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Review Article

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Supercritical Fluid Extraction: A Green and Sustainable Approach for the Isolation of High-Value Compounds from Natural Sources

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ABSTRACT

Supercritical Fluid Extraction (SFE) has emerged as a green and sustainable technique for isolating high-value bioactive compounds from natural sources. This method leverages the unique properties of supercritical fluids, particularly supercritical carbon dioxide (SC-CO_2), to enhance the selectivity, efficiency, and environmental sustainability of the extraction process. Compared with traditional methods that use solvents, SFE has several benefits, such as leaving behind very little solvent, causing less damage to heat-sensitive compounds, and improving the amount extracted. This review provides a comprehensive overview of the principles of SFE, including thermodynamics, phase behaviour, and selection of supercritical fluids. Furthermore, it highlights the optimization parameters that influence extraction efficiency, such as pressure, temperature, co-solvent use, and flow rate. The applications of SFE in the recovery of phytochemicals, essential oils, nutraceuticals, and marine-derived bioactive compounds are discussed, with emphasis on its role in the pharmaceutical, food, and cosmetic industries. Additionally, this review explores recent advancements in SFE technology, including its integration with other green extraction methods and novel equipment designs, while addressing the challenges associated with industrial-scale implementation. Finally, future perspectives on enhancing the efficiency, cost-effectiveness, and sustainability of SFE are outlined, reinforcing its potential as a key technology in green extraction science.

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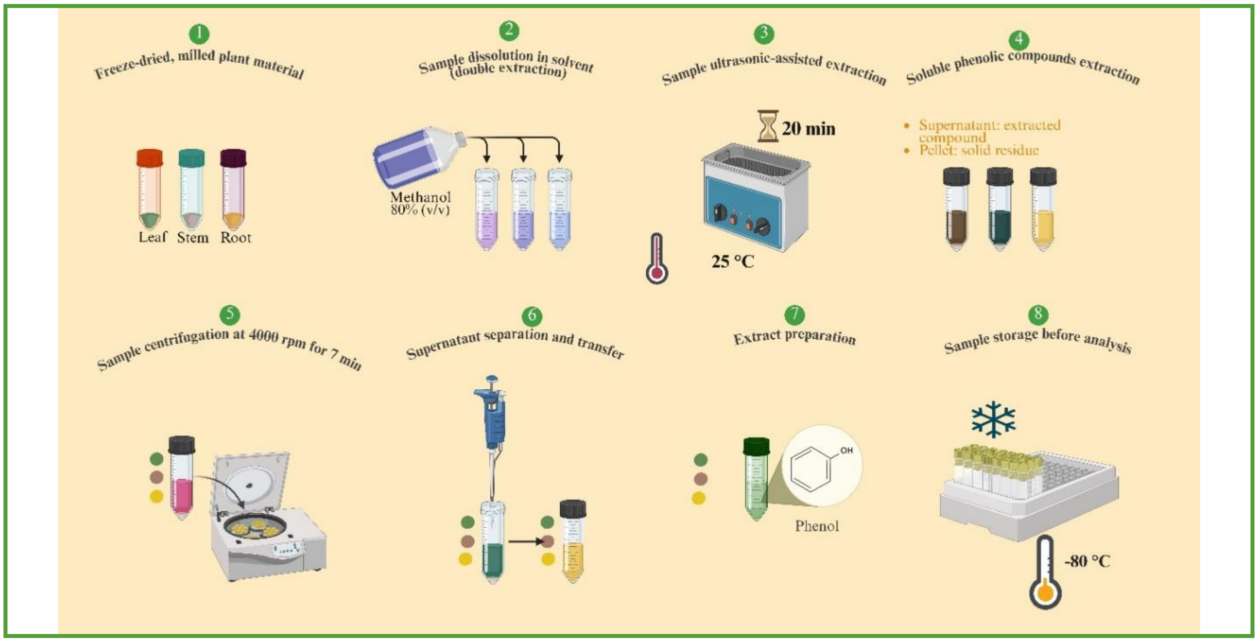
Graphical Abstract



