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Challenges and Opportunities for Pilot Scaling-Up Extraction of Olive Oil Assisted by Pulsed Electric Fields: Process, Product, and Economic Evaluation

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Featured Application: Pulsed Electric Fields (PEF), a non-thermal technology, can assist conventional olive oil extraction with a positive impact on production efficiency, maintaining the extra-virgin classification. This study evaluated the impact of PEF on the "Galega Vulgar" cultivar for the first time on a pilot scale. Its application at the industrial level should be investigated based on the promising results obtained.

Abstract: This study aimed to investigate the impact of Pulsed Electric Fields (PEF) technology in the extraction of olive oil on a pilot scale, using the "Galega Vulgar" olive variety as raw material. The extraction assisted by PEF had a malaxation time of 30 min and was compared with the traditional process of 45 min of malaxation. The main quality parameters of olive oil and the PEF's cost-benefit assessment were performed. The incorporation of PEF in olive oil production reduced the malaxation stage by 33% without compromising the yield or extra-virgin classification. This efficiency leads to a potential 12.3% increase in annual olive oil production, with a 12.3% and 36.8% rise in revenue and gross profit, respectively. For small-scale production, the considerable upfront investment required for PEF equipment may be a challenge in terms of return on investment. In this scenario, opting for a renting scheme is the best economic solution, especially given the seasonal nature of olive oil production. In medium- to large-scale production, the investment in PEF is a sound investment since it is possible to achieve, with an equipment cost of EUR 450,000 and a production output of 5 tons per hour, an annual ROI of 20%.

Keywords: pulsed electric fields; EVOO; "Galega Vulgar" cultivar; olive oil quality; PEF; pilot scale

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1. Introduction

Data reported by FAOSTAT show that between 2017 and 2021, global olive oil production increased by 0.2 million tons, reaching 3.3 million tons in 2021, with Spain the main contributor with a share of around 44%. The European Union's (EU) contribution will be around 71% in 2021, with Spain, Italy, Greece, and Portugal being the largest contributors [1].

In the same period, olive fruit production in the EU has gained importance, with an increase in harvested area and production of around 0.1 million ha and 2.1 million tons, reaching 5.0 million ha and 15.0 million tons in 2021, respectively [1]. The main olive varieties used in olive oil plant production in Portugal, mentioned in order of predominance, are "Galega Vulgar", "Cobrançosa", "Cordovil de Serpa", and "Arroniz". These plants are constrained to operate within the 2- to 3-month olive harvest period in autumn. In terms of production, small enterprises run with throughputs ranging from 0.4 to 2 tons/h of olive paste, and medium to large plants operate with throughputs ranging from 2 to 12 tons/h [2].

On the other hand, in 2022, the global olive oil market was valued at USD 14.2 billion. Projections from 2023 to 2030 forecast a growth of USD 14.6 billion to USD 18.4 billion, respectively. The growth this market is experiencing is due to increasing demand for olive oil across the food service and retail channels, in addition to the interest in trying out exotic cuisines where the popularity of *Olea europaea* fruit oil has been standing out by its health benefits, namely, the virgin oil segment [3].

In this context, olive oil extraction processes are continuously gaining relevance. The traditional olive oil extraction process essentially involves (i) the crushing of olive fruit to break plant tissues and allow oil release; (ii) the malaxation phase of the olive paste (at vacuum or not) is carried out by continuous agitation to induce the oil drop coalescence phenomena (typically < 25 RPM, <30 °C, <1 h); and lastly (iii) the mechanical recovery of the oil by centrifugation or pressing. Then, the olive oil obtained is usually filtered or decanted to remove any possible solid residues prior to bottling [2,4]. The improvements in the yield of olive oil extraction are focused on malaxation, where time and temperature increase play the main role. However, this may also have a negative impact on the sensorial and quality parameters of olive oil [5] since the predominant reactions in this stage seem to be chemical oxidation reactions, which are favored by the incorporation of oxygen into the olive paste [6].

To overcome the drawbacks of the traditional process, important research efforts are being devoted to finding non-thermal innovative physical techniques to enhance olive oil production, such as ultrasound, microwave, and Pulsed Electric Fields (PEF) [5]. PEF is a non-thermal technology based on pulsed power that promotes cell electroporation by gently opening pores in the cell membrane using precise, targeted, and short-time electrical pulses [7]. For this, the food matrix is placed between or pumped through two electrodes. The main components of a system for the application of PEF are the pulse generator and the treatment chamber, and the main parameters are electric field strength and specific energy [8].

