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Review

Valorization of Olive Leaves through Polyphenol Recovery Using Innovative Pretreatments and Extraction Techniques: An Updated Review

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Abstract: Olive leaves are naturally generated as a by-product during olive harvesting and olive oil production. Usually discarded with no specific use, they are a valuable source of bioactive compounds that should not be overlooked. Their valorization must therefore be achieved through the recovery of their polyphenols using an ecological strategy. Conventional extraction is commonly known as an energy- and solvent-consuming process, whereas emerging and innovative extraction technologies, such as ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), pulsed-electric-field-assisted extraction (PEF), high-voltage-electric-discharge-assisted extraction (HVED), supercritical fluid extraction (SFE), infrared-assisted extraction (IAE), and "Intensification of Vaporization by Decompression to the Vacuum" (IVDV), are considered more sustainable and environmentally friendly. The aim of this review is to provide a comprehensive and updated overview of the valorization of olive leaves through both pretreatment and extraction techniques via an analysis of the recovered polyphenols and their potential applications.

Keywords: olive leaves; polyphenols; pretreatment techniques; extraction; innovative techniques; emerging technologies

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1. Introduction

The olive tree (*Olea europaea* L.) belongs to the family Oleaceae [1]. A broad variety of olive cultivars are endemic to tropical and warm areas [2], specifically the Mediterranean countries that have been cultivating *Olea europaea* due to its oil and medicinal value since antiquity [1]. Nowadays, the increase in the demand for olives and olive oil is generating more by-products and, as a result, poses a serious concern from both environmental and bio-economical points of view [3]. This fact has prompted researchers to focus on waste valorization and implement green and sustainable strategies to reduce the negative impact of disposal [4]. The by-products derived from olive harvesting and the olive oil industry include olive pomace, mill wastewater, and leaves, twigs, and other plant residues [5,6]. Olive leaves, whether falling accidentally during harvesting or resulting from regular tree pruning, represent a considerable biomass that can reach up to 25% (depending on

the harvesting mode) of the total weight harvested, yet this mass is not fully exploited. Instead of being disposed of as waste, leaves can be used as a valuable source of secondary metabolites that can exhibit a wide range of biological effects [7–10], making them beneficial as potential ingredients for the food, cosmetic, and pharmaceutical industries [3,11,12].

Increased awareness in this regard has encouraged the development of relevant and optimized pretreatment and extraction techniques that are intended to intensify the recovery of phenolic compounds from olive leaves. Each method has its advantages and disadvantages that affect the extraction yield and the biological activities of the extracted polyphenols. Time, temperature, solvent composition, and mechanical constraints are the main parameters that affect the efficiency of the extraction of bioactive molecules, in addition to the texture of the sample, the compound to be extracted, and its location within the plant matrix [13,14].

This review article primarily focuses on reporting the most recent studies on the pretreatments applied to olive leaves, the intensification of polyphenol extraction techniques applied to them, and their main industrial applications. It encompasses articles published within the last five years; retrieved from the Google Scholar, PubMed, and ScienceDirect databases; and selected based on subjects related to the extraction of polyphenols from olive leaves. The main keywords included the following: oleuropein, phenolic compound, olive leaves, and innovative extraction technique. All relevant references were considered to provide a comprehensive overview of the valorization of olive leaves through the extraction process.

2. Olive Leaves

Olive leaf extracts mainly comprise phenolic compounds such as oleuropein and hydroxytyrosol, which make up approximately 6–9% of leaf dry matter [15]. Oleuropein belongs to the secoiridoid group; it is responsible for the bitter taste found in olives. It is produced through the esterification reaction between 3,4-dihydroxyphenyl ethanol (hydroxytyrosol) and the glucoside of elenolic acid [16]. Moreover, hydroxytyrosol is produced during the hydrolysis of oleuropein. The hydroxytyrosol acts as an anti-inflammatory agent [17] and provides antioxidant properties by preventing the formation of free radicals and lipid oxidation due to the presence of an o-diphenolic group in its structure [16]. Hydroxytyrosol is well known for its protective role against cardiac diseases [18] and for improving lipid metabolism by minimizing obesity risk [19].

On the other hand, olive leaves are rich in sugars, especially mannitol. The latter is a bioactive substance that has preserving properties. Due to its importance, mannitol alcohol extract was studied for its use in pharmaceutical applications and was produced in yields between 2.81% [20] and 4.64% [21]. Olive leaves are also rich in lignins, constituting up to 35.72% of their composition [21]. The surfaces of olive leaves contain a high quantity of triterpenes, especially oleanolic and maslinic acids, known for their antimicrobial, antitumor, anti-inflammatory, and anti-HIV activities [22]

The diversity of bioactive compounds depends on different factors, e.g., the genotype [23,24] and the cultivar [25–27], climate variations, collection season, etc. For example, the highest polyphenol content was detected in different cultivars (Arbequina, Manzanilla, and Picual) during the summer season. According to Lorini et al., this is probably due to the positive effect of high temperatures on the synthesis of these bioactive molecules [28].

3. Pretreatment of Olive Leaves

Prior to polyphenol recovery from olive leaves, various pretreatments are applied to enhance the extraction yield. Grinding, performed just before extraction, not only increases the surface area of the solid material but also (and mainly) shortens the solute-solvent diffusion path length, significantly contributing to improved extraction yields [17]. Other pretreatment methods have been tested in view of ameliorating the recovery yield of bioactive molecules, such as drying [29], infrared irradiation [30], and "Intensification of Vaporization by Decompression to the Vacuum" [31].

3.1. Pretreatment by Drying

In the majority of studies [29,32–41], drying was conducted prior to polyphenol extraction from olive leaves. However, few papers have compared drying techniques and their effect on polyphenols [42,43]. The impact of the drying process of olive leaves (Aydin and Mugla types) on the extracted phenolic yield was studied. Microwave drying at 360 W or 540 W (5 min) was compared to oven drying (70 °C, 24 h) and to ambient air drying (20 days). The highest phenolic content of both olive leaf types was obtained when the samples were dried in an oven at 70 °C for 24 h. The efficiency of this method was followed by microwave drying at 540 W, ambient air drying, and finally microwave drying at 360 W. On the other hand, oven drying also gave rise to the maximal antioxidant activity of the Aydın samples (10.22%) compared to the lowest value obtained via microwave drying at 360 W [44].

Another study compared oven drying (45 °C or 70 °C for 2 days) to the room-temperature (25 °C) air drying (10 days) or vacuum-freeze-drying (2 days) of olive leaves (Manzanilla variety). The results showed that high-temperature drying significantly reduced the extracted phenolic and flavonoid content. The highest polyphenol content was found after room-temperature air drying (51.48 mg GAE/g), followed by freeze drying (51.07 mg GAE/g), oven drying at 45 °C (40.09 mg GAE/g), and finally oven drying at 70 °C (17.58 mg GAE/g). The highest levels of oleuropein (≈80 mg/g dw) and hydroxytyrosol (≈0.36 mg/g dw) were found when olive leaves were air-dried at room temperature [45].