Introduction

Supercritical Fluid Extraction (SFE) has been widely used for the extraction of taste and fragrance components from complex matrices, without the use of organic solvents. This method relies on the utilization of gases in a supercritical state, specifically under designated pressure and temperature conditions [1]. The latest advancements in SFE from 2007 to 2009 have occurred across various domains, including food science, natural products, by-product recovery, pharmaceuticals, and environmental sciences. This highlights the significant impact of SFE on obtaining high-value compounds from food and natural products, heavy metal recovery, enantiomeric resolution, and drug delivery systems [2]. SFE is a method used to separate chemicals and flavours from products such as coffee, tea, hops, herbs, and spices. It involves mixing a supercritical fluid with a mobile phase to enhance the solvating power. SFE is a simple, inexpensive, fast, effective, and virtually solvent-free sample pretreatment technique that is typically performed with pure or modified carbon dioxide. Factors influencing extraction yields include the solubility of the solute in the fluid, diffusion through the matrix, and the collection process. SFE was compared to conventional extraction methods in terms of selectivity, rapidity, cleanliness, and the ability to manipulate the extract composition. The principle of SFE is to optimize the solubility of materials and improving fractionation [3]. SFE is a nontoxic, inexpensive, non-flammable, and non-polluting method used in the palm oil industry. SC-CO_2 is a nontoxic, inexpensive, and non-polluting solvent for the extraction of natural products. It allows for almost 100% oil extraction, with organic-solvent-free extracts having superior organoleptic profiles. Malaysia, the second largest palm oil and palm kernel oil producer globally, utilizes SC-CO_2 for oil extraction, producing fractionated, refined, bleached, deodorized, and purified fatty acid fractions for downstream uses, such as toiletries and confectionaries [4]. SFE is gaining popularity in various industries for extracting valuable compounds from solid materials such as plant parts. To optimizing the process and achieving maximum extraction yield, reliable and robust mathematical modelling is crucial. This review critically discusses different mathematical modelling strategies for SFE in packed bed columns and evaluates their features, assumptions, validity, mathematical expressions, and applications. It also reviews studies on the SFE of plant matrices, highlighting the systems, models, and operational conditions. This review aims to help the scientific community identify the most suitable models and operating conditions for different systems in the SFE process [5]. Green extraction techniques (GreETs) have emerged as sustainable alternatives to the classical sample preparation procedures. They aim to improve selectivity and sensitivity, while reducing environmental and operator-related side effects. These techniques aim to reduce the energy and resource consumption, aligning with the principles of green chemistry. This review updates the state-of-the-art cutting-edge GreETs, focusing on improving analytical features, practical aspects, and applications in the biological, food, and environmental fields. Techniques include sorbent-based techniques, such as SPME and FPSE, solvent-based techniques, such as μQuEChERS, ultrasound-assisted extraction, microwave-assisted extraction, SFE, and pressurized solvent extraction [6]. Green technology has significantly affected the recovery of natural compounds in the food industry, with innovative extraction techniques such as supercritical fluid, pressurized liquid, microwave, ultrasound, and cold atmospheric plasma extraction. These methods, combined with green solvents such as deep eutectic and ionic solvents, offer a viable alternative to traditional extraction methods and prevent the formation of toxic effluents. However, these techniques have limitations including capital investment and running costs, which may pose significant challenges to their implementation and application [7]. Green extraction methods for natural products are a multidisciplinary field involving applied chemistry, biology, and technology. This paper introduces six principles of green extraction, a strategy for research and industrial applications, focusing on innovative technologies, process intensification, agro-solvents, and energy saving. The concepts and principles provide an updated view of technological efforts and diverse applications [8]. Natural resources are valuable and are rich in bioactive substances. Technology is crucial for the extraction of these substances. Scientists are exploring eco-friendly methods, including green solvents such as supercritical fluids and deep eutectic solvents, and physical auxiliary methods such as microwave- and ultrasonic-assisted protocols. Water-based green extraction methods are becoming increasingly popular because they are considered the least toxic solvents. This mini-review provides a starting point for readers interested in sustainable water-based extraction protocols of value-added compounds [9]. Recent advances in extraction techniques for biofuel production include conventional solvent extraction, physically supported solvent extraction, SFE, and novel extractions. This study provides a comprehensive review of these methods, their advantages and limitations, and recent case studies. The focus is on third-generation algal biofuel production, highlighting the potential of free from drying and cell disruption (FDC) routes to reduce energy consumption [10].

SFE is a green and sustainable method for the separation of high-value bioactive chemicals from natural sources, and was thoroughly explored in this study. It emphasizes the basic ideas, operational criteria, and benefits of SFE over traditional extraction techniques. The paper also highlights current developments, uses in many sectors, and the environmental advantages of supercritical CO_2 utilisation. The main goal is to provide thorough knowledge of SFE's possibilities of SFE in natural product extraction, thereby encouraging its acceptance in the food, nutraceutical, and pharmaceutical industries.

Principles of SFE

Definition and characteristics of supercritical fluids

Supercritical fluids (SCFs) are substances that are maintained above their critical temperature (Tc) and critical pressure (Pc), where they exhibit unique physicochemical properties that are intermediate between those of liquids and gases. In this supercritical state, the fluid possesses the diffusivity and viscosity of a gas, while maintaining the density and solvating power of the liquid. The most widely used SCF in extraction processes is supercritical carbon dioxide (SC-CO_2) owing to its mild critical conditions (Tc = 31.1 °C, Pc = 73.8 bar), non-toxic nature, and easy removal from extracts [11]. The unique characteristics of SCFs make them particularly attractive for application in the pharmaceutical, nutraceutical, and food industries. The tunable density of SCFs allows for selective solvation, which can be adjusted by manipulating pressure and temperature. According to Reverchon and De Marco (2006), the solubility of solutes in SCFs increases with pressure because of their higher density, thereby improving the extraction efficiency [12]. SCFs also replace organic solvents, thereby offering a better and more environmentally friendly extraction method. Herrero *et al.* (2010), for example, found that SC-CO_2 produced up to 23% more carnosic acid by more efficiently extracting antioxidants from rosemary leaves than ethanol-based extraction [13]. SCFs provide a durable, effective, and selective method to extract bioactive molecules. Modern green extraction methods are based on low viscosity, high diffusivity, and controllable solvating power [14]. Figure 1 displays the stepwise method for separating and conserving bioactive molecules from micro-algal cultures. This process involves procedures such as SFE, ultrasound-assisted extraction, and enzyme-assisted extraction to recover intracellular components. The bioactive components were concentrated and cleaned using downstream processing methods. Encapsulation techniques, such as Spray Drying and Microencapsulation, improve stability and functionality, resulting in the formulation of bioactive chemicals suitable for various biomedical and nutraceutical applications.

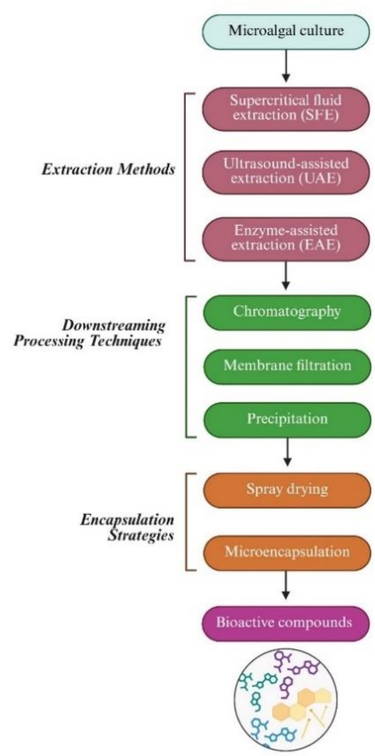


Figure 1. Schematic representation of the extraction, processing, and encapsulation strategies for obtaining bioactive compounds

