.
4. Furthermore, Supercritical fluid extraction may not be appropriate for extracting compounds that are soluble in water or blood plasma. The use of a co-solvent as a modifier is necessary for extracting polar compounds. Included in this list are methanol, hexane, aniline, toluene, and diethylamine[20].
5. Prolonged time (penetration of SCF into the interior of a solid is rapid, but solute diffusion from the solid into the SCF).
6. Modeling is inaccurate.
7. Scale is not possible (due to absence of fundamental, molecular-based model of solutes in SCF).
8. Consistency & reproducibility may vary in continuous production[11].

Application of Supercritical Fluid Extration:

1. **Food processing:**

The appealing properties of supercritical carbon dioxide, such as being nontoxic, inexpensive, odorless, colorless, non-flammable, and having near ambient critical temperature, low viscosity, and high diffusivity compared to liquids, have made it the top choice solvent for processing essential oils and food industry oils. Additionally, the color, structure, smell, and feel of the extracts can be managed, and using carbon dioxide for extraction helps preserve the product's aroma. Supercritical fluid extraction is employed instead of hexane for extracting soybean oil and has been experimented for extracting from corn, sunflower, and peanuts. Supercritical fluid extraction offers a unique benefit by not only substituting but also extracting oils with reduced iron and free fatty acid levels. Another use is the extraction of fat from food. The entire process was created specifically for commercial use, incorporating the mentioned standard design. The process of eliminating fat offers the benefit of creating potato chips with little to no fat. SFE can easily regulate the remaining fat in potato chips based on the desired taste. Considerable research has focused on using supercritical carbon dioxide to decaffeinate coffee. Therefore, it comes as no surprise that this was the initial method to be brought to market[21].

2. Nanoparticle formation using supercritical fluids:

SFE was employed in various situations to create micro-nanodispersed organic systems. Their unique solvent properties and ability to withstand large temperature variations make them valuable for industrial purposes. Generating a high enough super saturation for a precipitation reaction with traditional solvents is limited by the solubility's low dependence on temperature and the technical challenge of quickly exchanging heat. Given this consideration, one particular method worth noting is the use of liquid CO2 as a refrigerant. During this process known as contact cooling, the solution containing the active compound is sprayed at -78 °C into a CO2 stream, leading to the formation of particles through crystallization in the droplets. Considering toxicological compatibility, the lack of combustibility, and the advantageous critical characteristics of CO2 (pc=74 bar, Tc=31°C), the RESS method (rapid expansion of supercritical solutions) seems highly appealing, as additional procedures to eliminate remaining solvent may not be necessary. Nevertheless, SF-CO2 is capable of acting as an oxidizing agent towards oxidation-sensitive compounds like β-carotene, which is why it is not suitable for use as a precipitation medium. In both the GAS process and the PCA process, SF-CO2 is used as the precipitation medium instead of water for organic solvents. In the SEDS process, the organic active-compound solution and SF-CO2 are rapidly extracted by bringing them into contact in a coaxial mixing nozzle. Nevertheless, so far only incidences of particle creation in the micrometer size range have been documented [22].

3. Particle Design in Drug Delivery Applications:

Most pharmaceutical processes for particle generation and pretreatment operations are still basic, ineffective, and severely restricted. The conventional high-energy milling method for particle size reduction is ineffective and prone to morphological and crystallographic alterations. Changes like that could modify the physical and chemical stability of the downsized material. Using SFT for crystal and particle engineering of pharmaceutical materials and drug delivery systems presents significant potential in this field. The constraints restrict the ability to create particles in sizes ranging from micro to submicron. Recently, the SAS method has demonstrated significant promise in generating micron-sized particles for various compounds like insulin, lysozyme, trypsin, methylprednisolone, and hydrocortisone[23].

4. Plant material extraction:

The extraction industry is utilizing supercritical fluid due to its numerous advantageous qualities that can be taken advantage of. In comparison to traditional solvent extraction methods, supercritical fluid extraction is a quicker process with greater precision, requiring fewer parameters to track. The solvents used are eco-friendly, leading to a higher quality of extraction yield. The processing of plant material is extremely intricate, taking into account factors such as plant nature, processing parameters, solvent physicochemical properties, and mass transfer phenomena. Supercritical fluids have been widely utilized for extracting plant materials. Fatty acid, essential oil, flavonoids, saponins, phenolic group, and carotenoid have been obtained from different plants through adjusting the extraction process[24].

5. Supercritical drying:

Supercritical drying surpasses the critical point of the working fluid to prevent the typical liquid-gas transition observed in regular drying. It is a method of eliminating liquid in a carefully controlled manner, much like freeze drying. It is typically utilized in making aerogel and in preparing biological samples for scanning electron microscopy. When a substance transitions from a liquid to a gas in the phase diagram, it evaporates causing a decrease in liquid volume. While this occurs, the tension on the surface of the solid-liquid connection resists any objects the liquid is clinging to. Fragile formations such as cell walls, dendrites in silica gel, and the small components of microelectromechanical devices are prone to breakage due to surface tension when the interface passes through. In order to prevent this situation, the sample can be transitioned from liquid to gas without crossing the liquid-gas boundary on the phase diagram; during freeze-drying, this involves going around to the left (low temperature, low pressure). Nevertheless, certain formations are disturbed by the solid-gas boundary. Alternatively, supercritical drying takes a different path by moving to the right side of the line, where both temperature and pressure are high. This transition from liquid to gas does not go through a phase boundary, but goes through the supercritical region where the difference between gas and liquid becomes irrelevant. Carbon dioxide and freon are appropriate fluids for supercritical drying. In its supercritical state, nitrous oxide acts as a potent oxidizer despite having physical characteristics like carbon dioxide. Supercritical water is a strong oxidizer due in part to its high critical point temperature and pressure of 374 °C and 647°K and 22.064 Mpa, respectively[25].

II. CONCLUSIONS

In the past two decades, there has been a rise in the utilization of supercritical fluid extraction in natural product research. SFE-based techniques show great potential in the field of analytical chemistry. They can also be used effectively as a tool to optimize and test the feasibility of non-analytical applications, such as exploring the possibility of expanding SFE for industrial use. Utilizing automated analytical SFE tools enables quick evaluation of SFE feasibility at a low cost and in a short amount of time. SFE techniques have been utilized for extracting an extensive variety of extracts, oils, oleoresin, and various bioactive compounds (such as alkaloids, terpenes, and phenolics), including individual compounds. SFE and SFC have a wide range of uses in qualitative analysis, such as in the analysis of various samples like food items, natural products, agrochemicals, environmental samples, fuels, lubricants, artificial polymers, oligomers, organometallic compounds, pharmaceutical agents, and chiral compounds essential for biology. SCF provides a more sustainable and selective option for qualifying and quantifying natural products compared to conventional methods. In collaboration, SCF-driven extraction techniques show significant potential and therefore deserve additional research.

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