Doğan and collaborators compared the efficiency of polyphenol extraction from olive leaves (Ayvalık variety) dried under different conditions: ambient conditions (1 week), oven drying (65 °C, 24 h), infrared drying (2500 W, 65 °C, 24 h), and microwave drying (180 W, 10 min). In general, the best yields were obtained with microwave drying for gallic acid (0.41 mg/g), caffeic acid (5.40 mg/g), luteolin 7-glucoside (16.56 mg/g), rutin hydrate (4.44 mg/g), and tyrosol (9.12 mg/g). As for oleuropein, the yields were as follows: 16.06 mg/g, 19.29 mg/g, 19.59 mg/g, and 19.99 mg/g for oven, microwave, infrared, and ambient drying, respectively [46].

3.2. Pretreatment by Infrared Radiation

Infrared waves are a form of electromagnetic radiation with a penetration capacity in a given matrix that is inversely proportional to the wavelength of these waves [47]. With the aim of intensifying polyphenol recovery from olive leaves, the latter were subjected to infrared irradiation (*Ired-Irrad*®) [48] (15 to 30 min) prior to the traditional water bath extraction (90 min, 60 °C, and a solvent of 75% ethanol/water). Compared to the untreated leaves, IR pretreatment enhanced both the total phenolic yield (measured in mg GAE/g) and the antioxidant activity by the same percentage, i.e., 50%, for the 15 min IR treatment and by 100% for the 30 min IR pretreatments [30]. The efficiency of this pretreatment was mainly attributed to the molecular vibrations (stretching, bending, rocking, and twisting) caused by the infrared irradiation [49,50].

3.3. Intensification of Vaporization by Decompression to the Vacuum" (IVDV)

IVDV was also tested as a pretreatment method to enhance polyphenol extraction from olive leaves. IVDV is a patented [51] thermomechanical technology based on a rapid treatment under saturated steam pressure (with an increase rate of 12 bar/s) followed by a pressure drop toward a vacuum within less than 0.02 s. Due to the decompression to a vacuum, the internal water of the olive leaves is likely to suddenly evaporate, expanding the product and creating microscopic alveolation within its structure. This porosity is mainly responsible for the intensification of the mass transfer phenomenon, thus enhancing the recovery of polyphenols from olive leaves [52–54]. An optimization of the pretreatment parameters (olive leaves' initial water content, time, and saturated steam pressure), prior to the water bath extraction of total phenolic compounds in 100% water or a hydroalcoholic (50% ethanol) solvent, was conducted using central composite design. The optimal polyphenol yield was 1.8 mg GAE/g DM, with W = 24.3%, T = 27 s, and P = 7.5 bar for

extraction in 100% water and 8.9 mg GAE/g DM with W = 39.8%, T = 27 s, and P = 7.5 bar for the hydroalcoholic solvent (50% ethanol) extraction. IVDV pretreatment tripled the extractability of polyphenols and their biological activities (measured using DPPH, FRAP, and CUPRAC) compared to the untreated samples and enhanced the recovery of oleuropein and hydroxytyrosol by 600% and 238%, respectively. This effectiveness was attributed to the IVDV-induced damage to the adaxial and abaxial surfaces of the olive leaves, a finding that was observed using scanning electron microscopy [31].

4. Conventional Solvent Extraction (CSE)

The majority of the recent papers dealing with the traditional solvent extraction of polyphenols from olive leaves assessed innovative green new deep eutectic solvent (DES) generation [5,55–60] (see Table 1). Olive leaves are generally washed, dried, and ground prior to the extraction process, with the operating conditions (temperature, liquid-to-solid ratio, stirring speed, and DES concentration) mainly optimized using response surface methodology [5,55,57]. Total phenolics [5,55,57] (ranging from 25 mg GAE/g DM to 106.25 mg GAE/g DM) and flavonoid content [5,57] (ranging from 26 RtE/g to 35 RtE/g) were optimized according to the oleuropein content [55]. Antiradical capacity and ferric reducing power were the main biological activities studied [5,57].

The efficiency of deep eutectic solvents (choline chloride and carboxylic acids) was compared to ethanol in terms of polyphenol recovery from olive leaves. Response surface methodology (2^2 rotatable central composite design) was employed to assess the effect of temperature and water addition on the efficacy of extraction in terms of total polyphenols. The highest polyphenol content was obtained with a [Ch]Cl:acetic acid deep eutectic solvent under the optimal conditions of 54.1 °C and 50% water addition. This phenolic compound yield, determined using Ultra-High-Performance Liquid Chromatography MS (UHPLC-MS), was 15% higher than that obtained with ethanol, suggesting that DESs are efficient green and Generally Recognized as Safe (GRAS) alternatives to organic solvents [55].

Table 1. Conventional solvent extraction of polyphenols from olive leaves.

Extraction Conditions	Optimization and Optimal Conditions	Quantitative Analysis	Qualitative Analysis	Ref.
CSE DES Compared to ethanol extraction 20 g/L 1 h 400 rpm	2^2 central composite rotatable design Variables: For extractions using ethanol or DES: Temperature Percentage of added water Responses: Phenolic content Oleuropein content Optimal conditions: For extraction using DES: 50% water in relation to DES mass 54.1 °C For extraction using ethanol: 0.50% water (*w*/*w*) 54.1 °C	UHPLC-MS Maximal phenolic compound extraction: [Ch]Cl:acetic acid 470.03 mg/kg	Not studied	[55]
CSE DES LA-Gly (Lactic acid-glycin) (5:1) (*w*:*w*) 120 min 80 °C Compared to 70% (*w*/*v*) aqueous mixtures	Box–Behnken Variables: Proportion of DES/water (C_{DES}) Stirring speed (S_S) Liquid-to-solid ratio ($R_{L/S}$) Responses: Phenolic content Optimal conditions: 78% *w*/*v* 500 rounds per minute 36 mL/g	Folin–Ciocalteu Total polyphenol yield: 98.77 mg GAE/g DM Total flavonoid cotent: 26.44 mg RtE/g DM HPLC **Polyphenol** / **Content (mg/g DM)** Hydroxytyrosol: 8.2 Rutin: 0.28 Luteolin 7-O-glucoside: 2.59 Apigenin 7-O-rutinoside: 0.36 Luteolin 3′-O-glucoside: 0.36 Oleuropein: 2.88 Quercetin: 0.44 Apigenin: 0.01 **Sum**: **15.13**	DPPH Antiradical Activity: 773.21 µmol DPPH/g DM Ferric-Reducing Power: 461.18 µmol AAE/g DM	[5]

Table 1. *Cont.*

Extraction Conditions	Optimization and Optimal Conditions	Quantitative Analysis	Qualitative Analysis	Ref.
CSE Three different natural deep eutectic solvents: NADES malic acid (Ma), D-fructose (Fru), glycerol (Gly) in a 1:1:1 molar ratio (MaFruGly) Nanofluid 70% EtOH	Not studied	Folin–Ciocalteu Polyphenol yield: NADES: ≈25 mg GAE/g DM Nanofluid: ≈20 mg GAE/g DM 70% EtOH: ≈28 mg GAE/g DM	Not studied	[56]
CSE 600 rpm 120 min 50 °C	Central composite design Variables: Concentration of the DES Liquid-to-solid ratio Responses: Total polyphenol yield (Y_{TP}) Optimal conditions: 80% (*w*/*v*) 32 mL/g	Folin- Ciocalteu Total polyphenol yield: 106.25 mg GAE/g DM Total flavonoid yield: ≈ 35 mg RtE/g DM LC–DAD–MS Detected compounds: Oleoside Luteolin derivative Luteolin di-glycoside Quercetin derivative Luteolin rutinoside Oleuropein isomer Apigenin rutinoside Oleuropein	DPPH Antiradical activity: 1097.8 µmol DPPH/g DM Ferric-reducing power: 445.1 µmol AAE/g DM	[57]

CSE: conventional solvent extraction, DES: deep eutectic solvent, and NADES: natural deep eutectic solvent.

