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Non-thermal technologies in vegetable oil extraction: yield, composition, and antioxidant activity. A review

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SUMMARY: Traditional extraction methods for vegetable oils present limitations regarding oil yield and quality preservation. Given the significant role of vegetable oils in human nutrition and health, non-thermal technologies offer alternatives for extraction process optimization. This review examines three principal non-thermal technologies: supercritical fluid extraction (SFE), ultrasound-assisted extraction (UAE), and pulsed electric field (PEF) application. These methods are evaluated based on their effects on extraction yield, oil composition, and the preservation of antioxidant activity in seed oils. SFE exhibits efficacy in enhancing yield, recovering antioxidant compounds, and preserving fatty acid compositions. UAE demonstrates potential for improving extraction efficiency and maintaining antioxidant activity. PEF consistently increases extraction yields, though its impacts on antioxidant properties and fatty acid profiles require additional investigation. These non-thermal technologies present viable alternatives for extraction process optimization, although further research is needed to maximize yield and quality across diverse oil seed varieties.

KEY-WORDS: *Antioxidant preservation; Extraction optimization; Non-thermal processing; Vegetable oils.*

RESUMEN: ***Tecnologías no térmicas en la extracción de aceites vegetales: rendimiento, composición y actividad antioxidante. Revisión.*** Los métodos tradicionales de extracción de aceites vegetales presentan limitaciones respecto al rendimiento y la conservación. Dada la importante función de los aceites vegetales en la nutrición y salud humana, las tecnologías no térmicas ofrecen alternativas para la optimización de los procesos de extracción. Esta revisión examina tres tecnologías no térmicas principales: extracción por fluidos supercríticos (FSC), extracción asistida por ultrasonido (EAU), y aplicación de campo eléctrico pulsado (CEP). Estos métodos son evaluados en función de sus efectos sobre el rendimiento de extracción, la composición del aceite y la preservación de la actividad antioxidante en aceites de semillas. FSC exhibe una eficacia particular en la mejora de los parámetros de rendimiento, la recuperación de compuestos antioxidantes y la preservación de composiciones deseables de ácidos grasos. EAU demuestra un potencial significativo para mejorar tanto la eficiencia de extracción como el mantenimiento de la actividad antioxidante. CEP aumenta consistentemente los rendimientos de extracción, aunque sus impactos en las propiedades antioxidantes y los perfiles de ácidos grasos requieren investigación adicional. Estas tecnologías no térmicas presentan alternativas viables para la optimización del proceso de extracción, se necesita más investigación para maximizar los parámetros de rendimiento y calidad en diversas variedades de semillas y tipos de aceite.

PALABRAS CLAVE: *Aceites vegetales; Optimización de extracción; Preservación antioxidante; Procesamiento no térmico.*

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1. INTRODUCTION

Traditional mechanical, chemical, or combined methods are commonly employed in vegetable oil extraction (Nde and Foncha, 2020), but these approaches often compromise oil yield and quality. Non-thermal technologies have emerged as promising alternatives that offer several advantages in the extraction process. These technologies facilitate high-quality vegetable oil extraction while obtaining health-promoting fatty acids by preventing the loss of volatile compounds and minimizing the modification of fatty acid profiles. Additionally, these technologies are environmentally friendly due to the reduction in processing time, economic and energetic costs. This is achieved through their ability to operate at room temperature and generate disruption or damage to cellular membranes in raw vegetable material (Moreira *et al.*, 2018), thereby enhancing extraction efficiency.

Oils are essential nutrients in the human diet, providing a source of energy and essential fatty acids. Vegetable oils have been used for human consumption due to their fatty acids content, which can be classified into saturated (SFA), monounsaturated (MUFA), and polyunsaturated fatty acids (PUFA) (Azam *et al.,* 2019). There is compelling evidence highlighting the crucial role of fatty acids in human nutrition, including their therapeutic and prophylactic prevention, together with protection against diseases such as cardiovascular conditions or inflammation (Kumar *et al*., 2016). Therefore, employing methods to maintain the naturally existing antioxidant compounds in oils that help to prevent fatty acid degradation through oxidation are crucial. Fatty acids, particularly unsaturated fatty acids, are susceptible to oxidative processes. In foods, their degradation causes a reduction in sensory and nutritional value and generates toxic compounds (Viana da Silva *et al*., 2021). Oxidized oils negatively affect the human body, potentially causing modifications to deoxyribonucleic acid (DNA), ribonucleic acid (RNA), lipids, and proteins, which can lead to cellular damage, inflammation, and carcinogenesis (Metzner and Poaina, 2018). The extraction method significantly influences the quality of edible oil, as it can alter its fatty acid composition and the concentration of bioactive compounds.