Thermodynamics and phase behaviour

Understanding the thermodynamics and phase behaviour of SCFs is crucial for optimizing the extraction process. The behaviour of SCFs is governed by equations of state (EOS), such as the Peng-Robinson and Soave-Redlich-Kwong models, which predict phase equilibrium and solubility data under supercritical conditions [15]. Solute solubility in supercritical extraction is strongly influenced by the fluid density. The density of the fluid decreased with increasing temperature under constant pressure, thereby lowering its solubility. However, increasing the pressure at constant temperature increases the fluid density and solute solubility. Brunner (1994) first identified this interaction as the "crossover pressure" phenomenon [16]. Phase behaviour studies revealed that solubility is not linearly dependent on pressure or temperature alone, but rather on the density of the SCF (Table 1). For example, Sovová *et al.* (2001) demonstrated that the solubility of essential oils in SC-CO_2 increased significantly when the pressure increased from 100 to 300 bars, even though the temperature was constant at 40 °C [17]. Co-solvents (entrainers), such as ethanol or methanol, may be added to SCFs to change the polarity and improve the solubility of polar solutes. Such interactions are precisely predicted using thermodynamic models that combine fugacity and activity coefficients [18]. Thermodynamic and phase behaviour studies are instrumental in designing efficient SCF extraction systems. They provide a theoretical foundation for scaling up and optimizing the operating parameters to achieve a maximum extraction yield [19].

Table 1. Thermodynamic parameters and phase behaviour in SFE

Parameter	Description	Importance in SFE	Typical Range	Influence on Extraction	Ref.
Critical Temperature (Tc)	The temperature above which a substance cannot exist as a liquid, regardless of pressure	Determines the onset of supercritical behaviour	CO_2: 31.1°C; Ethanol: 241°C	Lower Tc allows milder extraction conditions	[20]
Critical Pressure (Pc)	Minimum pressure required to liquefy a gas at its critical temperature	Affects energy requirements	CO_2: 73.8 bar; Ethanol: 63 bar	Influences equipment design and safety	[21]
Density of SCF	Mass per unit volume under supercritical conditions	Affects solvating power	CO_2: 0.2-1.0 g/cm^3 (variable with P & T)	Higher density → better solvation → higher yield	[22]
Viscosity	Resistance to flow in SCF	Determines mass transfer rate	CO_2: ~0.03–0.1 cP	Lower viscosity → higher diffusivity → faster extraction	[23]
Diffusivity	Solute mobility in SCF	Influences extraction rate and efficiency	10^{-4}–10^{-3} cm^2/s	Higher diffusivity allows quicker penetration into plant matrix	[24]

Parameter	Description	Importance in SFE	Typical Range	Influence on Extraction	Ref.
Enthalpy of Solvation	Heat released or absorbed during solvation	Reflects solvent–solute interactions	Typically, exothermic	Influences selectivity and loading capacity	[25]
Solubility Parameter (δ)	Measure of solvent power	Key for selecting SCF-solute compatibility	CO_2: ~6.3 $cal^1/^2/cm^{31}/^2$	Matching δ increases solubility of target	[26]
Phase Behavior	Relationship between phases under changing P-T conditions	Guides process optimization	Binary/ternary phase diagrams used	Determines operating window, prevents phase separation	[27]
Crossover Pressure	Pressure where solubility behaviour reverses with temperature	Determines optimal operating zone	Depends on solute-SCF pair	Above it: solubility ↑ with T; Below it: solubility ↓	[28]
Co-solvent Effect	Modifies polarity and solubility	Enhances extraction of polar compounds	Ethanol, Methanol often used at 5-15% v/v	Alters phase equilibrium and thermodynamics	[29]
Selectivity	Ability to target specific compound types	Critical for purity and efficiency	Controlled via P, T, and modifiers	High selectivity reduces need for post-purification	[30]
Enthalpy and Entropy Change (ΔH, ΔS)	Governs solubility via Gibbs Free Energy $\Delta G = \Delta H - T\Delta S$	Indicates spontaneity of extraction	Typically, $\Delta H < 0$ and $\Delta S > 0$	A negative ΔG implies favorable extraction	[31]

Selection of SCFs

The choice of SCF is primarily dictated by the nature of the solute and the matrix. The key selection criteria include critical parameters (Tc and Pc), polarity, toxicity, flammability, and environmental impact. Carbon dioxide is the most commonly employed SCF owing to its moderate critical conditions, inertness, and Generally Recognized as Safe (GRAS) status by the Food and Drug Administration (FDA) [32]. To improve polarity, modifiers such as ethanol, methanol, or water are sometimes added to SC-CO_2 for the extraction of polar chemicals. For instance, Mendes *et al.* (2003) found that the addition of 10% ethanol added to SC- CO_2 during grape seed extraction increased the phenolic content by 35% [33]. The alternative SCFs are nitrous oxide, ethane, propane, and even water (for subcritical water extraction) (Table 2).

Although propane and ethane are suitable for nonpolar extractions, their flammability limits their commercial use. Although high running temperatures restrict its use, subcritical water (Tc = 374 °C, Pc = 221 bar) has emerged as a possible green solvent for extracting thermally stable polar chemicals [34].

Table 2. Properties of common SCFs

SCF	Tc (°C)	Pc (bar)	Polarity	Notes
CO_2	31.1	73.8	Non-polar	Non-toxic, inert, affordable
Propane	96.7	42.5	Non-polar	Flammable, good solvent
Ethanol	240.8	63	Polar	Used as co-solvent
Water	374	221	Polar	High Tc and Pc

Mechanism of solute extraction

Solute dissolution into the SCF, diffusion throughout the plant matrix, and separation by depressurization constitute the numerous phases of the extraction process employing SCFs. Initially, SCF's low viscosity and high diffusivity of SCF help it pass through the porous structure of the material. It brings solutes to a separation vessel and breaks them according to their compatibility with the SCF [35]. The mechanism can be divided into four main stages: (1) SCF penetration and matrix swelling, (2) solute desorption, (3) solubilisation and transport, and (4) solute precipitation via depressurization or temperature reduction. The efficiency of each stage depends on factors such as particle size, temperature, pressure, and co-solvent presence [5]. The extraction kinetics has been studied extensively developed a widely used mathematical model to describe the SC-CO_2 extraction kinetics for essential oils and fatty acids, which considers external mass transfer resistance and internal diffusion. The model has been validated by several researchers and has shown good agreement with experimental data across various plant matrices [36]. Researchers have demonstrated that applying higher pressures (up to 400 bars) during SC-CO_2 extraction of turmeric resulted in up to 90% curcuminoid recovery within 2 h, significantly reducing the extraction time compared to conventional methods [37]. Mass transfer may be further improved, and the yield is increased by ultrasonic- or microwave-assisted SCF extraction. These hybrid methods break down cell barriers and enhance SCF access to intracellular substances [38]. Mass transfer concepts and solvent-solute interactions generally define the SCF extraction process. Optimization of operation parameters may result in very selective and effective extraction techniques [39]. Figure 2 depicts a technique for obtaining phyto-constituents from plant materials: collection, drying, grinding, cold maceration, filtering, rotational evaporation, and storage. Widely used in herbal and medicinal research, this approach guarantees minimal degradation of thermolabile substances.

