

Comparative analysis of pressurized liquid extraction (PLE) and expanded solvent extraction (ESE) for bioactive compound recovery: a literature review

Any Eduarda Nanes de Oliveira Farias^{1*}, Robertta Jussara Rodrigues Santana¹, Marcelo da Costa Mendonça^{1,2},
Thiago Rodrigues Bjerk^{1,2}, Elton Franceschi^{1,2}

¹ Universidade Tiradentes, Aracaju, Sergipe, Brasil

² Instituto de Tecnologia e Pesquisa, Aracaju, Sergipe, Brasil

*Any Eduarda Nanes de Oliveira Farias: Instituto de Tecnologia e Pesquisa; addresses; any05011999@hotmail.com

Abstract: The growing global demand for sustainable and efficient processes to extract bioactive compounds has driven the development of innovative high-pressure technologies. Among these, PLE, Pressurized Liquid Extraction and ESE, Expanded Solvent Extraction stand out due to their ability to increase the yield and quality of extracts compared to conventional methods. Both techniques use elevated pressures to enhance solvent interaction with plant matrices, promoting better solubilization and recovery of target compounds. Specifically, PLE operates by applying high temperatures and pressures to liquid solvents, accelerating the extraction process and reducing overall solvent consumption, which contributes to greater environmental efficiency and cost reduction. Meanwhile, ESE employs an expanding gas, commonly carbon dioxide (CO₂), which decreases the viscosity of the solvent medium and increases its diffusivity. This unique mechanism allows more effective penetration of the solvent into the plant matrix structure, resulting in higher selectivity and greater yield, especially for phenolic compounds. This review thoroughly analyzes both techniques, addressing their fundamental principles, operational advantages, limitations, and applications across various industrial sectors, including food, cosmetics, and pharmaceuticals. Literature data indicate that ESE generally shows better performance in terms of selectivity and yield of phenolic compounds, making it suitable for processes aiming to maximize the extraction of these bioactives. On the other hand, PLE stands out for its versatility and broad applicability, being easily integrated into already established industrial processes. Understanding the differences and complementary strengths of PLE and ESE is essential for researchers and industry professionals seeking optimized extraction strategies aligned with sustainability goals and product quality.

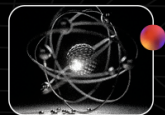
Keywords: Extraction. Bioactive Compounds. Sustainability.

1. Introduction

The growing appreciation for natural products and the increasing demand for environmentally sustainable production processes have driven the development of more efficient and selective extraction methods for bioactive compounds (Mustafa and Turner 2011 [1]). These compounds, widely found in plant matrices, possess functional properties of great interest to the pharmaceutical, food, and cosmetic industries, being associated with antioxidant, anti-inflammatory, antimicrobial, and other

biological activities (Carvalho and colleagues 2023 [2]). However, conventional extraction methods such as maceration and Soxhlet extraction, although still in use, present limitations related to long processing times, high solvent consumption, and the degradation of thermolabile compounds (Ferreira and colleagues 2022 [3]).

In this context, high-pressure technologies have emerged as promising alternatives. Among them Pressurized Liquid Extraction (PLE) and



Expanded Solvent Extraction (ESE) have been extensively studied due to their ability to enhance yield, selectivity, and extract quality. PLE operates by applying high pressures and temperatures to liquid solvents, which promotes better solubilization of target compounds, reduces extraction time and solvent usage, and is considered a green extraction technique (Picot-Allain and colleagues 2021 [4]). Conversely, ESE involves the expansion of a solvent with gases such as carbon dioxide (CO₂), reducing viscosity and increasing diffusivity, which improves penetration into plant tissues and, consequently, extraction efficiency, especially for specific compound classes like phenolics (Granone and colleagues 2023 [5]).

Although both techniques rely on high pressure, their operational principles, chemical selectivity, and industrial applicability differ significantly. There are still gaps in the literature regarding direct comparisons between these two methods, particularly concerning extraction efficiency for specific compounds, environmental impact, and feasibility at industrial scale (Ballesteros-Vivas and colleagues 2021 [6]).

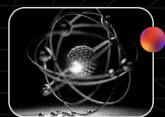
Therefore, this study aims to present a critical literature review on PLE and ESE techniques, discussing their fundamental principles, operational parameters, advantages, limitations, and industrial applications. The comparative analysis intends to support strategic decision-making for more effective and sustainable extraction methods that meet current market demands.

2. Methodology

This study is a qualitative, narrative literature review. The search for studies was conducted during 2025 in the scientific databases Scopus, Web of Science, and ScienceDirect. The following descriptors were used, combined with Boolean operators: “pressurized liquid extraction” AND “expanded solvent extraction” AND “bioactive compounds”, as well as their Portuguese equivalents: “extração com líquido pressurizado” AND “extração com solvente expandido” AND “compostos bioativos”.