5. Emerging and Innovative Technologies

In addition to conventional extraction, emerging and innovative techniques, such as those using ultrasound, microwaves, pulsed electric fields, high-voltage electrical discharges, infrared irradiation, and supercritical fluid extraction, are being employed to intensify the recovery of polyphenols from olive leaves. In the majority of the reported studies, the leaves are washed, dried, and ground before the extraction process.

5.1. Ultrasound-Assisted Extraction (UAE)

UAE is one of the most widely used techniques for the recovery of polyphenols from olive leaves. It is typically performed using either an ultrasound bath [32,34,36,61–63] or an ultrasound probe emitter [17,35,64–66]. The authors of some studies employed response surface methodology (Box–Behnken and central composite designs) to optimize the relevant experimental parameters, including the liquid-to-solid ratio, ultrasound power, pH, time, temperature, and solvent composition. This optimization is intended to maximize the concentrations of total polyphenols, flavonoids, and oleuropein and antioxidant activity [17,32,34–36,67]. Following extraction, the recovered extracts are usually filtered or centrifuged before spectrophotometric or chromatographic detection and quantification of polyphenols are performed. The pertinent studies explored various effects, such as anticancer, antioxidant (DPPH, CUPRAC, ABTS, TEAC, and FRAP), anti-inflammatory, and antibacterial (see Table 2).

UAE has demonstrated its potential as a green method for intensifying polyphenol recovery from olive leaves. Its efficiency has been compared to that of CSE [62]. The results indicate that UAE enhanced total phenolic and flavonoid content by 14.31% and 19.50%, respectively, compared to CSE. Results from ultra-performance liquid chromatography with diode array detection have confirmed that UAE intensifies the recovery of compounds such as caffeic acid, rutin, oleuropein, luteolin-7-O-glucoside, o-coumaric acid, luteolin-4-O-glucoside, apigenin-7-O-glucoside, luteolin, verbascoside, and apigenin compared to CSE. Additionally, UAE extracts exhibit higher antioxidant activities compared to those obtained with CSE, as observed in DPPH (18.5% higher), ABTS (12.5% higher), FRAP (10.9% higher), and CUPRAC (17.6% higher) assays. Finally, the antimicrobial activity (MIC and MBC) of UAE extracts has yielded satisfactory results against the foodborne pathogens *Y. enterocolitica* and *S. aureus*.

In addition to water [61,63] and hydroalcoholic solvents [17,32,34,36,37,62,64,65], researchers have explored the combination of natural deep eutectic solvents (NADES) with ultrasound (140 W, 37 kHz) to develop innovative and environmentally friendly processes for polyphenol recovery from olive leaves. The highest total phenolic yield (187.31 mg GAE/g DM) and flavonoid yield (12.75 mg ApE/g DM) were achieved using a choline chloride–fructose–water solvent (in a 5:2:5 ratio) [34]. On the other hand, oleuropein (1630.80 mg/kg DM) and caffeic acid (112.77 mg/kg DM) were more effectively recovered with a glucose–fructose–water solvent (in a 1:1:11 ratio), even outperforming MeOH extraction. Substituting organic solvents with NADES has been suggested to be a cost-effective and environmentally friendly alternative.

The efficiency of UAE (20 kHz) in intensifying polyphenol recovery from olive leaves has primarily been attributed to the acoustic cavitation phenomenon. Increasing the sonication time from 5 min to 1 h boosted oleuropein recovery from 2.75 to 28.16 µg/mL [65]. Microscopic observations revealed two mechanisms responsible for the efficacy of polyphenol extraction via ultrasound: (1) the erosion of the olive leave cuticle and (2) the fragmentation of surface protrusions. These physical changes were observed on the surfaces of sonicated olive leaves (cuticular layers and hairs) and were correlated with enhanced polyphenol recovery.

Table 2. Ultrasound-assisted extraction of polyphenols from olive leaves.

Extraction Conditions	Optimization and Optimal Conditions	Quantitative Analysis	Qualitative Analysis	Ref.
UAE bath: 60 °C	Box–Behnken design Variables: Ultrasound power (150–270 W) Extraction time (10–50 min) Ethanol concentration (50–90% EtOH) Liquid/solid ratio (10–50 mL/g (v/w)) Responses: Total phenolic content Oleuropein content Optimal parameters 260.47 W 10 min 53.27% 30 mL/mg	Folin–Ciocalteu Total phenolic content in optimal conditions: 197.32 mg/g DM HPLC detected compounds: Oleuropein Rutin Luteolin-4′-O-glucoside Apigenin-7-O-glucoside Luteolin Quercetin Apigenin Oleuropein content under optimal conditions: 74.68 mg/g	DPPH Antioxidant activity: EC_{50} of OE: 0.29 mg/mL Cell viability (%) Anticancer activity: Polyphenols (150–200 µM) induced apoptosis in HeLa cells	[32]
UAE bath 140 W 60 min 37 kHz 55–75 °C Acoustic energy density 35 W/L Solvent: Comparison between UAE with control: 50% (v/v) aqueous methanol (30 mL g^{-1}, 75 °C) and NADESs: Glucose–fructose–sucrose–water (1:1:1:11) Glucose–fructose–water (1:1:11) Glucose–sucrose–water (1:1:11) Fructose–sucrose–water (1:1:11) Choline chloride (ChCl)–glucose–water (5:2:5) ChCl–fructose–water (5:2:5) ChCl–sucrose–water (4:1:4) ChCl–lactic acid (1:2) ChCl–malonic acid (1:1) ChCl–ethylene glycol (1:2) ChCl–glycerol (1:2)	Central composite design Variables: Amount of NADES (8.61–90%) NADES and liquid-to-solid ratio Responses: Total polyphenol yield Total flavonoid yield Antiradical activity Optimal parameters: Choline chloride–fructose–water (5:2:5) 42.69% 40.66 mL/g	Folin–Ciocalteu Total phenolic content in optimal conditions: 187.31 mg GAE/g DM Total flavonoid content in optimal conditions: 12.75 ApE/g DM HPLC-MS Detected compounds highest amount: Oleuropein: GFW: 1630.80 mg/kg DM Caffeic acid: GFW: 112.77 mg/kg DM	DPPH Antioxidant activity in optimal conditions: 480 µmol DPPH/g DM	[34]