This review aims to analyze the impact of the main non-thermal technologies researched in the oil extraction industry. Two of the primary technologies analyzed in this article, ultrasound-assisted extraction and pulsed electric field, have been studied in oil extraction processes due to their ability to enhance mass transfer processes by altering cell structure, thereby increasing the efficiency of bioactive compound extraction (Picart-Palmade, *et al*., 2019). The third technology analyzed is supercritical CO_2 fluid extraction, which is widely applied in the oil extraction industry due to its non-toxic nature and ease of separation from the final product. In the presence of carbon dioxide, the extraction temperature and presence of oxygen are low, resulting in high-quality extracted material. This review will focus on the effect of non-thermal technologies on yield, composition, and antioxidant activity, comparing them with conventional methods to highlight the benefits of employing these technologies in the extraction process of vegetable oils. The relevance of this manuscript lies in presenting complementary options and aiding in the selection of appropriate methodologies in relation to the raw material to improve oil yield from vegetable seeds without compromising the quality and health benefits of the product.

2. MATERIAL AND METHODS

2.1. Study design

This paper presents a systematic review conducted following the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) methodology.

2.2. Eligibility criteria

Inclusion criteria: (1) Original articles, (2) The application of non-thermal technology in the extraction process (supercritical fluid extraction; ultrasound assisted extraction; pulsed electric field). (3) The oil extraction from seeds, (4) The study included oil characterization and antioxidant assays of extracted oil. Exclusion criteria: (1) extraction of non-seed oils, (2) extraction of non-edible oils, (3) Missing the fatty acid profile or extraction yields.

2.3. Research methods

The search encompassed multiple databases including Google Scholar (Googleplex, Mountain View, California, USA), Scopus (Elsevier, Amsterdam, Netherlands), Springer (Springer Nature, Berlin, Germany), EBSCO (EBSCO Industries, Brimingham, Alabama, USA), and Dialnet (Dialnet Foundation, Logroño, Spain). Keywords employed in the search included "Ultrasound assisted extraction", OR "Pulsed electric field", OR "Supercritical fluid extraction", OR "seeds oil extraction" OR "edible oil extraction" or various combinations of the keywords. The search was limited to research published between 2018 and 2024. The flow diagram in Figure 1 visually outlines the process.

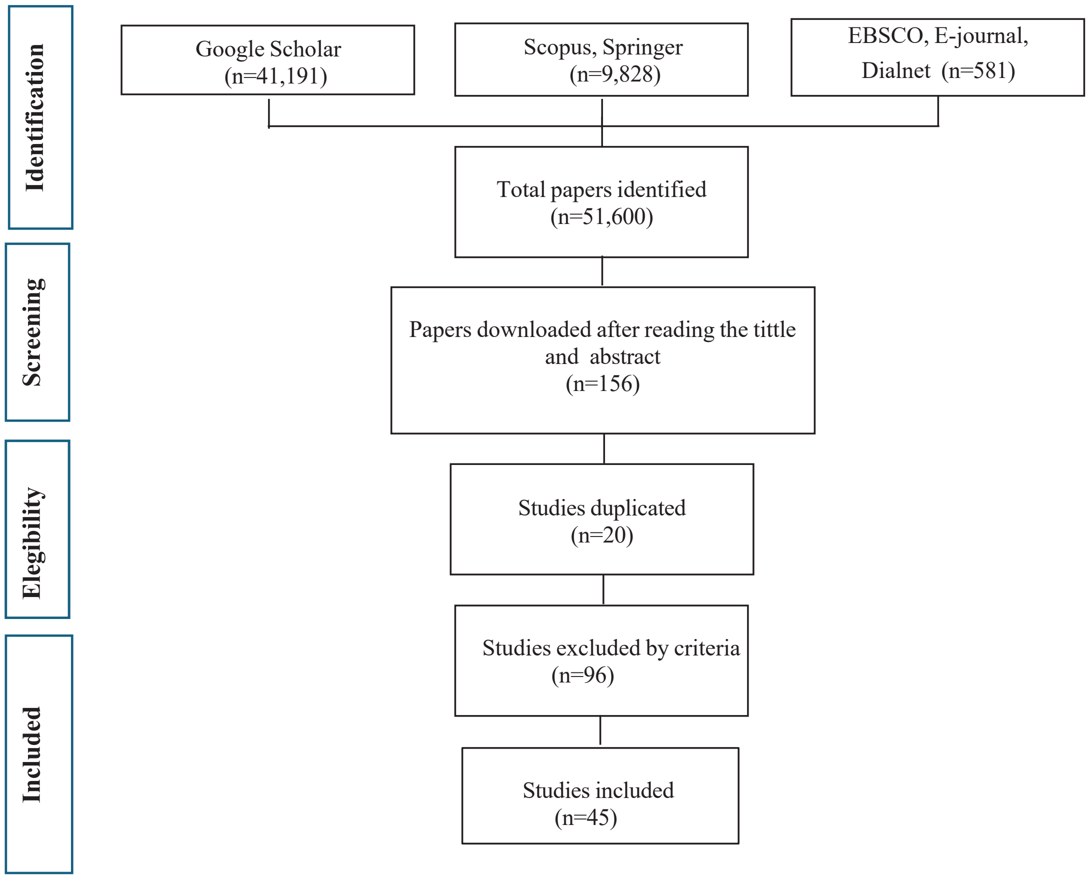

FIGURE 1. Methodology flow diagram. Description of the research of papers analyzed in this review. The number of papers included where determinate after the exclusion of studies with no relation with oil´s extraction, the application of non-thermal techniques in extraction process, studies duplicated and another criteria of inclusion as antioxidant activity or fatty acids profile.