Olive oil extraction assisted by PEF (after crushing or malaxation) has shown great efficiency in improving it by accelerating malaxation time while guaranteeing the EU legal standards of the highest quality olive oil. On the other hand, PEF is an interesting technology thanks to its incorporation into traditional processing lines, which is easy, more cost-effective, and eco-friendly [9]. Nevertheless, it is necessary to carry out more pilot-scale studies to confirm the promisor's results obtained for extraction assisted by PEF on a lab scale [10].

PEF implementation cost-benefit assessment is an important factor that needs to be taken into account before fully implementing it into an industrial olive oil process [10] since innovative technologies such as PEF are showing a high potential to provide products with improved quality and a reduced environmental footprint while reducing operation costs and improving the added value of the products [2], in addition to enhanced industrial competitiveness represented by energy efficiency.

This study investigates the impact of olive oil extraction assisted by PEF on a pilot scale using the "Galega Vulgar" cultivar of olive provided by small olive agriculture. The malaxation step, the main legal quality parameters of olive oil, and the cost-benefit assessment were analyzed. As far as the authors know, there is limited information concerning the olive oil extraction assisted by PEF at a pilot scale using the Portuguese "Galega Vulgar" cultivar olive fruit.

2. Materials and Methods

2.1. Plant Materials and Assay

Olive fruits (*Olea europaea* L.) from the "Galega Vulgar" cultivar, grown in Abrantes (Santarém, Portugal), cultivated in an irrigated orchard, were harvested on 27 and 28 October 2022 at the turning ripening stage and immediately transported to TAGUSVALLEY's pilot plant located in Abrantes (Portugal). After that, olive fruits were washed, separated from leaves and branches, and processed. The pilot-scale extraction tests were conducted with 1500 kg of fresh fruit.

2.2. PEF-Assisted Extraction Pilot System

The extraction pilot system was prepared to carry out olive oil production tests. This one comprised two parts: (1) a commercial olive oil extraction plant (OLIOMIO model 350-500_GLQE_10; up to 350 kg/h; Gandra; Vila Nova de Famalicão, Portugal), including a washing module (model DLE; up to 400 kg/h; 2.5 kW), a mill (model F2GL_350/500; up to 500 kg/h; 10 kW), a malaxation container (model F2GL_350), and a horizontal 2-phase centrifuge (model D350, 5.5 kW; up to 350 kg/h); and (2) a pilot PEF-equipment (model EPULSUS®-LBM3B-15; EnergyPulse Systems; Lisbon, Portugal). This equipment is based on a 9 kW generator that produces bipolar squared electric pulses at a maximum voltage of 15 kV and a maximum pulse current of 400 A. EPULSUS® is completed by a DN40 colinear treatment chamber (tube) with a 4 cm gap between the electrodes. In the production tests, the PEF system was installed before the malaxation container (Figure 1).

Figure 1. Steps of olive oil extraction line with the PEF chamber before the malaxer container. (**a**) Cleaning; (**b**) crushing; (**c**) PEF treatment; (**d**) malaxation; and (**e**) centrifugation.

2.3. Olive Oil Extraction Conditions

Olives were mechanically crushed (2800 rpm; 6 mm) and collected in the first malaxation tank. After the first tank was full, the olive paste was pumped at a flow rate of 2242 kg/h through the PEF chamber to the second malaxation tank, where it was malaxated in a stainless-steel horizontal container equipped with a helical mixing device (20 rpm). After the malaxation step, the olive paste was continuously pumped at 350 kg/h using a pump included in the OLIOMIO system to the horizontal 2-phase centrifuge (3200 rpm). In centrifugation, the olive oil was physically separated from the olive pomace and then stored in 1 L glass bottles. After 3 months of the decantation process, in a dark and room-temperature place, the olive oil was filtrated by cellulose-based fibrous filter plates (SA-295) in a system (Mori Luigi model FP220-0, San Casciano in Val di Pesa, FI, Italy). The final olive oil was bottled and then analyzed.