Table 2. *Cont.*

Extraction Conditions	Optimization and Optimal Conditions	Quantitative Analysis	Qualitative Analysis	Ref.
UAE bath 3 cycles (30 min each) distilled water 1:20 (*w*/*v*) 35 ± 5 °C	Not studied	Folin–Ciocalteu Total phenolic content: 20.19 mg GAE/g DM GC-MS Detected compounds: Oleuropein Tyrosol Syringic acid Benzoic acid Allopurinolphthalic acid	Sodium caseinate–olive leaf extract complexes DPPH Antioxidant activity: ≈40% ABTS Antioxidant activity: ≈80%	[61]
UAE bath 75% 40 kHz 60 °C 60 min 1:20 (*w*:*v*) 80% EtOH Comparison with conventional extraction (CSE)	Not studied	Folin–Ciocalteu Total phenolic content: CSE: 59.03 mg GAE/g DM UAE: 68.89 mg GAE/g DM Total flavonoid content: CSE 28.49 mg RE/g DM UAE 35.39 mg RE/g DM UHPLC analysis: Total extracted compounds: CSE: 1265.99 mg/100 g DM UAE: 1411.10 mg/100 g DM	Antioxidant activity: ABTS CSE: 258.82 µm TE/g DM UAE: 295.80 µm TE/g DM FRAP CSE: 552.05 µm TE/g DM UAE: 619.48 µm TE/g DM CUPRAC CSE: 1130.00 µm TE/g DM UAE: 1371.25 µm TE/g DM EC_{50} of DPPH radical scavenging CSE: 0.29 mg/mL UAE: 0.10 mg/mL	[62]
UAE bath 40 kHz Distilled water 1:20 (*w*/*v*) 90 min 35 ± 5 °C	Not studied	Folin–Ciocalteu Total phenolic content: 27 mg GAE/g DMs	Oxidative stability Microbiological Properties: Delay microbial growth during storage	[63]
UAE probe (UP400S) 1. Distilled water (100%, *v*/*v*) 2. Hydro-alcoholic solution (50%, *v*/*v*) For both all conditions are the same and compared with conventional extraction 40 °C 10 min Ratio of 2% (*w*/*v*) CSE: same conditions but with ultrasound replaced by stirring at 1200 rpm	Not studied	Folin–Ciocalteu Total Phenolic content: higher total phenolic content with hydroethanolic solutions CSE: 25.4 mg GAE/g DM UAE: 22.2 mg GAE/g DM TOF-LC-MS-MS	Antioxidant capacity Anti-inflammatory effects Bacterial growth inhibition	[64]

Table 2. *Cont.*

Extraction Conditions	Optimization and Optimal Conditions	Quantitative Analysis	Qualitative Analysis	Ref.
UAE bath 210 W Compared with simple ethanol maceration extraction	Box–Behnken design (BBD) Variables: Ultrasonic extraction time (80–160 min) Hydrochloric acid concentration (0.8–1.6 mol/L) Liquid-to-material ratio (40–60 mL/g) Responses: Hydroxytyrosol yield (mg/g) Optimal extraction conditions: Ultrasonication time: 120 min Hydrochloric acid concentration: 1.60 mol/L Liquid-to-material ratio: 60.00 mL/g	Yield of hydroxytyrosol in optimal conditions: 14.11 mg/g Concentration of hydroxytyrosol: Before purification: 2.27% After purification: 9.25%	Not studied	[17]
Comparison Ultrasound-assisted aqueous two-phase extraction (UAATPE) ultrasonic processor Comparison with ultrasound-assisted extraction and aqueous two-phase extraction	Box–Behnken design for UAATPE Variables: Ethanol concentration (32–38%) $(NH_4)_2SO_4$ concentrations (26–32%) pH (5.5–7.5) Extraction temperature (30–50 °C) Responses: Polyphenols yield (mg/g) Oleuropein content (mg/L) Optimal conditions: 35% (*w*/*w*) ethanol 29% (*w*/*w*) $(NH_4)_2SO_4$ pH 6.7 45 °C	Folin–Ciocalteu Total phenolic content: Maximum polyphenol content in optimal conditions: 34.06 mg/g HPLC Oleuropein Yield: Maximum oleuropein yield in optimal conditions: 44.13 mg/L	DPPH Radical scavenging activity 51.7%	[35]
UAE probe A single leaf was subjected to an ultrasonic field sonicated systematically on the lower surface side (abaxial) 20 kHz Maximal amplitude (100%) Continuous mode Specific delivered energy: 0.36 W/mL 20 ± 3 °C (maintained using a chiller) 80% EtOH Durations: 5 min, 15 min, and 60 min Compared to control	Not studied	Folin–Ciocalteu Total phenolic content: Maximal response after 60 min 48.75 µg eq. oleuropein/mL Control: 1.46 µg eq. oleuropein/mL Oleuropein content: 28.16 µg/mL	Not studied	[65]

Table 2. *Cont.*

Extraction Conditions	Optimization and Optimal Conditions	Quantitative Analysis	Qualitative Analysis	Ref.
UAE bath 40 kHz Compared to control	Central composite design Variables: Solid/liquid ratio (2–15%) Extraction time (10–50) Ethanol concentration (40–100%) Responses: Total extraction yield (%) Oleuropein content (mg/100 g) Total phenol content (mg GAE/100 g) Antioxidant activity (µmol TE/100 g) Optimal conditions: Solid-to-liquid ratio: 5.9% Ethanol concentration: 47% Extraction time: 50 min	Total extraction yield: 16.3% Folin–Ciocalteu Total phenolic content: 2227 mg GAE/100 g DM RP-HPLC-UV Oleuropein content: 419 mg/100 g DM	TEAC Antioxidant activity: 12095 µmol TE/100 g DM	[36]
UAE probe 20 kHz Amplitude: 79 µm 1/20 (*w*/*v*) 50 °C	Not studied	HPLC Maximal oleuropein content: 31 mg/g DM Maximal luteolin-7-O glucoside content: 4.1 mg/g DM Folin–Ciocalteu Total phenolic content: 113 mg GAE/g FDE Flavonoids assay Total flavonoids content: 13.2 mg QE/g FDE	Antioxidant activity: FRAP 435 mg Fe^{2+}g FDE DPPH 694.2 mg Trolox/g FDE ABTS 230.4 mg Trolox/g FDE	[37]
UAE bath 3 cycles 30 min each 35 ± 5 °C 1/20 (*w*/*v*)	Not studied	Folin–Ciocalteu Total phenolic content: 134.7 mg GAE/g DM	DPPH Antioxidant activity: 4.26% per mg of extract	[68]
UAE probe 24 kHz 100, 200, and 400 W	Not studied	Folin–Ciocalteu Total phenolic content: 100 W: 4.28 mg GAE/g DM 200 W: 11.19 mg GAE/g DM 400 W: 25.57 mg GAE/g DM	Not studied	[66]

UAE: Ultrasonically assisted extraction; FDE: freeze-dried extract.