3. RESULTS

3.1. Literature search and study characteristics

The search identified a total of 51,600 papers with the keywords used. After reading the title only 156 remain for the eligibility. After excluding duplicate reviews or articles that match with the exclusion criteria, 45 papers were analyzed and included in this revision (Figure 1).

3.2. Supercritical Fluid Extraction

3.2.1. Basis

Supercritical fluid extraction (SFE) occurs at temperatures and pressures where a fluid exists as both a liquid and a gas, surpassing its critical point or achieving a supercritical state. SFE is a process involving the separation of one component (extractant) from another (matrix) using supercritical fluids as the extracting solvent. Carbon dioxide (CO_2) is the most used supercritical fluid due to its ecologically acceptable properties, non-flammability, and chemical inertness. Its critical temperature is 31°C and critical pressure is 7.39 MPa (Sapkale *et al*., 2010).

SFE can be performed offline or online. In the offline method, dried and ground raw material is placed in an extraction vessel. The extractor containing the sample is supplied with supercritical solvent from the bottom. After extraction, the solutes are separated from the solvent through low pressure or temperature and collected via a depressurization valve in a separator. The online technique integrates SFE with gas or liquid chromatography (Yousefi *et al*., 2019). SFE with CO_2 (SFE-CO_2) efficiently yields high-quality oil in a single step, eliminating the need for additional solvents (Figure 2) (Ferrentino *et al*., 2020).

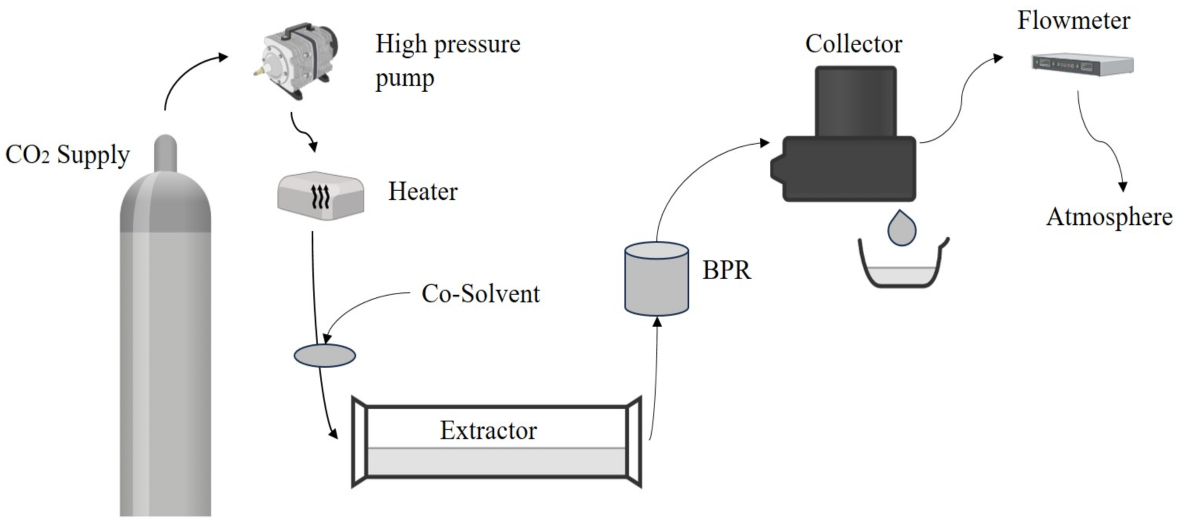

FIGURE 2. Flow diagram of supercritical fluid extraction. BPR – Back pressure regulator. The equipment consists of a CO2 supply stored in a high-pressure cylinder. For the CO2 acquire a supercritical state, the high-pressure pump increases the pressure, and the heater increases the temperature. In the process, a co-solvent is used. In the extractor, the seeds are placed to be in contact with the supercritical fluid, causing the dissolution of the compounds of interest. The BPR is a pressure regulator that makes the fluid go to the subcritical region, separating the extract from the solvent. The extract is obtained in the collector (Ahangari, *et al.*, 2021).