Regarding PEF treatment conditions, the applied electric field was 2 kV/cm in a monopolar positive pulse with a 40 µs pulse width at a frequency of 100 Hz. The pulse current was approximately 166 A, with an applied specific energy of 8.5 kJ/kg. These treatment conditions were determined using data from previous laboratory-scale tests (data not shown) and previously published results of olive oil extraction using pilot and industrial-scale PEF [6,11], with modifications.

In the control production (control), the olive paste passed through the PEF treatment chamber with the PEF system turned off. In this way, possible interferences in the treatment chamber were avoided, and processing times between malaxation and centrifugation were the same. The olive paste temperature was measured with a thermocouple thermometer (HI 935007, HANNA® instruments, Woonsocket, RI 02895, USA). Operating parameters for the olive oil production tests performed are presented in Table 1.

Table 1. Operating parameters for the olive oil extraction tests were determined with a standard protocol (control) and by applying PEF treatment (PEF).

Operating Parameters	Control	PEF
Malaxation time (min)	45	30
Temperature before PEF (°C)	33.1	31.2
Temperature after PEF (°C)	33.0	33.4
Temperature after malaxation (°C)	31.3	32.6
Mass flow of PEF chamber (kg/h)	2242	

2.4. Moisture and Oil Content of Olives and Pomace

Moisture content was calculated after drying 5 g of crushed olives and pomace samples in an oven at 100 °C (Selecta, Digitronic TFT, Barcelona, Spain) until constant weight. The results were expressed in percentages *w*/*w*. Regarding oil content, the Soxhlet extraction method was conducted on a water bath (Selecta, Precis-Bat, Barcelona, Spain) using n-hexane (99%) according to the reference method [12]. Dried, crushed olives, and pomace samples were placed into a filter paper cartridge and processed for a few hours. The results were expressed as a percentage of oil in fresh weight. The moisture and oil content results were compared between PEF-treated and control samples.

2.5. Olive Oil Analysis

2.5.1. Olive Oil Extraction Yield and Physicochemical Analysis

The yield of the extraction process was calculated by the difference between the oil content in fresh fruit and the remaining oil content in the olive pomace generated in the extraction process. These measurements were performed in triplicate. The olive oil yield is calculated as Equation (1):

$$\text{Olive oil yield}(\%) = \frac{\text{fruit oil content} - \text{pomace oil content}}{\text{fruit oil content}} \times 100 \quad (1)$$

General chemical parameters were determined using the standard protocols of the International Olive Council (IOC): free acidity (% of oleic acid) [13], peroxide value (meq O_2/kg) [14], K232, K268, K270, and ΔK [15].

2.5.2. Oxidative Stability

The oxidative stability of the oils was evaluated by means of the Rancimat apparatus (Mod. 743, Metrohm Ltd., Herisau, Switzerland) at 110 °C using an airflow of 20 L/h. Stability was expressed as the oxidation induction time in hours.

2.5.3. Total Phenolic Content

The total phenolic content (mg of caffeic acid/kg of oil) was obtained by triple extraction of a solution of oil in n-hexane with a methanol/water mixture (3:2). Folin–Ciocalteau reagent and calcium carbonate were added to a suitable aliquot of the combined extracts. Solution absorbance was measured at 725 nm in Perkin Elmer Lambda 365 UV/VIS equipment (Perkin Elmer, Waltham, MA, USA).

2.5.4. Tocopherols Content

Tocopherols were determined by HPLC with fluorescence detection following IUPAC Standard Method 2.432 [16]. Samples were dissolved in hexane (5 µg/mL) and analyzed with Perkin Elmer Series 200 equipment (Perkin Elmer, Waltham, MA, USA). The chromatograph was equipped with a quaternary pump, a thermostatted column compartment, and a fluorescence detector (LC295). A normal phase chromatography was performed with a silica HPLC column (LiChrospher® Si-60, 60 Å pore diameter, L × I.D. 250 mm × 4.6 mm, 5 µm particle size) (Merck, Darmstadt, Germany). For each sample, the volume analyzed was 20 µL. The temperature of the thermostatted column compartment was set at 16 °C. The separation of tocopherols was achieved using n-hexane:isopropanol (99.5:0.5, *v*/*v*) with a flow rate of 1.2 mL/min. The excitation and emission wavelengths in the detector were 290 nm and 330 nm, respectively. The quantification was performed by external calibration with tocopherol standards.