5.2. Microwave-Assisted Extraction (MAE)

The aqueous and hydroalcoholic MAE of polyphenols from dried and ground olive leaves (particle size < 0.272 mm to 0.5 mm) were tested with microwave powers ranging from 150 to 1500 W. Most of the studies used response surface methodology to optimize the operating conditions, including treatment time (0.5–40 min), temperature (50–150 °C), pH (3–9), and ethanol percentage (0–100%). Total phenolic content ranged between 10.45 mg GAE/g DM and 103.87 mg GAE/g DM, while oleuropein content varied from 11.59 mg/g DM to 60 mg/g DM [38–40,69] (see Table 3).

The optimization of polyphenol extraction from olive leaves cultivated in Brazil was carried out using MAE (water, 2.45 GHz, 1000 W) by varying pH, temperature, and irradiation time [39]. Response surface methodology (rotational central composite design) was adopted to enhance both the total phenolic content and the antioxidant activity. The highest phenolic yield (103.87 mg GAE/g DM), oleuropein content (11.59 mg OP/g DM), antioxidant activity (92.87%), and antibacterial capacity against *Escherichia coli* (MIC of 50 mg/mL) were obtained under the following optimal MAE conditions: 100 °C, 2 min, and pH 6. These extracts were thus suggested for use as potential antibacterial and antioxidant food additives.

Sánchez-Gutiérrez et al. compared the efficiency of MAE (800 W; 40, 60, and 80 °C for 3, 6, or 10 min) to the conventional Soxhlet process (5 h) in terms of polyphenol recovery from olive leaves [70]. Various solvents were tested, including water, ethanol/water blends (50% and 75%), and glycerol/water blends (5%, 10% and 15%). The total phenolic content of the extracts was then determined, and the identification of some compounds was conducted using High-Performance Liquid Chromatography (HPLC). The antioxidant and antimicrobial biological activities were also assessed. The optimal MAE parameters for polyphenol extraction were found to be 80 °C, 10 min, and 50% ethanol/water. Notably, MAE yielded a higher oleuropein concentration (40.49 mg/g DM) compared to the Soxhlet process (27.13 mg/g DM). The authors of this study did not specify the variety of olive leaves used, but the quantity of recovered polyphenols was 2.5 times less than that found by Martiny et al. [39]. Comparable results in terms of antioxidant activity were found for both Soxhlet and MAE extracts (up to 78 mg TE/g DM). On the other hand, MAE water extracts exhibited stronger antibacterial activities than MAE ethanol extracts, primarily due to the better recovery of hydroxytyrosol and elenolic acid derivatives in aqueous systems. MAE can therefore be introduced as an environmentally friendly, time-saving method that requires lower energy and solvent consumption compared to Soxhlet [70].

In several studies, the efficiency of MAE was compared to other innovative green techniques, including UAE [39,71,72]. A comparative study was conducted to evaluate the quantity and quality (antioxidant and antimicrobial activities) of polyphenols extracted (oleuropein and hydroxytyrosol) from Brazilian olive leaves using optimized MAE (water; 86 °C; 3 min), UAE (water; 27 °C; 29 min), and maceration (water; 25 °C; 24 h). MAE (104.22 mg GAE/g DM) proved to be the most efficient technique in terms of total polyphenol recovery, followed by UAE (80.51 mg GAE/g DM) and then maceration (57.28 mg GAE/g DM). The polyphenol content (104.22 mg GAE/g DM) recovered by Rosa et al. [72] was similar to that obtained by Martiny et al. (103.87 mg GAE/g DM) [39], both using the same raw material. Oleuropein and hydroxytyrosol exhibited a similar trend, with 14.468 mg OP/g DM and 0.590 mg HT/g DM for MAE, followed by 6.914 mg OP/g DM and 0.547 mg HT/g DM for UAE and 0.051 mg OP/g DM and 0.027 mg HT/g DM for maceration. Antioxidant activity was the same for the MAE and UAE extracts (90.03%), followed by the activity of maceration extracts (67.25%). The MAE extracts displayed stronger antibacterial activity against *E. coli* compared to the UAE extracts at different polyphenol concentrations (75, 50, 25, 10, and 5 mg/mL) [72]. The effectiveness of microwaves was mainly attributed to the heating process of the treated matrix induced by dipolar rotation and ionic conduction [73].

Table 3. Microwave-assisted extraction of polyphenols from olive leaves.

Extraction Conditions	Optimization and Optimal Conditions	Quantitative Analysis	Qualitative Analysis	Ref.
MAE 2.45 GHz 1000 W 1:50 (*w*:*v*) Distilled water	Factorial design 2^3 Variables: Irradiation times (2–6 min) pH (3–9) Temperatures (60–100 °C) After extraction, extracts were analyzed directly (fresh extract) or after freezing at –20 °C for one week Responses: Oleuropein content of fresh extract (mg/g) Oleuropein content of frozen extract (mg/g) Optimal conditions were found in fresh extract: Temperature: 60 °C Time: 6 min pH: 9	HPLC Oleuropein in optimal conditions: 15.607 mg/g DM	Not studied	[38]
MAE 2.45 GHz 1000 W 1:50 (*w*:*v*) Distilled water	Central composite rotational design Variables: Irradiation times (2–6 min) pH (3–9) Temperatures (60–100 °C) Responses: TPC (mg GAE/g DM) Antioxidant activity (%) Optimal conditions: Temperature: 100 °C Time: 2 min pH: 6	Folin–Ciocalteu Total phenolic content in optimal conditions: 103.87 mg GAE/g DM HPLC Oleuropein in optimal conditions: 11.59 mg/g DM	DPPH Antioxidant activity in optimal conditions: 92.87% MIC Antimicrobial activity against *E. coli* in optimal conditions: 50 mg/mL	[39]
MAE 1500 W 1:10 (*w*:*v*) Ethanol/Water	Box–Behnken design Variables: Extraction time (5–40 min) Temperature (50–150 °C) Percentage of ethanol (0–100% (*v*/*v*)) Responses: Total compounds Total AMPK bioactive compounds Optimal conditions for total compounds and oleuropein: 22.5 min 123 °C 100% ethanol Optimal conditions for total AMPK bioactive compounds: 23 min 111 °C 42% ethanol/water (*v*/*v*) Multiple response optimal conditions: 23 min 111 °C 100% ethanol	HPLC Total compounds in optimal conditions: 74.24 mg/g DM Oleuropein in optimal conditions: 60.00 mg/g DM Total AMPK bioactive compounds in optimal conditions: 9.5 mg/g DM Multiple response Total compounds: 74.39 mg/g DM Total AMPK bioactive compounds: 9 mg/g DM	Not studied	[40]

Table 3. *Cont.*

Extraction Conditions	Optimization and Optimal Conditions	Quantitative Analysis	Qualitative Analysis	Ref.
MAE 2.45 GHz 900 W max	Central composite design Variables: Microwave power (150–250 W) Extraction time (0.5–1.5 min) Solvent volume (50–100 mL) Responses: Total polyphenol ingredient (TPI) Total flavonoid ingredient (TFI) Antioxidant activity (AA) Optimal conditions: 230 W 1.5 min 63.16 mL of 30% acetonitrile solution	Folin–Ciocalteu Optimal TPI: 10.45 mg GAE/g DM Colorimetric method Optimal TFI: 9.69 mg CE/g DM	DPPH Optimal antioxidant activity: 96.34%	[69]

MAE: microwave-assisted extraction.