3.2.2. Applications

Several researchers have used SFE-CO_2 to extract vegetable oils and assess extraction yield, composition, and antioxidant activity of the resulting products (Table 1). Amani *et al.,* (2021) studied the extraction of oil from chilgoza (*Pinus gerardia)* seeds using SFE-CO_2 and found that a lower yield was achieved compared to Soxhlet extraction. Nevertheless, SFE-CO_2 demonstrated shorter extraction times at lower temperatures with no significant changes in fatty acid composition. Similarly, Han *et al.* (2020) employed SFE-CO_2 to obtain berberis (B*erberis dasystachya* Maxim.) oil with a higher concentration of unsaturated and polyunsaturated fatty acids, along with increased antioxidant activity in DPPH and ABTS assays compared to screw pressing and extraction by petroleum ether. Mazurek *et al.* (2022), working with berry seeds, investigated the effect of pressure on modifying the fatty acid profile and detected an increase in monounsaturated fatty acids in black currant seed oil by increasing the pressure in the method. Higher pressure resulted in a more significant dissolution of oil components.

TABLE 1. Overview of studies on oil extraction by supercritical fluid extraction

Seed oil	Optimal treatment conditions					Parameters analyzed		
	Pr [MPA]	T [°C]	Time [min]	Fr [kg·h^{-1}]	Yield [%]	Fatty acids composition [%]	AA [%/ mg·ml^{-1}]	Reference
Oleaster *(Eleagus mollis*)	32.5	60	180	NR	24.3- 28	44.7- 55.8 linoleic	12.2 mg·ml^{-1}	Wong *et al.* (2019)
						33.6- 40.6 palmitic		
						3.1- 5.5 palmitic acid		
Barberry	25	59	NR	2.2	12.5	34.8 linolenic	DPPH 89.6%	Han *et al.* (2020)
(*Berberis dasystachy*)						22 linoleic 21 oleic	ABTS 92.6 %	
						2.5 stearic		
						1.5 palmitic		
Perilla (*Perilla frutescens*)	26.7	45.6	60	0.9	14.9	49.53 alfa linoleic	DPPH 69.7%	Jiao *et al*. (2020)
Guava (*Psidium guajava*)	45	50	NR	NR	10.4	10.8 MUFA	DPPH 58.9%	Kapoor *et al*. (2020)
						75.2 linoleic		
Algerian fenugreek (*Trigonella foneum- graecum*)	35	54.1	NR	0.5	5.4	41.4 linoleic 28.9 oleic 12.5 palmitic	NR	Ismahene *et al.* (2021)
Moringa oleifera	40.3	40	30	42	25.25	69.7 oleic 7.35-7.63 behenic 5.45-5.99 stearic 5.44-5.73 arachidic	NR	Elsayed (2023)
Cucurbita sp.	35	NR	35	30	74.9	39.8 linoleic 35.3 oleic 13.3 stearic 10.74 palmitic	DPPH= 0.68 mg·ml^{-1}	Hu *et al.* (2023).
Opuntia ficus-*indica (OFI) L.* and *Opuntia dillenii (OD*	30	60	NR	1	OF= 8.3 and 7.7 OD= 7.4	62 linoleic 9.88-13.97 oleic 11.8-12.6 palmitic 0.37-0.42 alfa-linleic	DPPH (polar component) = 0.20 mg·ml^{-1} DPPH (No Polar component) = 0.47 mg·ml^{-1} DPPH (OFI)= 42.16 mg·ml^{-1} DPPH (OD)= 42.67 mg·ml^{-1}	Al-Naqeb *et al.* (2023)

Abbreviations: ABTS=(2, 2’- azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)), DPPH=2, 2-diphenyl-1-picrylhydrazyl, Fr=flow rate, FRAP=ferric reducing antioxidant power, MUFA=monounsaturated fatty acids, PUFA=polyunsaturated fatty acids NR=not reported, Pr=pressure, SFA=saturated fatty acids, T=Temperature, t=Time, UFA=unsaturated fatty acids.

Naupia-Belo *et al.* (2019) observed that increasing pressure led to an growth in the amount of oil extracted due to changes in fluid density. At the highest densities, the space between CO_2 molecules diminishes, enhancing interaction between oil and CO_2, leading to increased oil solubility in SFE-CO_2. Additionally, higher pressure caused significant cell wall rupture and improved solvent penetration into the extracted material. In contrast, Ismahene *et al.* (2021) found that increasing pressure beyond 4.00 MPa decreased diffusivity, making the passage of oil molecules through the matrix difficult and reducing the oil yield. Temperature, when held as a constant parameter, contributed to an increase in oil yield extraction when pressure and particle size were modified. Both temperature and pressure parameters are relevant due to their influence on the physical properties of SFE-CO_2, such as diffusivity, viscosity, and density. These parameters also affect its solvent power, and adjusting their values significantly modifies the solubility of the solute. SFE-CO_2 can also modify the fatty acid composition, increasing the proportion of MUFA and PUFA in the oil and extracting higher amounts of bioactive compounds with antioxidant properties as phenolics and antioxidant activity. This is because the cell wall rupture and changes in fluid density caused by pressure can increase the dissolution of the components of the oil. To take advantage of the benefits of this technology, it is essential to optimize temperature and pressure conditions depending on the raw material used for oil extraction, as these variables have a significant impact on extraction yield and quality.