2.5.5. Sensory Analysis

The sensorial analysis was performed by an accredited panel applying the standard protocol of the IOC [17] to determine the organoleptic characteristics and establish the olive oil classification. The attributes, positive (fruity, bitter, and pungent) and negative (defect), were evaluated on a 0–10 scale. For each parameter, the results are the median of the panel. The classification of olive oil is based on the median of its defects and fruity attributes. There are four possible classifications for olive oil: (a) Extra virgin olive oil: if the median of the defects = 0.0 and median of the fruity attribute > 0.0; (b) virgin olive oil: if 0.0 < median of the defects ≤ 3.5 and median of the fruity attribute > 0.0; (c) ordinary virgin olive oil: if 3.5 < median of the defects ≤ 6.0, or median of the defects ≤ 3.5 and median of the fruity attribute = 0.0; and (d) lampante virgin olive oil: if the median of the defects > 6.0 [17].

2.6. Statistical Analysis

Statistical analyses were performed using GraphPad Prism software version 9.0.0. (121) (Statsoft, Inc., Tulsa, OK, USA). The means of the parameters evaluated between the experimental treatments were compared by applying a one-way analysis of variance (ANOVA) followed by a post hoc Mann–Whitney's test ($p \leq 0.05$).

2.7. Economic Analysis

The present economic analysis is based on small-scale production, with production below 150 kg/h. Olive oil production is seasonal; therefore, three months per year were considered, with production taking place 24 h a day, seven days a week, totaling 2208 h of production per year. The investment analysis was conducted with a focus on achieving a target return on investment of 20%. Subsequently, the initial cost of the equipment was calculated based on the proposed ROI and factored in the expected rise in gross profit from the implementation of PEF. Estimates for medium- and large-scale productions were obtained based on a production rate of 5 tons/h.

The economic analysis had three main categories, as described below:

- *Raw Material Cost:*
  The cost of olives was obtained from the General Planning and Political Administration Office (GPP) [18,19]. The cost was calculated by averaging the market values of olives in November and December of 2022 and January and February of 2023.
  Cost of olives: 0.67 EUR/kg

- *Final Product Selling Price:*
  The market price of extra virgin olive oil was determined based on the market price observed in Portugal in the 32° week of 2023 [20]. Olive oil sold on this date is mainly produced from olives harvested during the months considered in the raw material cost.
  Cost of extra virgin olive oil: 6.42 EUR/L
- *Operational Costs:*
  Electricity was the only operational cost considered; other costs inherent to the process (e.g., labor, water consumption, packaging) are identical in both processing methods and therefore have no impact on the comparative analysis. The assumed cost per megawatt-hour is the European Union's average industry energy cost in the first semester of 2023, published by the Energy Services Regulatory Authority of Portugal (ERSE) [21].
  Energy price: 219.4 EUR/MWh
  ∑Machine Energy Consumptions per cycle:
  With PEF (malaxation 30 min): 14.20 kWh
  Without PEF (malaxation 45 min): 15.29 kWh

The economic analysis calculations made in this study were carried out by using the following equations:

$$\text{Energy Costs} = \sum \text{Machine Energy Consumptions per cycle} \times \text{Energy Price} \times \text{Number of cycles} \quad (2)$$

$$\text{Annual Production} = \frac{\text{Hours of Production}}{\text{Cycle Time}} \times \text{Production per cycle} \quad (3)$$

$$\text{Revenue} = \text{Annual Production} \times \text{Olive Oil Market Price} \quad (4)$$

$$\text{Gross Profit} = \text{Revenue} - (\text{Eletricity Costs} + \text{Raw Material Costs}) \quad (5)$$

$$\text{ROI} = \frac{\text{Difference in Gross Profit}}{\text{Cost of investment}} \times 100 \quad (6)$$

3. Results and Discussion

3.1. Process and Olive Oil Extraction Yield

The impact of applying treatment (PEF) on olive paste in combination with a reduced malaxation stage (30 min) was compared to the standard industrial protocol (control) with longer malaxation times (45 min) for 'Galega Vulgar' fruits at the turning stage. The proposed PEF treatment led to a significant 33% reduction in malaxation time, corresponding to a 9.4% reduction in the overall process time. These results can be important to industrial olive oil production.

