Vesna Nađalin [45]
Technical College of Applied Sciences, Zrenjanin/Serbia
Aleksandra Šućurović [46]
Technical College of Applied Sciences, Zrenjanin/Serbia
Gordana Ludajić [47]
Technical College of Applied Sciences, Zrenjanin/Serbia

THE ROLE OF SUPERCRITICAL CO_2 EXTRACTION IN SUSTAINABLE BIOPROCESSING

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Abstract:
Supercritical fluid extraction (SFE) with CO_2 is an environmentally friendly biotechnology method that enables selective extraction of bioactive compounds without toxic solvents. This study investigates the application of SFE in obtaining bioactive compounds from lavender flowers and its advantages over conventional extraction methods. The results demonstrate that pressure and temperature optimization significantly impact extraction yield and compound composition. Additionally, SFE reduces energy consumption and chemical waste, making it a sustainable alternative for industries relying on plant-derived bio actives. The findings support the implementation of SFE in climate-conscious bioprocessing.

Keywords: *Supercritical fluid extraction, CO_2 extraction, Biotechnology, Climate change, Sustainable processing*

Introduction

Climate change and environmental pollution necessitate sustainable approaches in biotechnology and industrial processes. Conventional solvent-based extraction methods used in the pharmaceutical, cosmetic, and food industries contribute to greenhouse gas emissions and environmental contamination. Supercritical fluid extraction (SFE), particularly with CO_2, represents a promising alternative, providing high selectivity, reduced waste, and lower energy consumption [1-3].

This study explores the potential of supercritical CO_2 extraction for obtaining high-value bioactive compounds from lavender flowers, comparing its efficiency and sustainability with traditional methods. The results highlight the importance of pressure and temperature control in optimizing extraction yield while minimizing environmental impact.

[45] vesna.nina@gmail.com, ORCiD: 0009-0006-3522-9544
[46] aleksandrasucurovic@gmail.com, ORCiD: 0009-0001-6931-0088
[47] gludajic@gmail.com, ORCiD: 0009-0001-1809-9446

1. Supercritical CO_2 Extraction Process

Supercritical CO_2 has properties between those of gases and liquids, making it a highly efficient solvent. When temperature and pressure exceed the critical point (figure 1: 30.98 °C, 72.79 atm,), CO_2 gains enhanced diffusivity and solvating power, enabling selective extraction of desired compounds [4, 5].

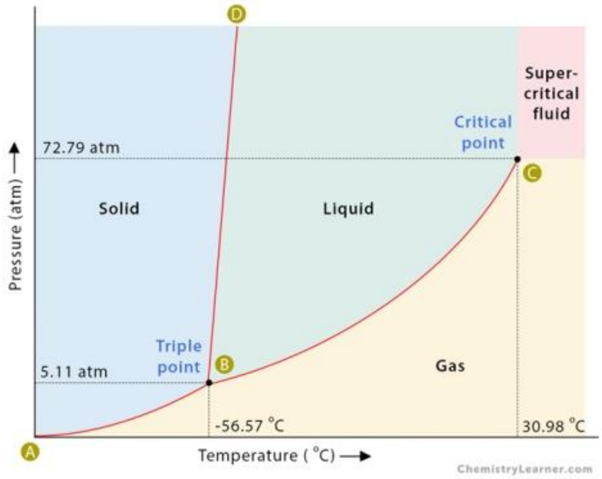

Figure 1. *Phase diagram for carbon dioxide (CO_2)*

Advantages of SFE in Biotechnology

Compared to conventional extraction methods, SFE offers several advantages:

- Eco-friendliness: Eliminates toxic solvents and minimizes chemical waste.
- Energy efficiency: Requires lower temperatures than steam distillation, reducing energy consumption.
- High selectivity: Enables precise control of extracted compounds.
- Recyclability of CO_2: Used CO_2 can be recovered and reused, further reducing environmental impact [6-10].

Due to these benefits, SFE is increasingly used in biotechnology, particularly in pharmaceutical and food industries, where purity and sustainability are critical factors [11, 12].

2. Experimental Study

Lavender flowers were subjected to supercritical fluid extraction (SFE) at various pressures (10–30 MPa) and temperatures (313, 323, and 333 K). The extraction yield was examined over time intervals of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 hours. The CO_2 flow rate was varied (0.095, 0.195, and 0.277 kg/h) to analyze extraction efficiency. The extraction was performed in a high-pressure extractor, and the collected extracts were analyzed using GC/MS (gas chromatography-mass spectrometry) and GC/FID (gas chromatography with a flame ionization detector).

3. Results and Discussion

Effect of Pressure on Extraction Yield

Pressure is one of the key parameters influencing the solvent density and dissolving power of supercritical CO_2. At higher pressures, CO_2 behaves more like a liquid, increasing its ability to dissolve and extract target compounds from plant material. However, excessive pressure can also lead to the extraction of unwanted waxes and heavier compounds, which may affect the purity of the extract. The cumulative extraction yield for 3 hours under the specified extraction conditions is presented in Table 1.

Table 1: *Results of Extraction Yield of Lavender Flowers with Supercritical CO_2 (Isothermal Process, T = 313 K)*

Pressure (MPa)	**CO_2 Density (kg/m^3)**	**Yield (g/100 g)**
10	630	5,16
15	789	5,40
20	840	5,07
25	879	6,00
30	910	7,08

The results indicate that 30 MPa provides the highest yield (7.08 g/100 g of plant material). However, the decrease in yield at 20 MPa suggests that at intermediate pressures, certain compounds may not be as efficiently extracted, potentially due to variations in solubility.