3.3. Ultrasound-Assisted Extraction

3.3.1. Basis

Ultrasound-assisted extraction (UAE) is characterized by simplicity, reduced treatment time, and minimal solvent usage. UAE easily integrates with other extraction methods and operates at room temperature, preventing oxidation and product decomposition (Louie *et al.,* 2020). Ultrasonic systems typically consist of a transducer that converts electrical energy to sonic energy and an emitter or reactor amplifying the waves. The most used equipment includes ultrasonic probe systems and ultrasonic baths (Figure 3). Originally designed for laboratory use, ultrasonic baths enable solid-solvent dispersion, while the more potent probe system, with lower ultrasonic dispersion, is preferred for smaller volumes. On an industrial scale, reactors with volumes ranging from 30 L to 1000 L, equipped with coupled probing systems, have been developed to scale up from laboratory ultrasonic baths (Pingret *et al*., 2013).

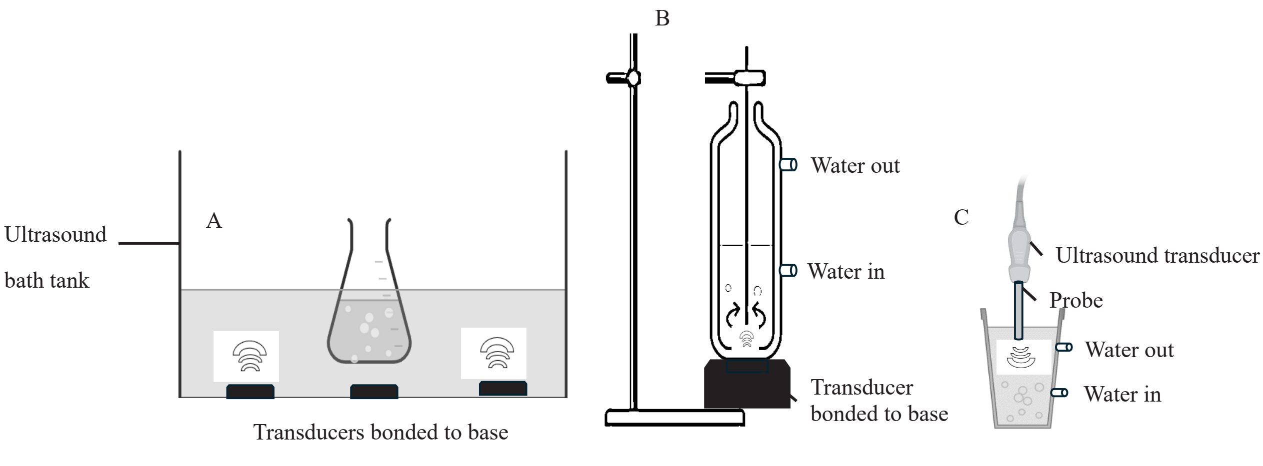

FIGURE 3. Ultrasound equipment. Ultrasonic system. A: Ultrasound bath, B: Ultrasound reactor with stirring, C: Ultrasound probe (Pingret *et al*., 2013).

In UAE, factors like amplitude, temperature, extraction time, pressure, acoustic power, frequency, and ultrasound intensity affect solvent penetration and intensity of mass transfer (Wong *et al*., 2019). The phenomenon of cavitation involves exposing plant material in a liquid medium to ultrasonic waves, generating vibration and acceleration that create bubbles in a negative pressure environment. As the pressure and temperature increase, bubble collapse occurs. When this collapse happens near the solid surface, resulting shock waves break the cell walls, facilitating solvent penetration into the plant material and allowing the release of bioactive compounds (Böger *et al.*, 2018).

3.3.2. Application

UAE has gained significant interest in vegetable oil extraction (Table 2), with the potential to maintain oil composition through short extraction times due to the cavitation phenomenon affecting transport and extraction rates (Wong *et al*., 2019).

TABLE 2. Overview of studies on oil extraction using ultrasound-assisted extraction