PEF treatment resulted in a slightly higher oil yield (1.7% increase) than the standard industrial protocol (Table 2). Thus, the oil content of the olive pomace obtained after PEF treatment was reduced by about 5.3% compared to the standard industrial protocol. Previous studies using the Spanish, Italian, and other cultivars of olive fruit at a lab scale had beforehand emphasized that PEF could increase the oil yield [6]. However, there is still a challenge in expanding the process that might come from the apparent non-linearity in scalability, optimization of several process factors, or cost involvement.

Thus, this study was carried out on a pilot scale, and therefore, it is difficult to control the parameters related to the overall process, such as product variability, residence time in each stage, and product losses. However, the significance of these findings lies in their applicability to industrial-scale operations and mass production. Conducting the study on a pilot scale provides valuable insights that closely mirror real-world scenarios, enhancing the relevance and practicality of the results.

Leone et al. (2022) [9] observed 89.19% extractability using the "Picholine" variety, applying PEF treatment at 26 °C in the same stage of the process with the same time of malaxation in an industrial olive oil plant. Navarro et al. 2022 [6], who performed pilot and industrial trials using "Manzanilla" and "Hojiblanca" cultivars, observed generally higher yields by applying PEF treatment in combination with reduced malaxation time (30 min), with extraction yields ranging between 53.4% and 64.4% in control samples and 56.4% and 72.1% in PEF samples, in terms of oil in olive and oil in pomace. As presented, the extraction yield depends on many variables, from the variety of olives and the state of ripeness at harvest to the production conditions. Therefore, the results must be carefully compared.

Table 2. Extraction yield, oil content, and moisture content of olives and pomace were obtained from the control and treated using PEF of olives from the "Galega Vulgar" cultivar.

Parameters	Olive Fruit	Pomace		Oil	
		Control	PEF	Control	PEF
Oil (% fresh weight)	15.4 ± 1.6	3.8 ± 0.3 [a]	3.6 ± 0.3 [a]	-	-
Moisture (% w/w)	60.9 ± 0.3	65.0 ± 2.1 [a]	65.5 ± 1.6 [a]	-	-
Yield (%)	-	-	-	75.3 ± 3.0 [a]	76.6 ± 1.6 [a]

Values are means ± standard deviation (SD). [a] Different superscript letters on the same row indicate a significant difference at $p \leq 0.05$.

Regarding malaxation temperature, it was observed a slight increase in temperature from 31.2 °C to 33.4 °C without significance after PEF treatment of olive paste. However, at the end of malaxation, the temperature decreased to 32.6 °C, resulting in a minor impact on the process and being non-relevant.

PEF treatment induces modifications in cell membranes, causing an increase in transmembrane potential, leading to the formation of pores and facilitating mass transfer during extraction processes [22]. The effects caused by PEF may explain the results obtained in this study, in which an increase in extraction efficiency was observed through the application of the treatment. The product processed by PEF achieved the same extraction yield as the control, with a 33% reduction in malaxation time. In the olive oil industry, production efficiency is a crucial factor for the company's profitability. Furthermore, given that the fruit harvest season is very short and the fruit is quite perishable, it is essential to make the most of olive oil extraction, minimizing losses associated with spoilage.

3.2. Chemical Quality of Olive Oil

The chemical quality of olive oil derived from traditional processes and extraction assisted by PEF technology indicated that both products fulfilled the legal limits established by the commission-delegated regulation (EU) 2022/2104 of 29 July [23] for the extra virgin olive oil (EVOO) classification for the main regulatory quality parameters analyzed, including acidity, peroxide value, K232, K268, K270, and ΔK (Table 3). Both products were considered EVOO, and no significant differences ($p > 0.05$) were observed.

Table 3. Trade standards for olive oils are obtained with a standard protocol (control) and by applying PEF treatment (PEF).

	Control	PEF
Acidity (% Oleic acid)	0.4 ± 0.0 [a]	0.2 ± 0.0 [a]
Peroxide value (meq O_2/kg)	4 ± 0.2 [a]	3 ± 0.5 [a]
K232	1.70 ± 0.02 [a]	1.45 ± 0.01 [a]
K268	0.16 ± 0.00 [a]	0.13 ± 0.00 [a]
K270	0.16 ± 0.00 [a]	0.13 ± 0.00 [a]
Delta K	0.00 ± 0.00 [a]	0.00 ± 0.00 [a]
Rancimat (h)	41.6 ± 1.1 [a]	34.8 ± 0.1 [a]
Total phenols (mg of caffeic acid/kg of oil)	322 ± 9.3 [a]	311 ± 19.5 [a]

Values are means ± standard deviation (SD). [a] Different superscript letters on the same row indicate a significant difference at $p \leq 0.05$.