5.3. Pulsed Electric Fields (PEFs) and High-Voltage Electrical Discharges (HVEDs)

Only a few studies have assessed the recovery of polyphenols from olive leaves using electro-techniques such as PEF or HVED treatments. The leaves are typically cleaned, dried, and then reduced to a defined particle size before undergoing PEF or HVED treatments [41,74,75]. Various parameters, including pulse duration, electric field strength, extraction time, applied voltage, and extraction solvents (both aqueous and hydroalcoholic blends), were studied (see Table 4).

The intensification of polyphenol recovery induced by PEFs is mainly attributed to the electroporation phenomenon, which enhances mass transfer [41,74]. The highest polyphenol content (20.75 mg GAE/g DM) was achieved using a 25% ethanol/water blend (v/v) during a 10 µs pulse duration of a PEF treatment (25 kV, 25 MHz). HPLC analysis showed that luteoline-7-O-glucoside (0.48 mg/g DM) and oleuropein (0.58 mg/g DM) were the predominantly identified polyphenols [74].

Other PEF parameters such as the geometry of the treatment chamber (rectangular or cylindrical) and the electric field strength have been shown to impact the efficiency of polyphenol recovery from olive leaves [7]. The optimal PEF conditions have included a rectangular-shaped chamber, a 25% ethanol/water blend (v/v), a pulse duration of 2 µs, an electric field strength of 0.85 kV cm^{-1}, a period of 100 µs, and an extraction duration of 15 min. These conditions resulted in a 38% increase in the extractability of total phenolic compounds and a 117% increase in oleuropein recovery. Other polyphenols, such as quercetin-3-O-rutinoside, luteolin-7-O-glucoside, apigenin-7-O-rutinoside, and luteolin-3′-O-glucoside, were also paired with enhancements ranging from 6 to 50% [7].

In addition to PEFs, HVED was tested as a green alternative to conventional extraction (CE) in terms of polyphenol recovery from olive leaves. Several parameters were investigated, including the nature of the solvent (0%, 25%, or 50% ethanol/water mixtures (v/v)), treatment stirring time (3 or 9 min), the gas used (nitrogen or argon), and the voltage applied (15, 20, or 25 kV) [75]. Polyphenols were characterized spectrophotometrically and chromatographically, and their antioxidant activity was measured. HVED (20 kV) intensified the recovery of polyphenols by 3.2 times compared to CE under the following conditions: 50% ethanol/water, argon, and 9 min of stirring. HVED intensifies the recovery of bioactive molecules through electrical breakdown in water, an intensive phenomenon accompanied by shock waves, bubble cavitation, liquid turbulence, and significant cell structure damage [75–77].

5.4. Supercritical Fluid Extraction (SFE)

SFE is a green method used for the recovery of terpenoids [7,29,42,78] and polyphenols [33,42,79–81] from olive leaves. In most studies, the leaves were dried, and their particle sizes were reduced to values ranging between 500 µm and 1 cm. The conditions of the drying process were shown to affect the SFE yield and the biological activities of the recovered polyphenols and terpenoids. For instance, the highest values for polyphenol yield and antioxidant activity were obtained when drying was carried out at 50 °C for 180 min and at 60 °C for 120 min, respectively [29]. Moreover, the polyphenol extraction yield was 1.8 times higher when SFE was conducted on dried leaves compared to fresh leaves. Different polyphenols and terpenoids were also identified and quantified in dried (e.g., wherein the major compound was oleuropein) and fresh (e.g., wherein the major compound was acetoxypinoresinol) leaves [42]. Supercritical CO_2 was used as a solvent in most of the studies, although it was sometimes combined with ethanol as a modifier [33,42,78–80] to enhance the efficacy of the extraction. The SFE pressures varied between 120 and 300 bar, the temperatures varied between 35 °C and 80 °C, and the time varied between 60 and 120 min [7,29,33,42,78–81].

Table 4. Pulsed-electric-field and high-voltage-electrical-discharge-assisted extractions of polyphenols from olive leaves.

Extraction Conditions	Optimization and Optimal Conditions	Quantitative Analysis	Qualitative Analysis	Ref.
PEF Rectangular chamber	Variables: Field intensity (fixed 1 kV cm^{-1}) Pulse period (1000 µs) Extraction duration (30 min) Pulse duration (10–100 µs) Extraction solvent (0–100% EtOH) Responses: Total phenolic content Antioxidant activity Optimal conditions for total phenolic content: 1 kV cm^{-1} 1000 µs 30 min 10 µs 25% EtOH Optimal conditions for antioxidant activity: 1 kV/cm 1000 µs 30 min 100 µs 75% EtOH	Folin–Ciocalteu Total phenolic content in optimal conditions: 20.75 mg GAE/g DM Control: 15.74 mg GAE/g DM HPLC Detected molecules: Quercetin-3-O-rutinoside Luteolin-7-O-glucoside Apigenin-7-O-rutinoside Luteolin-3′-O-glucoside Oleuropein	Differential Scanning Calorimetry Maximum antioxidant activity: T_{max}: 569 °C	[74]
PEF Rectangular chamber 1:3 (*w*/*v*) 22 °C 25% *v*/*v* aqueous ethanol solvent Control: (Comparison with conventional method)	Experimental Design Variables: Field intensity (0.7–1 kV cm^{-1}) Pulse duration (1–10 µs) Pulse period (100–1000 µs) Extraction duration (15–30 min) Responses: Total phenolic content Antioxidant activity Optimal conditions for total phenolic content: 0.85 kV cm^{-1} 2 µs 100 µs 15 min Optimal conditions for antioxidant activity: 0.85 kV cm^{-1} 10 µs 1000 µs 30 min	Folin–Ciocalteu Total phenolic content in optimal conditions: 24.80 mg GAE/g DM Control: 19.2 mg GAE/g DM HPLC Detected molecules: Luteolin diglucoside Quercetin-3-O-rutinoside Luteolin rutinoside Luteolin-7-O-glucoside Apigenin-7-O-rutinoside Luteolin-3′-O-glucoside Luteolin aglycone Oleuropein	Differential Scanning Calorimetry Maximum antioxidant activity: T_{max}: 488 °C	[41]