Supercritical fluids: Types and applications

Carbon dioxide (CO_2) as a green solvent

Carbon dioxide (CO_2) is the most widely used supercritical fluid (SCF) owing to its environmentally friendly nature, moderate critical parameters (Tc = 31.1 °C and Pc = 73.8 bar), and excellent physicochemical properties. It is non-toxic, non-flammable, chemically inert, inexpensive, and readily available. Furthermore, its easy post-extraction removal and low environmental footprint make it a sustainable and green solvent for numerous industrial applications [40].

SC-CO_2 is particularly efficient for extracting non-polar to moderately polar compounds. The solvating power of SC-CO_2 increases with increasing pressure as its density increases, enabling the selective extraction of lipids, essential oils, alkaloids, carotenoids, and other bioactive compounds.

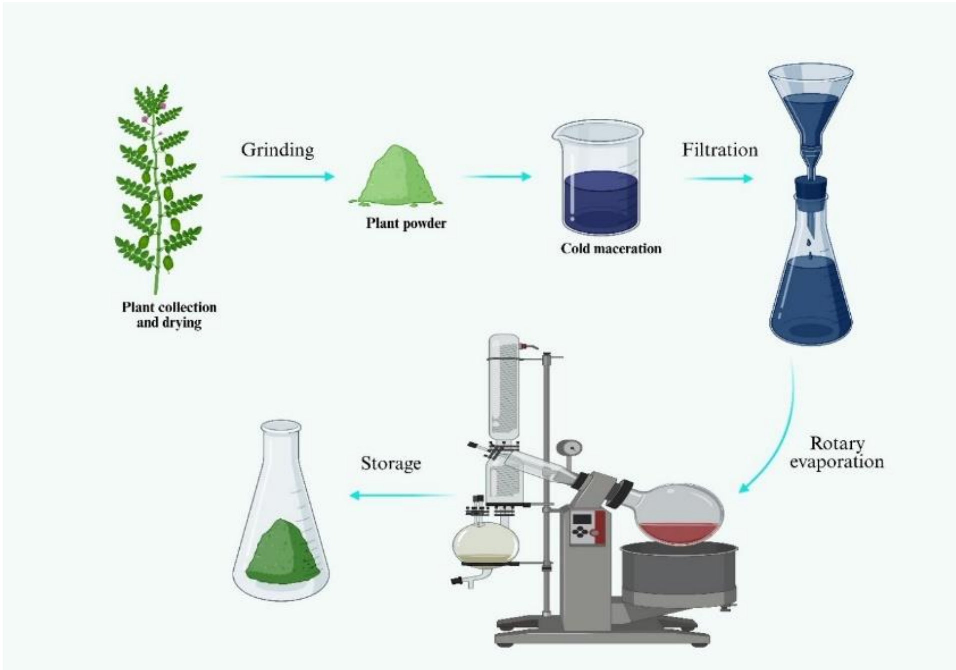


Figure 2. Schematic illustration of the plant extraction

Its mild temperature conditions prevent thermal degradation, making it ideal for thermolabile compounds, especially in the food and pharmaceutical industries [41].

Researchers have shown that SC-CO_2 extraction of carnosic acid from rosemary is more efficient than conventional methods, offering a higher purity yield without the need for organic solvents. Similarly, Reverchon and De Marco (2006) highlighted SC-CO the ability to extract valuable compounds from natural sources, with minimal thermal and oxidative degradation [42].

Decaffeinating coffee and tea also makes great use of SC-CO_2, which selectively eliminates caffeine while maintaining the taste and fragrance. In pharmaceuticals, it functions in drug encapsulation, particle generation, and sterilization agent creation. The non-toxic profile has allowed both the European Food Safety Authority (EFSA) and the U.S. FDA to approve it for food and pharmaceutical uses [43].

The SC-CO_2 adoption also supports the green chemistry principles. Since CO_2 is typically a by-product of fermentation or combustion, its reuse in extraction processes does not contribute additional emissions, aligning with circular economic goals. Overall, SC-CO_2 stands out as a clean, efficient, and scalable solvent for green extraction technologies [44].

Alternative supercritical fluids and co-solvents

While CO_2 is the predominant SCF used in extractions, other supercritical fluids and co-solvents have also been explored to enhance the extraction efficiency, especially for polar compounds that are less soluble in SC-CO_2. Alternative SCFs include nitrous oxide, propane, ethane, ammonia, and subcritical water, each offering specific advantages and limitations depending on the extraction target and matrix [45]. Propane (Tc = 96.7 °C, Pc = 42.5 bar) is a non-polar SCF that demonstrates excellent solvating power for lipophilic compounds. Due to its low critical pressure, it is suitable for extracting oils, fragrances, and terpenoids. However, their flammability limits their industrial applications unless used in controlled environments [46].

Ethanol and methanol are common co-solvents (modifiers) added to SC-CO_2 to increase their polarity. These modifiers improve the solubility of polar molecules such as phenolics, flavonoids, and glycosides. Mendes *et al.* (2003) demonstrated that adding 10% ethanol to SC-CO_2 during grape seed extraction increases the yield of polyphenols by 35%, highlighting the importance of solvent polarity in selective extraction [47].

Subcritical water extraction (SWE) utilizes water at temperatures between 100 °C and 374 °C, and pressures sufficient to maintain it in a liquid state. Under these conditions, the dielectric constant of water decreases, making it behave like an organic solvent capable of extracting phenolic compounds, alkaloids, and other polar constituents [48].