In terms of oxidative stability, the product obtained with PEF technology showed a shorter oxidation induction time than the control; however, it was without statistical significance, as shown in Table 3. The values found in this study are similar to those reported by [24] for "Galega Vulgar" olive oil from irrigated orchard olives, with values ranging from 33 to 38 h. Rodrigues et al. (2023) analyzed extra virgin olive oils from the "Galega Vulgar" cultivar from different geographical locations in Portugal and observed a higher range of oxidative stability but lower than the results obtained in the current study, with values ranging between 13 and 31 h. Oxidative stability is related to the shelf life of olive oils. Normally, the longer oxidative stability is related to the longer shelf life of olive oils under similar storage conditions [25].

Phenolic compounds present in olive oil are strong antioxidants and radical scavengers [26], helping to stabilize the product during its shelf life and providing sensory characteristics like bitterness and pungency [27]. The health benefits promoted by the consumption of olive oil are confirmed by EFSA [28]. Polyphenols can provide a health claim for olive oil in that they contribute to the protection of blood lipids from oxidative stress [29]. The phenolic content of olive oil can vary between 50 and 1000 mg/kg of cafeic acid [30], depending on cultivation (place, climate, variety, and olives' level of maturation at the time of harvesting), extraction process (time processing, exposure to oxygen, temperature), and storage [31]. In this work, PEF treatment did not significantly affect the total phenolic content of olive oil. This content decreased by 3.7% with the PEF treatment. A study carried out with the Arbequina cultivar for small-scale olive oil extraction revealed the same trend, but more pronounced, with a 25% decrease in total phenol content with the application of PEF treatment and 30 min of malaxation in comparison with the respective control [32]. However, the malaxation temperature of this process with PEF was 15 °C, much lower than the malaxation temperature reached in this study (30 °C). The application of PEF in the "Galega Vulgar" monovarietal cultivar has not yet been studied; however, studies with other varieties in similar conditions have reported an increase in phenolic content with PEF treatment [9,33].

3.3. Impact of PEF Technology on Tocopherols

Tocopherols play an important role in the prevention of the oxidation of mono- and polyunsaturated fatty acids (PUFAs) [34], which helps in the stability of products during shelf life. The α-tocopherol homologue is the most common in many edible oils, and in extra virgin olive oil, it is the major tocopherol. The consumption of tocopherols has potential health benefits, like the prevention of cardiovascular diseases, adjuvants in cancer treatment, and the prevention of diabetes and obesity [35].

Table 4 shows the concentration of α-tocopherols, β-tocopherols, γ-tocopherols, σ-tocopherols, and total tocopherols in control and PEF olive oils. No significant differences ($p > 0.05$) were observed.

Table 4. Tocopherol content (mg/kg) in control and PEF olive oils was obtained.

	Control	**PEF**
α-toc	313 ± 6.1 [a]	289 ± 15.0 [a]
β-toc	4 ± 0.7 [a]	3 ± 0.6 [a]
γ-toc	9 ± 1.6 [a]	8 ± 0.2 [a]
σ-toc	0 ± 0.0 [a]	0 ± 0.0 [a]
Total	326 ± 8.3 [a]	300 ± 15.8 [a]

Values are means ± standard deviation (SD). [a] Different superscript letters on the same row indicate a significant difference at $p \leq 0.05$.

Nuno Rodrigues et al. (2023) [25] analyzed "Galega Vulgar" extra virgin olive oils from seven Portuguese locations obtained by the traditional extraction process and concluded that the total tocopherol content ranged between 299.9 mg/kg and 394 mg/kg, which is in line with the values obtained in the present study. Puértolas & Marañón (2014) [33] quantified total tocopherols in the traditional extraction process with the *Arroniz* variety, resulting in a concentration of 192 mg/kg. With the application of PEF, the concentration increased to 220 mg/kg, with the α-tocopherol isomer being the most abundant, with a significant increase upon application of PEF. However, in another study, Leone et al. (2022) [9] did not find any differences between PEF and control EVOOs respecting this isomer. In line with the various previous studies and the different trends observed, the variability of this compound in EVOO depends on genetic and agronomic conditions and not on the process of extraction [36].