Seed oil	Optimal treatment conditions					Parameters analyzed			
	P [W]	T [°C]	t [min]	A [%]	F [KHz]	Yield [%]	Fatty acid composition [%]	AA [%, mg·ml⁻¹/Eq Trolox.]	Reference
Hemp (*Cannabis sativa L.)*	800	45	60	NR	NR	31.7	NR	DPPH 76.5%	Kenari and Dehghan (2020)
Passion fruit (*Passiflora edulis*)	165	60	30, 50	NR	25	29	59-61 PUFA 59-61 linoleic 17.4 oleic	NR	Massa *et al.,* (2021)
Red fruit (*Pandanus conoideus*)	200	67	80	100	24	9.7	NR	DPPH 0.0377 to 0.0502 $mg \cdot ml^{-1}$	Susanti *et al*., (2022)
Madhuca longifolia	NR	35	35	40	NR	59.7	46 oleic 22 palmitic 21 stearic 10 linoleic	ABTS= 39.8 $mg \cdot ml^{-1}$ DPPH= 0.10 $mg \cdot ml^{-1}$	Thilakarathna *et al.,* (2023)
Apple seed	18-70	30	5-30	20-80	NR	14.7-18.1	35.5 linoleic	0.22 mg eq Trolox/g	Gasparini *et al.,* 2023
Rubus fructicosus	NR	45	15	NR	NR	87.34	64.86 linoleic 16.52 oleic 11.28 alfa linolenic 4.2 palmitic 3.14 stearic	NR	Matei *et al.* (2023)
Vaccinium macrocarpon	NR	NR	11.8	95	NR	21.98	36 linolenic 30-31 alfa linolenic 24 oleic 5.9-6 palmitic 1.28 stearic	NR	Piasecka *et al.*, (2023)

Abbreviations: A=amplitude, DPPH=2,2-diphenyl-1-picrylhydrazyl, F= frequency, FRAP= ferric reducing antioxidant power, P=power, PUFA=polyunsaturated fatty acids, SFA=saturated fatty acids, NR=not reported, MeqTE/Kg- 1=miliequivalents of Trolox equivalents per kilogram, t=time, T=temperature.

UAE technology has been applied for oil extraction in various seeds. In the study of Taticchi *et al.* (2019) *Ogliarola garganica* seed oil was extracted using ultrasound-assisted extraction. The results showed a 22.7% increase in yield compared to the control solvent extraction. The acquisition of bioactive compounds improved, particularly with increased concentrations of hydrophilic phenols and alpha tocopherols. Another study demonstrated the effectiveness of ultrasound as a pre-treatment for *Forsythia suspensa* seed oil, comparing the composition and antioxidant activity of oil processed by UAE, Soxhlet, hydro distillation, and SFE-CO_2. Results indicated higher oil quality with increased antioxidant activity when seeds were processed with ultrasound and ethanol as solvent (Ming *et al.,* 2019). Isopencu *et al.* (2018) observed that oil yield was primarily affected by the intensity, time, and temperature of the ultrasound-assisted extraction process in extracting sea buckthorn seed oil.

Most of the studies on oil extraction using UAE technology have shown that manipulation in the parameters significantly impacts oil quality and recovery. Temperature, at elevated values, can result in less intense bubble collapse, leading to reduced oil extraction and total phenol content, potentially causing the loss of thermolabile compounds (Susanti *et al*., 2022). Böger *et al.* (2018) observed a negative effect of increased temperature on yield, with higher yields achieved at lower temperature values. This behavior may be attributed to the reduced vapor pressure of the solvent at low temperatures, resulting in fewer cavitation bubbles and greater intensity of bubble collapses due to high pressure between the inside and outside of the bubbles. Senrayan and Venkatachalam (2018) found that extended exposure to ultrasound waves could cause degradation of compounds due to the large amount of energy delivered by UAE, and the cavitation increases the contact surface between solid and liquid. Massa *et al*. (2021) observed that increasing temperature and exposure time in ultrasound-assisted extraction favored oil recovery. Exposure time to cavitation enhanced cell wall rupture, boosting oil yield. Elevated temperature promoted oil extraction through the thermodynamic effect, reducing solvent viscosity and surface tension while improving the diffusion coefficient. However, excessive increases in time, temperature, or solid-solvent ratio may lead to adverse effects.

Other important parameters to consider that can affect oil extraction are ultrasound amplitude and solid-solvent ratio. Sánchez *et al.* (2019) noted that increasing ultrasound amplitude results in higher absorbed power, thereby enhancing the extraction process. However, this elevated ultrasound power may also lead to the degradation of certain compounds, such as tocopherols, or cause a dilution due to the increased amount of extracted oil. Wong *et al.* (2019) and Kenari and Dheghan (2020) explained that an increase in the solid-solvent ratio promoted mass transfer owing to a higher contact area and an increase in the concentration gradient between the two phases. UAE technology has advantages over traditional methods in preserving the fatty acid composition and recovering bioactive compounds (phenols and tocopherols), as it operates at shorter times and lower temperatures. However, excessive increases in parameters such as time and temperature can be counterproductive to the recovery of bioactive compounds. Prolonged exposure to bubble collapse at high pressure and temperature can degrade these compounds. Optimizing the parameters of UAE, including time, temperature, and amplitude according to the raw material of the oil of interest, is essential to maximize oil yield and preserve the integrity of bioactive compounds. However, it is important to find the right balance, as excessive values of these parameters can lead to degradation of sensitive compounds.