Table 4. *Cont.*

Extraction Conditions	Optimization and Optimal Conditions		Quantitative Analysis	Qualitative Analysis	Ref.
HVED Rectangular chamber (Comparison with conventional method)	Multifactorial design 2 designs of 12 experiments (argon and nitrogen)		UPLC-MS/MS Detected molecules: Apigenin Diosmetin Hydroxytyrosol Luteolin Oleanolic Acid Oleuropein Quercentin 1- For argon Folin–Ciocalteu Maximal total phenolic content: 65.99 mg GAE/g 2- For nitrogen Folin–Ciocalteu Maximal total phenolic content: 47.21 mg GAE/g	1—For argon DPPH Maximal antioxidant activity: 32.53 µmol TAE/g FRAP Maximal antioxidant activity: 443.36 µmol FE/g 2—For nitrogen DPPH Maximal antioxidant activity: 31.81 µmol FRAP Maximal antioxidant activity: 561.93 µmol FE/g	[75]
	1—For argon Variables: Concentration of ethanol (0–50% EtOH) Voltage (15–20 kV) Treatment time (3–9 min) Responses: Total phenolic content Antioxidant activity Optimal conditions for total phenolic content: 50% ethanol 20 kV 9 min Conditions for maximal DPPH antioxidant activity: 50% ethanol 20 kV 3 min Conditions for maximal FRAP antioxidant activity: 50% ethanol 15 kV 9 min	2—For nitrogen Variables: Concentration of ethanol (0–50% EtOH) Voltage (20–25 kV) Treatment time (3–9 min) Responses: Total phenolic content Antioxidant activity Optimal conditions for total phenolic content: 50% ethanol 20 kV 3 min Conditions for maximal DPPH antioxidant activity: 50% ethanol 25 kV 9 min Conditions for maximal FRAP antioxidant activity: 50% ethanol 25 kV 3 min			

PEF: pulsed electric fields; HVED: high-voltage electrical discharge.

Temperature was shown to have a more significant impact on the SFE of polyphenols from olive leaves than pressure. For example, increasing the temperature from 55 °C to 80 °C enhanced the polyphenol yield from 362 ppm to 1647.23 ppm at 120 bars and from 366 to 597.6 ppm at 200 bars. A negative interaction between pressure and temperature was revealed. Antioxidant activity was also enhanced with an increasing temperature, while it was negatively influenced by pressure. Conversely, increasing the SFE pressure from 200 to 250 and 300 bar enhanced polyphenol recovery from 5.83 to 9.76 and 13.12 mg GAE/g DM at 50 °C. It also boosted the hydroxytyrosol concentration from 0.42 to 0.73 and 1.35 mg/g. Antioxidant activity followed the same trend as polyphenol content, increasing from 274.91 to 321.25 and 365.18 µg/mL when intensifying the pressure from 200 to 250 and 300 bar [33].

Polyphenol identification, in most papers, was conducted using chromatographic methods, and the identified compounds are listed in Table 5.

Under SFE conditions of 120 bar, 80 °C, and 50% EtOH-CO_2, oleuropein was detected (1278.5 ppm), followed by hydroxytyrosol (55.10 ppm) and verbascoside (43.6 ppm) [80]. These compounds were also identified under different SFE conditions (35–60 °C; 100–200 bar) [81].

5.5. Infrared-Assisted Extraction (IAE)

After demonstrating its efficiency as a pretreatment [30], infrared irradiation was also used as a treatment to enhance the recovery of bioactive polyphenols from olive leaves. Infrared irradiation exerts a heating effect on intracellular fluid, causing its vaporization and thereby rupturing cell membranes/walls. This thermal energy is generated by the molecular vibrations induced by the infrared radiation. Moreover, some solvent characteristics are modified during IR, such as surface tension and viscosity, increasing the likelihood of solubilization and the recovery of more compounds [49,82,83].

To the best of our knowledge, no previous researchers used infrared technology to intensify polyphenol extraction from olive leaves except for Abi-Khattar et al. [84]. In their study, a central composite design was used to investigate the impact of time (60–180 min), temperature (38–77 °C), and ethanol content (40–80%) on the recovery of total phenolic compounds. Compared to water bath (CSE) extraction, under optimal conditions, IAE improved the total polyphenol yield by 30%, the oleuropein concentration by 18%, and the hydroxytyrosol content by 21%. This was achieved with 27% lower organic solvent consumption. The biological activities of the extracts were also ameliorated by IAE, with antiradical activity increasing by up to 25% and antioxidant capacity by up to 51% compared to CSE. However, no significant difference in the antimicrobial effect against *Staphylococcus aureus* (20 strains) was observed between IAE and WB, as both exhibited similar minimum inhibitory concentrations. Similarly, a comparable inhibition of Aflatoxin B1 secretion by the fungus *Aspergillus flavus* was observed for IAE and WB [84]. The fundamental principles of infrared radiation include high heat transfer efficiency and direct product heating. The penetration properties allow one to achieve a good balance between surface and bulk heating. For all the aforementioned reasons, IAE intensifies the mass transfer phenomenon of polyphenols from various matrices compared to conventional methods [85–90].

5.6. Pressurized Liquid Extraction (PLE)

PLE has emerged as a prominent technique for the extraction of valuable compounds from olive leaves. The results obtained by Lama-Muñoz et al. [91] demonstrated superior efficiency in comparison to dynamic maceration. Optimal PLE conditions of 190 °C, 5% leaf moisture content, and an 80% aqueous ethanol concentration led to higher extraction levels of oleuropein and luteolin-7-O-glucoside. This result suggests that PLE is a more efficient method for obtaining these bioactive compounds from olive leaves.

Table 5. Supercritical fluid extraction of polyphenols from olive leaves.

Extraction Conditions	Optimization and Optimal Conditions	Quantitative Analysis		Qualitative Analysis	Ref.
SFE 150 bar 40 °C Leaves and sea sand ratio: 1:1.5 (m/m) Solvent: CO_2 and ethanol (6.6%) Solvent flow rate: 23 g/min 60 min	Not studied	HPLC-ESI-TOF/MS Phenolic compounds Secologanoside Hydroxytyrosol Elenolic acid glucoside isomer 1 Vanillin Elenolic acid glucoside isomer 2 Ferulic acid Oleuropein isomer 1 Oleuropein isomer 2 Syringaresinol Pinoresinol Acetoxypinoresinol Diosmetin Triterpenoids Maslinic acid Oleanolic acid Ursolic acid Major phenolic compound in fresh olive leaves: Acetoxypinoresinol: 37 μg per 30 mg of extract Major phenolic compound in dried olive leaves: Oleuropein: 42 μg per 30 mg of extract Extraction yields: Fresh leaves: 9.3% Dried leaves: 16.7%	Hepatoprotective effect of fresh and dried olive leaf extracts: Helped to improve liver fibrosis Both caused by CCl_4 treatment	[42]
SFE 250 bar 80 °C Leaves and glass beads mixture Solvent: CO_2 80 min 6 g/min SFE was compared to Soxhlet extraction, in this case fresh leaves were used Ratio: 1/100 (*w*/*v*) Solvent: n-hexane 300 min	3 condition compared: 1. 50 °C, 180 min 2. 60 °C, 120 min 3. 70 °C, 60 min	Folin–Ciocalteu Total phenolic content: 1. 32.2 mg GAE/g DM 2. 36.1 mg GAE/g DM 3. 30.2 mg GAE/g DM Extraction Yield: 1. 3.5% 2. 3% 3. 2.8% GC–MS Detected terpenoids: Farnesyl acetate Spathulenol Palmitic acid Methyl eicosanoate Octacosane γ-tocopherol Oleic acid β-Sitostenone γ-sitosterol Stigmasterol n-hexatriacontane Oleanolic acid Uvaol	DPPH Antioxidant activity AA: 1. 64% 2. 73% 3. 48% EC_{50}: 1. 1.2 μgmL^{-1} 2. 1.1 μgmL^{-1} 3. 2.1 μgmL^{-1}	[29]