Ionic liquids and deep eutectic solvents are emerging as tunable green co-solvents that can be used in conjunction with SCFs. Although their applications are still in the early stages of research, their potential in enhancing solubility and selectivity is promising [49].

Different SCFs and co-solvents increase the general spectrum of chemicals for which supercritical extraction is used. Solute polarity, thermal stability, matrix type, and target industry—that is, pharmacologic, food, and cosmetics—all influence the choice. Combining co-solvents and SCFs customizes extraction settings for the best selectivity and efficiency [32].

Comparison with conventional extraction methods

SFE has several advantages over conventional extraction methods such as solvent extraction, Soxhlet extraction, and steam distillation. Traditional methods often involve large volumes of organic solvents, prolonged extraction times, and high temperatures, which can degrade thermolabile bioactive. In contrast, SFE offers a faster, cleaner, and more selective extraction [50].

Solvent toxicity is one of the main drawbacks of the traditional techniques. Residues from solvents might linger in the final extracts, raising safety issues, especially in food and medicinal applications. As a safer substitute, SC-CO_2 is non-toxic and leaves no adverse residues. Moreover, easy depressurization allows CO_2 to be readily removed from the extracts, thereby eliminating the need for sophisticated purification techniques [51].

Efficiency and selectivity are also key strengths of the SFE. The tunable density of SCFs allows modulation of their solvating power by adjusting the pressure and temperature. This leads to higher extraction yields and better control over target compound recovery. Kitzberger *et al.* (2007) showed that SC-CO_2 achieved 95% caffeine removal from green coffee beans in just 3 h, whereas conventional solvent methods required over 12 h with additional steps [52].

Thermal degradation is another concern in the conventional methods. Steam distillation and Soxhlet extraction involve high temperatures, which can destroy volatile or heat-sensitive compounds. SFE, operating at near-ambient temperatures, preserves these compounds and improves extract quality. For instance, the extraction of essential oils from lavender using SC-CO_2 preserved over 90% of linalool, a key fragrance compound, while conventional steam distillation degraded up to 40% [1]. Is SFE more environmentally friendly than standpoint? This cuts trash creation and reduces the demand for dangerous chemicals. Widespread industrial usage may be hampered by the initial equipment costs and high-pressure operating requirements [1]. SFE offers a better substitute in terms of safety, efficiency, product quality, and environmental effects, even if traditional approaches are still in use, because of their simplicity and cheaper starting costs. Its increasing use in cosmetics, food technology, and medications has emphasized its importance in green extraction research [50].

Applications of SFE in the extraction of high-value compounds

Phytochemicals from medicinal plants

SFE, particularly with CO_2, has emerged as an efficient and green method for the isolation of phytochemicals from medicinal plants. Phytochemicals such as alkaloids, flavonoids, terpenoids, and polyphenols possess potent therapeutic properties and are widely used in pharmaceuticals, cosmetics, and traditional medicine [53]. SC-CO_2 provides several advantages for extracting these compounds: low operating temperatures to preserve thermolabile constituents, selective extraction by modifying the pressure and temperature, and absence of toxic solvent residues. Moreover, co-solvents, such as ethanol, can be used to enhance the solubility of polar phytochemicals [54]. Scientists have shown the efficient extraction of flavonols and phenolic acids from sea buckthorn leaves using SC-CO_2 with ethanol as a co-solvent, yielding high-purity extracts with strong antioxidant activity. Similarly, Bhattacharya *et al.* (2008) reported that SC-CO_2 was successful in extracting with anolides and bioactive steroidal lactonesfrom *Withania somnifera* (Ashwagandha), which are valuable for their adaptogenic and anti-inflammatory effects [55]. Figure 3 depicts the development and selective breeding of wild *Brassica spp.* plants into many grown vegetable types. Some sections of the plant have been improved by deliberate modification and domestication to provide the desired features. While broccoli was improved for both stems and blooms, cauliflower, and cabbage were specifically cultivated for their floral buds. In contrast, char/kale strains were created from nutrient-dense leaves.

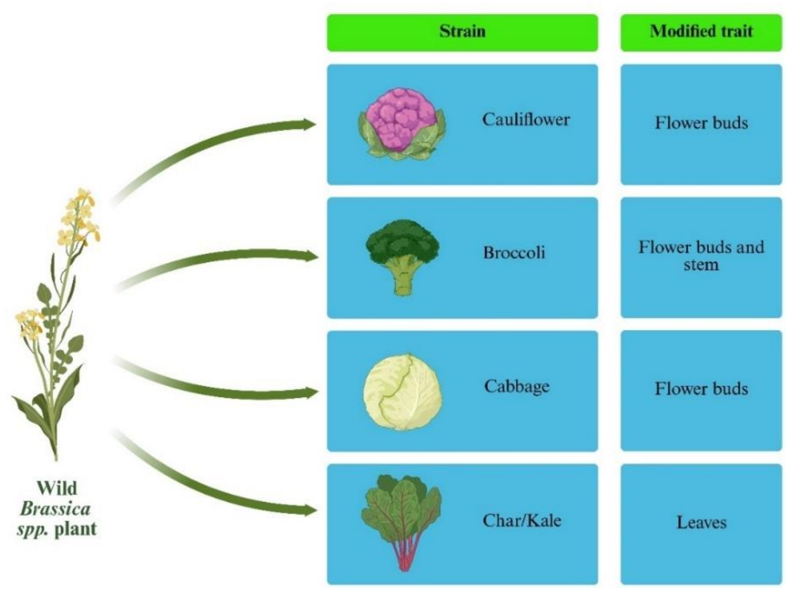


Figure 3. Domestication of wild *Brassica* spp. into various vegetable crops with modified traits

This trait selection process underlines the agricultural importance of Brassica species in contemporary diets, and shows the variety of edible forms obtained from a single wild progenitor.