3.4. Pulsed Electric Field

3.4.1. Basis

Pulsed electric field (PEF) is a non-thermal technology designed to replace or complement traditional thermal processing of foods. PEF induces electroporation of cell membranes, enhancing the diffusivity of valuable components of plant tissues at room temperature (Barba *et al*., 2015). Short, high-power electrical pulses are delivered to a product in a treatment chamber between electrodes, with pulse duration ranging from nanoseconds to milliseconds and electric pulse field strength varying from 100-300 $V \cdot cm^{-1}$ to 20-80 $kV \cdot cm^{-1}$. A typical PEF unit comprises a high-voltage pulse generator, a treatment chamber with a fluid-managing assembly, and a monitoring and control system (Figure 4).

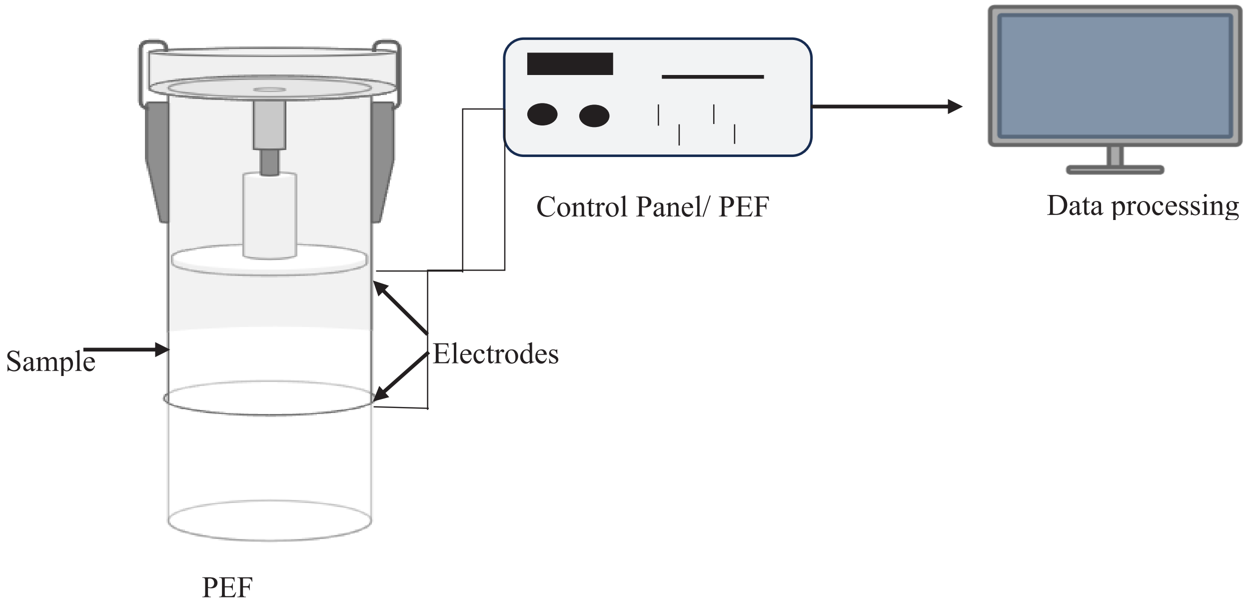

FIGURE 4. Pulsed electric field system. Pulsed electric field equipment. The equipment consists in a chamber where the sample is placed between two electrodes. The electrodes are used to apply the electric field, and a PEF generator with a control panel is used to adjust the electric field parameter (Ranjha *et al*., 2021).

3.4.2. Application

In an application of PEF to extract oil from olive pastes (2kV·cm^{-1}, frequency 25 Hz, pulse width 50 μs), the extraction yield was 85.5%, which was higher than by Soxhlet extraction (79.5%). Regarding oil quality, the volatile fraction of the experimental sample did not show significant differences in the saturated and unsaturated C5 aldehydes, C6 aldehydes, and total esters. The concentration of phenolic compounds in the oil slightly increased in the number of dialdehyde forms of decarboxymethyl oleanolic acid linked to hydroxytyrosol (3,4-DHPEA-EDA or oleoresin) and to tyrosol (p-HPEA-EDA or oleocanthal) compared to the control test. The PEF treatment resulted in an increase in phenolic compounds compared to the control test. When applied to the malaxed olive paste, PEF improved the release of phenols and their solubilization into the oil phase (Veneziani *et al*., 2019).