Effect of Temperature on Selectivity

Temperature plays a dual role in supercritical extraction. On one hand, increasing the temperature reduces CO_2 density, potentially lowering its solvating power. On the other hand, higher temperatures enhance the vapor pressure of volatile compounds, increasing their tendency to be extracted. Therefore, an optimal balance between solvent density and compound volatility is required to achieve selective extraction of desired bio actives. Table 2 illustrates the influence of temperature on extraction yield at 10-30 MPa, demonstrating how different temperatures affect the solubility of target compounds such as linalool, caryophyllene, and linalool acetate.

Table 2: *Influence of temperature on extraction yield*

Temperature (K)	Pressure (MPa)			Major Compounds (%)
	10	20	30	
	Yield (g/100 g)			
313	5,16	5,07	7,08	Linalool (29.76), Caryophyllene (6.22)
323	4,98	7,06	7,25	Linalool acetate (26.94), Terpinen-4-ol (2.64)
333	3,71	4,33	7,87	Linalool acetate (27.11), Terpinen-4-ol (3.39)

From the data, it is evident that higher temperatures (333 K) favor the extraction of esters such as linalool acetate, which are essential for fragrance and pharmaceutical applications. However, increasing the temperature, may lead to the degradation of thermo sensitive bioactive compounds, which is an important factor to consider in the optimization of extraction conditions.

Energy Efficiency and Sustainability of Supercritical CO_2 Extraction Compared to Steam Distillation

Studies have demonstrated that SFE is more efficient and environmentally friendly compared to conventional steam distillation and solvent extraction methods. SFE has been shown to have better selectivity and the capability to produce extracts of higher purity and quality.

Akgun et al. [13] extracted lavender flowers using supercritical carbon dioxide at relatively low pressures (8–14 MPa) and relatively low temperatures ranging from 308 to 323 K, with different flow rates of the extraction solvent. Under these extraction conditions, the obtained extracts predominantly contained essential oil. Similar results were obtained by Luu Thai Danha and colleagues [14] in their study on the supercritical CO_2 extraction of lavender flowers. Reverchon et al. [2] investigated the supercritical CO_2 extraction of lavender flowers at pressures of 8–10 MPa and temperatures ranging from 308 to 333 K. They concluded that the highest yield of essential oil in the extracts was achieved at lower pressures (9 MPa). The composition of the essential oil obtained by supercritical CO_2 extraction was compared with that of the essential oil isolated by hydrodistillation, revealing that the content of the dominant component, linalool acetate, was significantly higher (34.7%) in the extracts obtained by supercritical CO_2 extraction compared to those obtained by hydrodistillation (12.1%).

Supercritical CO_2 extraction (SFE) offers significant advantages over steam distillation, particularly in terms of energy efficiency, environmental sustainability, and the preservation of bioactive compounds [15-22]. Steam distillation requires high temperatures (~100°C), leading to increased energy consumption, CO_2 emissions, and thermal degradation of bioactive compounds, reducing their quality and bioactivity [20, 21]. In contrast, SFE operates at temperatures between 30 and 40°C, allowing for the preservation of thermolabile components while significantly reducing energy consumption and environmental impact [15-19, 21]. Additionally, steam distillation consumes large amounts of water for steam generation, producing wastewater and making it unsustainable in regions with limited water resources [22]. SFE does not require water, thereby minimizing environmental pollution and supporting green chemistry principles [19]. While traditional extraction methods use organic solvents such as hexane, which pose environmental and health risks, SFE utilizes CO_2, which is non-toxic, inert, and recyclable, enabling full recycling and waste reduction [19-21]. Due to these advantages, SFE represents a more sustainable and technologically superior method in bioprocessing for the pharmaceutical, food, and cosmetic industries compared to steam distillation [22]. In Table 3, are presented comparison of SFE and HD in terms of yield and sustainability.

Table 3: *Comparison of SFE and Steam Distillation in Terms of Yield and Sustainability*

Parameter	Steam Distillation (HD) [X]	Supercritical CO_2 Extraction (SFE) [Y]
Extraction Yield (%)	2.39 (flowers) / 0.52 (leaves)	5.16 – 7.87 (depending on P and T)
Linalool (%)	48.44	25.24 – 29.76
Linalool Acetate (%)	11.85	22.83 – 27.11
Caryophyllene (%)	2.20	5.06 – 6.22
Extraction Temperature (°C)	~100 °C (high)	30–40°C (low)
Process Time (h)	2–3 hours	1–3 hours
Water Consumption	High (large amounts of water used)	None
Solvent Used	Water (steam)	CO_2 (recyclable)
Energy Consumption	High	Low
Thermal Degradation Risk	High	Low
Selectivity	Low (co-extraction of unwanted polar compounds)	High (adjustable solvent properties)
Waste Generation	High (water waste, plant residue)	Low (CO_2 is recycled, minimal waste)

4. Conclusion

This study demonstrates that supercritical CO_2 extraction (SFE) is a technologically and environmentally superior alternative to conventional steam distillation (hydrodistillation, HD) for obtaining high-quality lavender extracts.

As industries increasingly seek environmentally friendly and sustainable technologies, the adoption of SFE can play a crucial role in reducing the ecological footprint of essential oil extraction and biotechnological processes. Future research should focus on scaling up industrial SFE applications to improve efficiency and cost-effectiveness. The development of hybrid extraction techniques may further enhance both sustainability and selectivity. Integrating renewable energy sources into SFE systems could provide additional reductions in carbon emissions and improve overall environmental benefits. In the context of climate change and sustainable bioprocessing, SFE aligns with global efforts to transition toward green technologies. Its potential for reducing resource consumption, minimizing waste production, and improving energy efficiency highlights its role as a key innovation in environmentally responsible biotechnology.

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