SFE has also been shown to be effective in the isolation of anticancer agents. Compounds such as curcumin from turmeric (*Curcuma longa*) and camptothecin from *Camptotheca acuminata* have been successfully extracted using SCF technology, with higher yields and better bioactivity preservation than conventional methods. In many cases, particle size reduction and pre-treatment (e.g., drying or grinding) of plant materials significantly enhance the extraction efficiency by increasing the surface area [56]. Moreover, SFE promotes fractionation, thereby enabling selective recovery of many chemicals from a single plant matrix. In pharmaceutical development, where purity and chemical specificity are absolutely important, this skill is highly sought after [57]. Therefore, SFE is a strong, environment-friendly technique for obtaining valuable phytochemicals that meet the objectives of contemporary green chemistry and pharmaceutical development [53].

Essential oils and aromatic compounds

Essential oils and aromatic compounds are complex mixtures of volatile constituents including terpenes, esters, alcohols, aldehydes, and ketones. They are extensively used in perfumery, aromatherapy, food flavouring, and pharmaceuticals. Traditional extraction methods, such as steam distillation, often degrade these volatile compounds owing to prolonged exposure to high temperatures. SFE is a superior alternative for preserving the integrity and aroma profile of essential oils [58]. SC-CO_2 is the most suitable SCF for extracting essential oils because of its non-polar nature, which matches well with the lipophilic characteristics of many volatile compounds. By adjusting the pressure and temperature, specific components can be selectively extracted, enabling fractionation and avoiding degradation of heat-sensitive compounds [59]. It has been reported that SC-CO_2 extraction of lavender oil preserves over 95% of linalool and linalyl acetate, key aromatic constituents, whereas steam distillation leads to substantial losses. Similarly, the extraction of clove oil using SFE yielded a higher eugenol content and better sensory quality than hydrodistillation [60].

Table 1 provides a comprehensive overview of the application of SFE for isolating essential oils and aromatic compounds from various natural plant sources. The table summarizes the key details, including the source material, major target compounds, and supercritical fluid (SCF), primarily SC-CO_2, along with optimized extraction conditions, such as pressure, temperature, and duration. It also notes the use of co-solvents (mainly ethanol) to enhance extraction efficiency, particularly for polar or complex compounds. The yield of extracted bioactive compounds was reported as a percentage of dry weight, highlighting the SFE efficiency compared to conventional techniques. Additionally, the remarks column elaborates on the unique advantages offered by SFE, such as improved selectivity, enhanced purity, better preservation of thermolabile compounds, and absence of harmful solvent residues. These data support the potential of SFE as a green, sustainable, and high-performance extraction technology for natural products in pharmaceutical, cosmetic, nutraceutical, and food applications.

Table 3 indicates the applications of SFE for the isolation of Essential Oils and aromatic compounds.

Table 3. Applications of SFE for isolating essential oils and aromatic compounds from natural sources

Plant Source	Target Compound(s)	SCF Used	Extraction Conditions *(Pressure/Temperature/Time)*	Co-solvent Used	Yield (% w/w)	Research Findings	Ref.
Lavandula angustifolia	Linalool, Linalyl acetate	CO_2	150 bar / 40 °C / 60 min	Ethanol (5%)	2.50%	Comparable to steam distillation, faster extraction, and better aroma preservation	[61]
Cymbopogon citratus	Citral, Geraniol	CO_2	200 bar / 45 °C / 90 min	Ethanol (10%)	1.80%	Enhanced selectivity for citral with ethanol addition	[62]
Rosmarinus officinalis	1,8-Cineole, α-Pinene, Camphor	CO_2	250 bar / 50 °C / 60 min	None	2.10%	SFE yields higher purity extracts with strong antioxidant activity	[42]
Origanum vulgare	Carvacrol, Thymol	CO_2	300 bar / 55 °C / 120 min	Ethanol (7%)	3.00%	High bioactivity and antimicrobial potency in SFE extract	[63]
Mentha piperita	Menthol, Menthone	CO_2	100 bar / 35 °C / 45 min	None	1.50%	Gentle temperature preserves menthol content effectively	[64]
Cinnamomum verum	Cinnamaldehyde, Eugenol	CO_2	280 bar / 60 °C / 60 min	Ethanol (5%)	3.20%	Strong antioxidant and antimicrobial potential	[65]
Boswellia serrata	Boswellic acids, Incensole	CO_2	350 bar / 65 °C / 90 min	Ethanol (15%)	2.70%	Effective in extracting resinous aromatic compounds	[66]
Pelargonium graveolens	Geraniol, Citronellol	CO_2	150 bar / 40 °C / 60 min	Ethanol (10%)	2.00%	High fragrance retention, suitable for cosmetics/perfu	[67]

Plant Source	Target Compound(s)	SCF Used	Extraction Conditions *(Pressure/Temperature/Time)*	Co-solvent Used	Yield (% w/w)	Research Findings	Ref.
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Zingiber officinale	Gingerols, Shogaols	CO_2	300 bar / 60 °C / 120 min	Ethanol (10%)	3.40%	Superior antioxidant and anti-inflammatory activity in SFE extract	[68]
Curcuma longa	Curcumin, Turmerones	CO_2	320 bar / 55 °C / 120 min	Ethanol (5%)	4.10%	SFE offers clean extract with enhanced bioavailability and minimal degradation	[69]

SFE also avoids the problem of solvent residue, which is a common concern in organic solvent extraction. Additionally, the ability to produce solvent-free, high-purity essential oils makes SC-CO_2 extraction particularly attractive to the natural cosmetics and organic food industries [70]. Additionally, SFE, used professionally for essential oil extraction from rose, peppermint, citrus peels, and other botanicals, may be scaled for industrial use. The mild and adjustable character of the process guarantees excellent product quality, which appeals to luxury markets where natural authenticity and purity are highly appreciated [58]. Ultimately, SFE provides a scalable, clean, and effective method for the extraction of aromatic components and essential oils, thereby conserving volatile profiles and producing goods of great economic value [58].