Table 5. *Cont.*

Extraction Conditions	Optimization and Optimal Conditions	Quantitative Analysis	Qualitative Analysis	Ref.
Enhanced Solvent Extraction 120 bar 80 °C Solvent: CO_2 and ethanol (1:1) (*v*/*v*) 120 min 10 g/min	Not studied	UPLC-MS-ESI-QTOF Compounds: Luteolin-7-glucoside: 6.14 µg/mg extract Oleuropein: 55.47 µg/mg extract Verbascoside: 1.9 µg/mg extract Total polyphenols: 71.57 µg/mg extract	DPPH Antioxidant capacity (EC_{50}): 42.9 µg/mL	[79]
SFE Three pressures were studied (200, 250, and 300 bar) 50 °C CO_2, 60% ethanol (ratio 1:3 *w*/*v* solid:liquid) 60 min Comparison with solvent extraction (SE): 60% ethanol 1:20 (*w*/*v*) 25 °C 8 h	Not studied	Folin–Ciocalteu Total phenolic content: SFE-200 bar: 5.83 mg GAE/g DM SFE-250 bar: 9.76 mg GAE/g DM SFE-300 bar: 13.12 mg GAE/g DM SE: 11.28 mg GAE/g DM HPLC Detected compounds: Chlorogenic acid Ferulic acid Hydroxytyrosol Vanillin Vanillinic acid Quercetin Caffeic acid	DPPH EC_{50} SFE-200 bar: 274.91 µg/mL SFE-250 bar: 321.25 µg/mL SFE-300 bar: 365.18 µg/mL SE: 382.43 µg/mL	[33]
SFE 120 and 200 bar 55 and 80 °C CO_2, 50% ethanol 120 min 10 g/min	Not studied	UPLC-ESI-TOF MS Detected compounds: Hydroxytyrosol Caffeic acid Apigenin Apigenin 7-glucoside Luteolin Luteolin-7-glucoside Verbascoside 3-hydroxytyrosol Rutin hydrate Quercetin Lucidumoside C Ligstroside Diosmetin Oleuropein Total polyphenols: 120 bar 55 °C: 362 ppm 120 bar 80 °C: 1647.23 ppm 200 bar 55 °C: 366 ppm 200 bar 80 °C: 597.6 ppm	DPPH AAI: 120 bar 55 °C: 0.36 µg DPPH/µg extract 120 bar 80 °C: 1.06 µg DPPH/µg extract 200 bar 55 °C: 0.42 µg DPPH/µg extract 200 bar 80 °C: 0.615 µg DPPH/µg extract	[80]

Table 5. *Cont.*

Extraction Conditions	Optimization and Optimal Conditions	Quantitative Analysis	Qualitative Analysis	Ref.
SFE Pressure (100–200 bar) Temperature (35–60 °C) CO_2 density: (0.51–0.84 g/cm^3) SC-CO_2 flow rate: 40 g/min Liquid solution flow rate at 1 mL/min	Not studied	HPLC Detected compounds: Oleuropein Hydroxytyrosol 7-glucosides of luteolin Apigenin Verbascoside Maximal oleuropein (% *w*/*w*): 36% (35 °C, 150 bar, 0.84 g/cm^3)	Not studied	[81]

SFE: supercritical fluid extraction.

Another study compared different olive leaf cultivars and extraction methods [92], revealing that while the Soxhlet extraction method outperformed PLE with regard to most of the analyzed variables, PLE offered significant advantages. PLE exhibited shorter extraction times (5 min vs. 4 h), lower solvent consumption, and reduced energy costs compared to Soxhlet extraction, making it a more resource-efficient choice for potential industrial applications. This study suggests that PLE can be considered an optimal technique for obtaining antioxidant extracts and recovering bioactive compounds when factors like time and resource savings are taken into account. Furthermore, the ability to enhance the antioxidant properties of PLE-extracted compounds through complexation with β-cyclodextrin and the optimization of PLE conditions provided additional strategies for improving the quality and functional properties of the obtained extracts [93].

Moreover, an optimization of high-pressure-assisted extraction conditions was carried out [94]. The results show that this optimization significantly increased the total phenolic content, antioxidant capacity, and oleuropein content compared to conventional extraction, likely due to structural changes that improved mass transfer rates. These findings collectively demonstrate the potential of PLE as a superior method for obtaining valuable bioactive compounds from olive leaves, with variations depending on cultivars and complexation techniques.

6. Industrial Applications

In general, olive leaf extracts have shown potential uses in the food [95–97], cosmetic [3,98–100], and pharmaceutical [101–105] fields, with a primary focus on functional foods [63,68]. For example, the oxidative stability of a French sauce was tested over a storage period of 90 days after the addition of olive leaf extracts (OLEs) obtained via UAE [63]. The results demonstrated that the use of OLE (1500 and 2000 mg/kg) improved the sample's shelf life by retarding the microbial growth of lactic acid bacteria. OLE was therefore suggested to be a natural preservative that can be used as a substitute for synthetic molecules commonly used in sauce formulation.

On the other hand, the potential fortification of gluten-free breadsticks with olive leaf extracts was suggested to extend the shelf life of this product [68]. Polyphenol-rich extracts (500 and 1000 mg/kg) obtained using ultrasound were incorporated into the formulation. Textural property tests, color tests, antioxidant activity tests, sensory analyses, and oxidation stability tests were conducted on the baked breadsticks. The enriched samples exhibited better nutritional and functional activity than the control, with higher antioxidant activity and bioavailability of polyphenols. The latter extended the breadsticks' shelf life by stabilizing the fortified products against lipid oxidation [68]. Nonetheless, the major drawback of the application of OLE in food is the intrinsic taste and odor that need to be masked to enhance the acceptability of the products by consumers [63]. In the cosmetic sector, olive leaf extract has exhibited strong potential as an anti-aging ingredient due to its ability to inhibit elastase, collagenase, and tyrosinase at a concentration of 5 mg/mL [3]. Moreover, olive leaf extract has been found to have added value in the pharmaceutical sector. For instance, according to the study by Soliman et al., OLE may have a preventive effect against diabetes-related reproductive problems due to its antioxidant activity and capacity to regulate testicular steroidogenesis [101].

7. Conclusions

Olive production and olive oil processing generate substantial quantities of leaves, which are considered phenolic-rich by-products. The phenolic compounds in these leaves can vary qualitatively and quantitatively depending on several factors, including geographical zone, time of year, cultivar, and climatic conditions. Oleuropein and other related phenolic compounds, existing in olive leaf extracts, have demonstrated antioxidant, antimicrobial, anti-inflammatory, and other health-related advantages. Given the potential benefits of olive leaf utilization, various pretreatments and extraction methods have been investigated and compared. The most commonly used procedures for the ex-

traction of phenolic compounds from olive leaves include ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction. These techniques offer several practical advantages and can improve the extraction yields of bioactive compounds. In recent years, statistical optimization approaches and emerging technologies have been proposed for the extraction of polyphenols, leading to higher extraction yields, lower operational costs, and a reduced environmental impact.

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