The inclusion criteria were: (i) original studies or systematic reviews addressing the PLE and/or ESE techniques for the extraction of bioactive compounds; (ii) articles focusing on industrial applications in the food, cosmetic, or pharmaceutical sectors; and (iii) studies presenting comparative data on extraction yield, selectivity, or extract quality. Exclusion criteria included duplicate articles, studies focused exclusively on other techniques (e.g., supercritical or microwave extraction), conference abstracts, and publications lacking relevant data to the review’s objective.

A total of 110 articles were initially identified through database searching. After screening titles and abstracts, 58 articles were selected for full-text reading, and 21 studies were included in the final analysis. Extracted information was organized into comparative tables covering aspects such as plant matrix type, solvents used, operational conditions (pressure, temperature,



time), yield, phenolic compound content, and industrial applicability.

3. Results and Discussion

The reviewed literature reveals significant differences and complementarities between Pressurized Liquid Extraction (PLE) and Expanded Solvent Extraction (ESE) techniques in terms of extraction efficiency, selectivity, operational parameters, and industrial scalability.

3.1. Extraction yield and efficiency

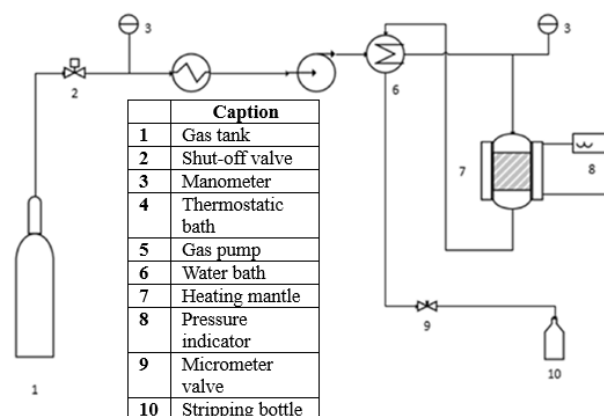
Across the analyzed studies, Expanded Solvent Extraction (ESE) generally exhibited higher extraction yields, particularly when targeting phenolic compounds. This superior performance is attributed to the physicochemical characteristics of expanded solvents, especially when using carbon dioxide (CO₂) as a co-solvent. The use of CO₂ reduces viscosity and enhances diffusivity, thereby improving solvent penetration into plant matrices (Lama-Muñoz et al., 2020 [7]; Souza et al., 2019 [8]; Rodrigues et al., 2016 [9]; Rubi et al., 2019 [10]).

Rodrigues and colleagues (2016 [9]) developed a three-step process to obtain different fractions from *Moringa oleifera*, using supercritical carbon dioxide (scCO₂), ethanol expanded with CO₂, and pressurized hot water extraction. The extraction yield using 50% ethanol was twice as high as that obtained with scCO₂. These green and sustainable solvents enabled the recovery of

a wide range of bioactive compounds from *Moringa oleifera* leaves, outperforming conventional systems for phenolic recovery such as maceration and Soxhlet extraction (Rubi et al., 2019 [10]).

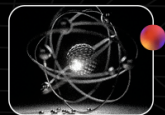
The efficiency observed in these processes is directly related to the design of high-pressure extraction systems. The following diagram illustrates the path of the pressurizing gas, typically CO₂, from the storage cylinder to the final extract collector. The presence of a shut-off valve and a manometer at the beginning of the system ensures proper control and safe monitoring of internal pressure, which are essential for maintaining stable operating conditions (Figure 1) (Ruíz-Domínguez et al., 2021 [11]).

Figure 1. Scheme of the high-pressure extraction process.



(The authors, 2025)

The gas is preheated in a thermostatic bath and then driven by a pump toward the extraction vessel. To guarantee precise thermal conditions



during the extraction process, the system combines a water bath and a heating mantle, which maintain the required temperature for efficient solubilization of target compounds. A pressure indicator located near the extractor allows for fine adjustments and real-time monitoring of system performance.

In the final stage, a micrometer valve controls the depressurization and flow of the solvent extract mixture, which is then collected in a separation flask. This configuration is consistent with the requirements of Pressurized Liquid Extraction and Expanded Solvent Extraction techniques, both of which are recognized for their efficiency in solvent penetration into the plant matrix and the selective recovery of phenolic compounds and other metabolites of interest. Previous studies have shown that well-regulated pressure and temperature conditions are critical for improving both yield and selectivity, especially in the extraction of bioactive compounds with antioxidant potential (Krambeck et al., 2020 [12]).

These elements of the system highlight the importance of simultaneous control over temperature and pressure to optimize extraction efficiency and selectivity factors that directly affect the quality of the extracts and the feasibility of scaling the process to an industrial level (Le et al., 2023 [13]).

3.2. Selectivity for phenolic compounds

Selectivity is a key parameter when the goal is to enrich specific compound classes. ESE demonstrated greater selectivity for phenolic compounds, including flavonoids and tannins. The unique behavior of the expanded solvent phase, resulting from the presence of CO₂ or other gases, creates a more tunable polarity, allowing fine control over solvent power (Callejón and colleagues 2022 [13]).