Nutraceuticals and functional foods

Nutraceuticals and functional foods, which offer health benefits beyond basic nutrition, represent a rapidly growing segment of the food and health industries. Compounds, such as omega-3 fatty acids, carotenoids, phytosterols, tocopherols, and polyphenols, are frequently targeted for their antioxidant, anti-inflammatory, cardioprotective, and anti-aging properties. SFE is increasingly utilized to obtain these bioactive compounds because of its non-toxic, residue-free process, and high extraction efficiency [32]. For instance, SC-CO_2 has been used to extract lycopene and β-carotene from tomato peels with high efficiency, providing natural antioxidants for use in functional foods and supplements. SFE also excelled in the extraction of tocopherols (vitamin E compounds) from plant oils. A study by Dutta and Bhattacharjee (2008) demonstrated that SC-CO_2 extraction of rice bran oil retained significantly higher tocopherol content than hexane extraction [71]. Omega-3 rich oils, particularly EPA and DHA, from microalgae or fish by-products are another major target. Traditional solvent extraction often results in oxidation and loss of these sensitive fatty acids. In contrast, SFE operates at lower temperatures in an oxygen-free environment, thus preserving the integrity of these lipids. For example, Shahidi and Synowiecki (1997) showed that SC-CO_2 extraction of fish liver oil preserved over 90% of omega-3 content, outperforming solvent-based methods in terms of both yield and stability [72]. SFE also has applications in removing undesirable compounds such as cholesterol from animal fats and caffeine from coffee, thereby improving the nutritional profile of food products. Its use in enriching plant extracts with bioavailable polyphenols further supports its role in functional food development [73]. SFE is a promising green technology that provides premium, solvent-free extracts with maintained bioactivity and extended shelf life for the manufacture of functional food components and nutraceuticals [12].

Bioactive compounds from marine and microbial sources

Marine organisms and microorganisms are rich sources of bioactive compounds including polysaccharides, lipids, pigments, antibiotics, and enzymes. These compounds exhibit diverse pharmacological properties such as anticancer, antimicrobial, and anti-inflammatory activities. The effective and sustainable extraction of these compounds is challenging because of the sensitivity of marine biomolecules and the complexity of microbial matrices. SFE offers a solution that provides mild, selective, and solvent-free extraction [74]. Microalgae, such as *Spirulina*, *Chlorella*, and *Dunaliella* produce carotenoids (e.g., astaxanthin and β-carotene), sterols, and polyunsaturated fatty acids. SC-CO_2 has been successfully used to extract these valuable compounds while maintaining their bioactivity. Mendes *et al.* (2006) reported the efficient extraction of astaxanthin from *Haematococcus pluvialis* using SC-CO_2, achieving higher yields than solvent-based methods [75]. Marine macroalgae also contain sulfated polysaccharides and polyphenols. Although their high polarity poses a challenge for SC-CO_2, the use of ethanol as a co-solvent has enabled the effective recovery of polar antioxidants and anti-inflammatory agents. Moreover, SFE has shown promise in extracting lipophilic compounds such as sterols and omega-3 fatty acids from marine by-products such as fish heads and krill [76]. In microbial biotechnology, SFE has been employed for the recovery of secondary metabolites such as antibiotics and pigments. For instance, SFE was used to isolate erythromycin from fermentation broth with minimal degradation, offering a cleaner alternative to liquid-liquid extraction [77]. The major advantages of SFE in marine and microbial applications include reduced thermal degradation, minimal contamination, and ease of scale-up. It also facilitates process integration with bioreactors and the downstream purification steps [78].

Advantages and challenges of SFE

SFE advantages

Supercritical CO_2 is a non-toxic, non-flammable, and chemically inert solvent ideal for extracting bioactive compounds from plants, food, and other natural sources. They can be easily separated from the extracted material through depressurization, ensuring purity and safety in industries such as pharmaceuticals, nutraceuticals, and food. This aligns with green chemistry principles [79]. Traditional extraction methods such as solvent extraction, Soxhlet extraction, and steam distillation leave harmful residues in the extract. On the other hand, SC-CO_2 operates without residual solvents by reducing the pressure after extraction. This environmentally friendly process ensures that the compounds are free from harmful chemicals, making them crucial for food, cosmetic, and pharmaceutical applications [80]. SCFs, particularly CO_2, have a highly tunable solvating power through pressure and temperature control. This allows for selective extraction of specific compounds, making the process more efficient. For instance, certain bioactive compounds, such as terpenoids or lipids, require higher pressures, whereas others, such as polyphenols or flavonoids, require different conditions. This optimization results in higher purity extracts [32]. SC-CO_2, a low-temperature extraction technique, is ideal for preserving heat-sensitive compounds, such as essential oils, vitamins, and antioxidants, ensuring that their bioactivity remains intact and their functional properties are preserved, enhancing their efficacy in various applications. SFE is faster than traditional methods due to its efficiency in mass transfer and low viscosity. It can penetrate matrices and dissolve compounds quickly, reducing extraction times and achieving higher yields of bioactive compounds such as essential oils from plants. SC-CO_2 is a sustainable, eco-friendly extraction method that reduces environmental pollution, uses abundant, recyclable carbon dioxide, and minimizes waste, making it ideal for large-scale industrial applications [81]. SFE is highly scalable and suitable for both laboratory and large-scale industrial extractions, enabling continuous extraction processes and improved efficiency in large manufacturing settings [82].

SFE challenges

SFE systems are expensive owing to their high equipment and operational costs. High-pressure conditions require specialized infrastructure, making them less attractive for small-scale operations or industries with tight budgets. Additionally, the high cost may limit SFE's widespread adoption of SFE in developing countries, where cost efficiency is a key factor in decision-making [83]. SFE offers adjustable solvating power, but determining optimal parameters such as pressure, temperature, and flow rate for extraction can be complex. This requires an understanding of the system and experimentation, which can be time-consuming and costly, especially in industries with diverse raw materials. The need for co-solvents to enhance polar compound extraction may also complicate this process [84]. Supercritical CO_2, a non-polar fluid, has limited solvating power for highly polar compounds, such as polyphenols, alkaloids, and sugars. Adding co-solvents can improve extraction, but raises operational costs and affects extract purity. It may still be challenging to extract some highly polar compounds efficiently, necessitating alternative supercritical fluids or traditional solvent-based methods [85]. High-pressure SFE systems pose safety risks owing to the engineering and handling of CO_2. Proper management and specialized knowledge are crucial for safe operations. Detecting leaks in colourless and odourless CO_2 systems can be challenging. Safety protocols and modern engineering solutions can mitigate these risks [86]. Despite its success in industries such as pharmaceuticals, food, and cosmetics, SFE lacks a comprehensive understanding of its emerging applications. As new bioactive compounds and raw materials have been discovered, further research is needed to determine the optimal extraction methods, potentially delaying widespread adoption in new industries [87]. SFE may not be as effective for obtaining compounds from complex or heterogeneous matrices, such as plant tissues with tough cell walls or difficult materials, such as woody plants. Even with pre-treatment, the extraction efficiency may be lower than that of softer or more homogeneous materials, increasing the time, cost, and complexity of the extraction process [5].