The application of PEF in oil extraction from plant seeds is limited (Table 3). Haji-Moradkhani *et al*. (2019) used the technology to extract *Cannabis sp.* seed oil, finding that a PEF intensity of 3 kV·cm^{-1} and press speed of up to 0.33 Hz gave optimal yield, resulting in an extraction efficiency of 28.0%. Mohseni *et al.* (2019) observed a positive effect of PEF in the oil extraction of Niger seeds using PEF with microwave-assisted extraction. They found a significant effect ($p < 0.05$) on the individual variables but not in the interaction of the variables ($p > 0.05$). This effect was attributed to the PEF variables causing enhancement in oil extraction due to the electrical destruction of cells, allowing for increased solvent penetration. However, higher intensity could lead to a decrease in oil extraction efficiency. Furthermore, the PEF plus microwave treatment affected the fatty acids profile by decreasing unsaturated fatty acids and increasing saturated fatty acids ($p < 0.05$) due to the susceptibility of unsaturated fatty acids to elevated temperatures. PEF can enhance cell membrane permeability and rupture, resulting in positive effects on oil extractability and quality (including bioactive compounds as phenolic compounds an antioxidants). Additionally, this technology enhances the recovery of phenolic compounds due to its ability to cause electrical destruction of cell walls, allowing better solvent penetration. Further research is necessary to optimize extraction conditions, as excessive increases in electric field intensity could negatively impact oil yield. Another important aspect to highlight is the potential use of PEF in combination with other extraction technologies, further enhancing oil recovery.

Table 3. Overview of studies on oil extraction using a pulsed electric field

Seed oil	Optimal treatment conditions				Parameters analyzed		
	I [kV·cm⁻¹]	*EI* [kJ·kg⁻¹]	*t* [min]	Yield [%]	Composition [%]	AA [mg·ml⁻¹]	Reference
Niger (*Guizotia abyssinica*)	0-5	NR	2.6	35	74.6 linoleic	NR	Mohseni *et al.* (2019)
Hemp (*Cannabis Sativa L.*)	3	NR	NR	27.9	NR	NR	Haji-Moradkhani *et al.* (2019)
Pecan nuts (*Carya illinoinensis*)	5	0.8	NR	88.7	NR	NR	Rábago-Panduro *et al.* (2021)
Coriander (*Coriandrum sativum L.*)	0-1.75	NR	NR	0.39	NR	0.41	Ghazanfari *et al.* (2023)
Vitis vinifera	5	NR	5	8.18	63.9 linoleic 7.61-8.61 palmitic 2.05-2.11 oleic 0.44-0.45 stearic	NR	Ćurko *et al.* (2023)
Paeonia sp.	5	NR	NR	29	Nr	NR	Xu *et al.* (2024)

Abbreviations: I=intensity, EI=electric intensity, t=time, UFA=unsaturated fatty acids.

4. CONCLUSIONS AND PERSPECTIVES

4.1. Conclusions

Non-thermal technologies represent a promising alternative to overcoming the limitations of traditional extraction methods by improving yield and oil quality. Supercritical fluid extraction (SFE) is the most extensively studied due to its ability to use CO_2 in its supercritical state as a solvent. Its capacity to operate at shorter times and lower temperatures enhances extraction yield while maintaining the antioxidant activity of the product. Ultrasound-assisted extraction is an alternative for vegetable oil extraction, highlighting the advantage of increased yield. However, it is important to note that the samples at prolonged ultrasound exposure may exhibit decomposition of fatty acids and a change in their profile. Concerning antioxidant activity, it is either maintained or improved through this method. Pulsed electric field (PEF), though used in vegetable oil extraction on a limited industrial scale, requires more in-depth research to understand its effects.

Overall, non-thermal technologies facilitate cell membrane rupture and improve mass transfer, optimizing oil extraction process by increasing yield and bioactive compound availability. Their ability to operate at shorter times and lower temperatures contributes to better antioxidant compounds recovery and minimal fatty acids degradation. However, further exploration and research are necessary for non-thermal technologies to establish their efficacy, excessive increase in process parameters such as temperature, time, electric field intensity or ultrasound amplitude, may have counterproductive effects on oil recovery. Continued research is essential to adapt these technologies to different oilseeds and establish optimal processing conditions.

4.2. Perspectives

The utilization of non-thermal technologies in vegetable oil extraction has demonstrated notable process enhancements, resulting in increased yields, elevated antioxidant compound levels, enhanced activity, and a favorable fatty acid composition of the product. However, it is crucial to note that not all non-thermal technologies produce the same effects in vegetable oil extraction. For instance, some technologies may result in lower yields but produce oil of superior quality enriched with bioactive compounds compared to oils extracted using conventional methods.

This highlights the need for dedicated research aimed at optimizing extraction processes. Evaluating the most appropriate techniques and their optimal conditions to achieve higher yields and improve oil quality, while simultaneously tailoring these parameters to the unique characteristics of the specific plant under consideration, is essential. Such efforts have the potential to facilitate the integration of these innovations into industry. This, in turn, drives the industry to shift towards more efficient extraction methods while also promoting oils with improved applications and properties.

Furthermore, certain non-thermal technologies, such as high voltage electric field, cold plasma, and their combinations, are employed for extracting bioactive compounds. These techniques, although not extensively studied in the context of vegetable oil extraction, hold the potential to increase yield, improve fatty acid profiles, and enhance the antioxidant activity of extracted vegetable oils.

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