Studies with different raw materials confirm this performance, with a higher yield of phenolic compounds observed in passion fruit pomace when using ethanol expanded with CO₂ compared to conventional methods (Viganó and colleagues 2016 [14]).

In contrast, although PLE shows lower selectivity for phenolics, it promotes broader co-extraction, which can be advantageous in formulations aiming to preserve the full phytocomplex. However, this broader profile may also lead to the extraction of undesirable components, requiring additional purification steps (Jiang et al. 2021 [15]).

3.3. Operational considerations

From an operational standpoint, both techniques share comparable pressure ranges (100–120 bar) and extraction durations (typically 60–120 minutes) (table 1).

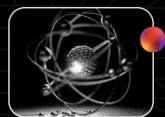


Table 1. Scheme of the high-pressure extraction process.

Parameter	PLE vs. ESE
Extraction yield	Both techniques offer high yields, though ESE may provide superior performance.
Selectivity	PLE: moderate to high; ESE: high, especially for phenolic compounds.
Extraction time (min)	Similar for both: 60–120 minutes.
Temperature (°C)	40–80 °C for both methods.
Pressure (bar)	Both operate efficiently between 100 and 120 bar.
Solvent system	PLE: water, ethanol, acetone; ESE: CO ₂ plus co-solvent (e.g., ethanol).
Antioxidant activity	Higher and more stable in ESE-derived extracts.
Sustainability	ESE more sustainable due to CO ₂ recyclability; PLE uses less solvent overall.
Industrial application	PLE: food, cosmetics, pharma; ESE: cosmetics, nutraceuticals, premium extracts.

PLE requires elevated temperatures to enhance solubility and mass transfer, whereas ESE relies on physical solvent modification through gas expansion, which can be performed at slightly lower temperatures, helping preserve thermolabile compounds (Frohlich and colleagues 2023 [16]).

Solvent consumption is another key distinction. PLE, while more efficient than conventional methods, often uses greater solvent volumes than ESE. ESE's use of compressed gases like CO₂ allows reduced liquid solvent usage, contributing to greener and more sustainable processes. However, ESE systems are often more complex and require precise control over solvent composition and expansion parameters. (Okajima and colleagues 2021 [17]).

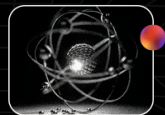
3.4. Industrial applicability and integration

In terms of scalability and integration into industrial workflows, PLE holds a relative Advantage (Perra and colleagues 2023 [18]). Its “operational simplicity”, compatibility with conventional solvents, and lower requirement for specialized gas-handling infrastructure facilitate adoption in existing production lines (Souza and colleagues 2019 [19]).

ESE, on the other hand, although less commonly implemented at industrial scale, has shown growing interest in high-value sectors, especially in cosmetics and functional foods. Its enhanced selectivity and reduced environmental impact align well with clean label trends and sustainability certifications (Santo and colleagues 2023 [20]).

3.5. Environmental and economic aspects

Environmental impact is an essential consideration in modern extraction protocols. ESE emerges as more sustainable in many contexts, due to lower organic solvent use and



the potential recycling of gases like CO₂. However, initial setup costs and operational complexity may limit its application in small- to medium-scale industries (Granone and colleagues 2023 [5]).

PLE, while slightly less green due to higher solvent use, remains environmentally preferable when compared to traditional methods like Soxhlet. Its lower energy consumption, shorter extraction time, and ease of use support its designation as a “green technology,” particularly when ethanol or water are used as solvents (Machado and colleagues 2025 [21]).

4. Conclusion

The comparison between Pressurized Liquid Extraction (PLE) and Expanded Solvent Extraction (ESE) shows that both techniques have valuable and complementary applications. ESE stands out for its higher selectivity and environmental advantages, while PLE offers greater operational simplicity and industrial feasibility. Rather than favoring one method, the choice should depend on the target compounds, raw material characteristics, and process goals. Further research is recommended to optimize solvent systems and assess scalability, especially for sustainable applications.

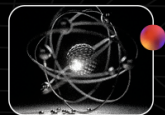
Acknowledgement

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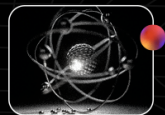
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5. List of figures and tables

Figure 1. Scheme of the high-pressure extraction process.

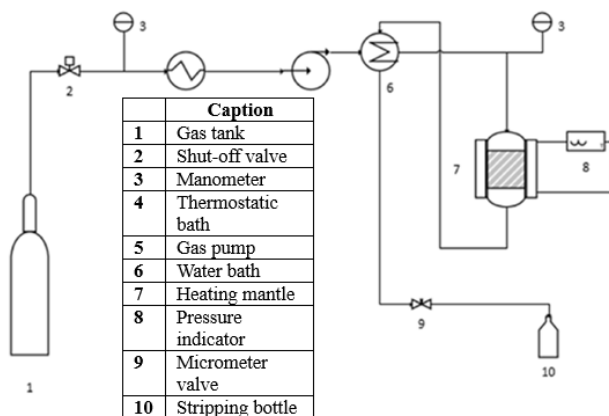


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