Recent advances and future perspectives in SFE

Innovations in SFE equipment and techniques

SFE technology has recently advanced towards scalability, selectivity, and efficiency. Significant increases in extraction yields and operational stability have resulted from the evolution of high-pressure pumps, exact temperature and pressure control systems, and improved extraction vessels. The higher throughput made possible by innovations such as continuous-flow SFE devices has made the process more appropriate for major industrial applications. Furthermore, improved process control made possible by automation and real-time monitoring systems guarantees consistency and repeatability of the extraction results. The integration of advanced separation techniques such as supercritical fluid chromatography (SFC) with SFE has further expanded the capabilities of this technology. This combination allows for more precise fractionation and purification of the extracted compounds, opening up new possibilities in fields such as pharmaceutical and nutraceutical production. Additionally, the development of novel co-solvents and modifiers has enhanced the selectivity of SFE, enabling targeted extraction of specific compounds from complex matrices. These advancements have not only improved the efficiency of SFE processes, but also broadened their applicability across different industrial sectors. Janghel A. *et al.* summarize supercritical fluid extraction as a separation method using supercritical fluids, primarily CO_2, to extract chemicals and flavours from products like coffee, tea, herbs, and spices. The process involves subjecting the mobile phase to high pressures and temperatures near or above the critical point to enhance solvating power. This technique is simple, fast, cost-effective, and nearly solvent-free. Factors influencing extraction yields include solute solubility, matrix diffusion, and collection processes. The authors highlight SFE's advantages over conventional extraction methods in terms of selectivity, speed, cleanliness, and extract composition manipulation. The SFE principle involves optimizing solubility of target materials in supercritical CO_2 and improving fractionation. The method allows for easy separation of the extract from the solvent through simple expansion [3].

Integration with other green extraction methods

Researchers have combined SFE with other green extraction methods, such as ultrasonic-assisted extraction (UAE), microwave-assisted extraction (MAE), and enzymatic extraction, to enhance extraction efficiency and extend the spectrum of target molecules. By combining SFE with these techniques, one may increase the general recovery of bioactive chemicals and simultaneously reduce extraction time and solvent usage. For instance, mass transfer rates have been demonstrated to be improved by ultrasonic-assisted SFE, thereby enhancing the extraction yield of polyphenols and essential oils. Similarly, enzymatic pre-treatment may help break down plant cell walls, thereby enabling improved solute absorption into the supercritical fluid.

Emerging applications in pharmaceutical and cosmetic industries

SFE has been embraced by the beauty and pharmaceutical sectors, as it can extract high-purity bioactive chemicals without using harmful organic solvents. SFE is utilized in pharmaceutical applications to extract alkaloids, flavonoids, and other bioactive compounds, with possible therapeutic advantages. The cosmetic sector has also adopted SFE to acquire the necessary oils, antioxidants, and plant-based active compounds utilized in skincare formulations. Furthermore, the use of SFE in the synthesis of nano-formulated drug delivery systems is of increasing interest, as it helps to produce nanoparticles with improved stability and bioavailability.

Future research directions

Many research disciplines will likely revolutionize SFE technology in the future. One intriguing approach is to examine additional supercritical fluids beyond carbon dioxide (CO_2), including water and ethanol, which may provide superior solubility for certain bioactive compounds. Another important focus is the development of enviornmentally friendly co-solvents that can increase extraction efficiency without compromising sustainability. Furthermore, improvements in artificial intelligence (AI) and computer modelling appear to be crucial for optimizing SFE parameters. Machine learning methods aid in reducing trial-and-error experimentation and improving overall process efficiency by assisting in anticipating the ideal extraction conditions for different plant matrices. Moreover, waste valorization via SFE is becoming increasingly significant as initiatives aim to recover valuable molecules from agricultural and food sector residues, thereby supporting a circular bio-economy. Recent advances in SFE technology have made SFE an increasingly realistic and sustainable substitute for synthesizing important compounds. By adding new ideas, exploring novel applications, and leveraging artificial intelligence-driven optimization, SFE is expected to continue to evolve as the primary green extraction technique in the coming years.

Conclusion

SFE is a green and sustainable approach to isolating important chemicals from natural sources. As industries gravitate towards ecologically benign and efficient extraction technologies, SFE offers a viable replacement for conventional solvent-based methods. In particular, carbon dioxide (CO_2), a supercritical fluid, has various advantages, including reduced solvent residues, selective extraction, and preservation of thermolabile bioactive compounds. Moreover, the efficiency and flexibility of SFE in many diverse applications are enhanced by the ability to change operating parameters such as pressure, temperature, and co-solvent inclusion. SFE has demonstrated remarkable capabilities for extracting bioactive components from nutraceuticals, medicinal plants, essential oils, and marine sources. Its advantages—minimal environmental impact, higher extraction selectivity, and higher component purity—make it a favourable method for food processing, cosmetics, and medicines. However, several problems, such as costly equipment pricing, challenging working conditions, and limited scalability, must be addressed if we are to be more generally utilized. Owing to innovations in equipment design combined with other green extraction methods, recent technological breakthroughs in SFE have significantly improved their efficiency and applicability. The growing demand for sustainable extraction techniques has emphasized the need for continuous research and development in this field. Future research should focus on enhancing the process conditions, developing reasonably scaled-up plans, and examining different supercritical fluids to widen the SFE spectrum. Strong and environmentally friendly SFE is compatible with global initiatives aimed at reducing environmental effects and ensuring the high-quality synthesis of significant natural compounds. As extraction technology continues to develop and regulatory support for green chemistry approaches increases, SFE is likely to be crucial in the future of bioactive chemical separation.

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