3.4. Sensory Evaluation

Table 5 shows the sensory evaluation perceived by the panel test. Both control and PEF olive oils were considered extra virgin olive oil (EVOO), according to the profile attributes analyzed, since the median of the defects is 0.0 and the median of the fruity attribute is above 0.0 [17]. The median intensity of fruity and pungent attributes was slightly lower in the PEF sample compared with the control sample; however, in the PEF sample, neither defects nor off-flavors were detected. In general, PEF did not affect the sensory properties of the "Galega Vulgar" cultivar of olive oil.

Table 5. Sensory evaluation of control and PEF olive oils was obtained.

Attributes	Parameters	Control	PEF
Positive	Fruity *	3	2.5
Positive	Bitter *	2	2
Positive	Pungent *	4.5	3.5
Negative	Defects *	0	0
Final classification		EVOO	EVOO

* CVr% for each parameter was below 20%.

3.5. PEF Economic Analysis

The introduction of PEF into the existing production process has yielded positive outcomes in terms of efficiency, contributing to a significant reduction of 15 min in the malaxation stage. This process improvement does not compromise the quality parameters of olive oil when compared to the traditional process without PEF. Thus, the price of the final product is not compromised when PEF is applied and should be similar to the market price of extra virgin olive oil. The 15 min reduction in processing time holds considerable economic implications. Considering a production cycle involving 350 kg of olives, the implementation of PEF can increase annual olive oil production by 12.3%, which translates to an increase in revenue and gross profit of 12.3% and 36.8%, respectively (Table 6).

Table 6. Economic viability results of control and PEF olive oils.

	Control	PEF
Olive production per cycle (kg)	350	350
Cycle time (min)	160	145
Revenue (EUR)	215,819	242,252
Gross profit (EUR)	18,368	25,123
Olive oil production (L)	33,617	37,734
Energy consumption (kW)	48,791	49,948

Considering the scale of production, achieving a reasonable annual return on investment (ROI) of 20% would require an initial investment in equipment of EUR 31,000. However, this price significantly deviates from market rates. Consequently, investing in PEF might not be the optimal economic decision for low-volume production. In such instances, it is advisable to explore equipment rental options, especially given that production only occurs during a three-month period each year.

Despite olive oil plants worldwide being predominantly composed of small enterprises with production capacities ranging from 0.4 to 2 tons/h of olive paste, the majority of global olive oil production occurs in medium- to large-scale olive processing plants capable of producing between 2 and 12 tons/h [2]. In this case, considering a production of 5 tons per cycle and no increase in electrical consumption, the cost of equipment to achieve an ROI of 20% would be EUR 450,000. These results lead to the conclusion that PEF represents a worthwhile investment for medium- to high-olive oil productions.

From a sustainability perspective, the implementation of PEF results in a notable 8.8% reduction in electricity consumption per liter of olive oil produced, consequently reducing greenhouse gas emissions. As companies worldwide increasingly prioritize eco-friendly practices, the integration of technologies like PEF emerges as a viable option to improve olive oil production sustainability.

It is noteworthy that the intrinsic design of the PEF installation, characterized by its seamless integration into the existing production and minimal maintenance requirements, eliminates the need for process modifications. Therefore, considerations related to labor, water consumption, and consumables (ex. packaging) were not considered when comparing the economic output of the two production methods.

4. Conclusions

The application of PEF led to a significant 9.4% reduction in processing time without compromising the olive oil's organoleptic and physicochemical characteristics. Both products derived from PEF and the traditional method were classified as extra virgin olive oil. Pre-treating with PEF also presents clear advantages at the industrial level compared to traditional processes since the malaxation time can be reduced to 33%, allowing considerable energy savings.

In the studied production scale, the reduction in time resulted in a 12.3% increase in annual olive production and a subsequent rise of 12.3% in revenue and 36.8% in gross profit. Nonetheless, the improved economic margin in small production lines was not enough to offset the high upfront cost of PEF equipment. In those cases, renting should be considered, especially since production only occurs during a period of 3 months per year. Medium- to large-scale production lines can offset the initial investment, and therefore, careful consideration of scale is crucial when opting for the purchase or renting of PEF in olive oil production processes.

PEF technology can be implemented in the olive oil industry with great economic returns. Therefore, more research should be conducted on higher production scales to confirm the study results.

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