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Review

Pulsed Electric Field Applications for the Extraction of Bioactive Compounds from Food Waste and By-Products: A Critical Review

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Abstract: The food processing industry is a continuously developing sector that uses innovative technologies to efficiently process food products. During processing, food industries generate substantial amounts of by-products in the form of waste materials. This food waste consists of organic matter rich in bioactive compounds, such as polyphenols, carotenoids, and flavonoids. Improper management of food waste can adversely affect both the environment and human health, leading to environmental pollution and the release of greenhouse gas emissions. Thus, proper food waste management has become an urgent global issue. The presence of bioactive compounds (mainly polyphenols, flavonoids, and anthocyanins, but also carotenoids, alkaloids, proteins, lipids, and carbohydrates) in food waste holds the potential to transform them into valuable resources. Several sectors, including food and energy, have recognized food waste as an innovative source. Recently, much emphasis has been placed on optimizing the extraction yield of such bioactive compounds through the utilization of environmentally friendly and sustainable methodologies and solvents. Pulsed electric field (PEF)-assisted extraction is an emerging technique that holds promise for the utilization of waste materials. PEF technology can efficiently optimize the extraction of valuable compounds within a shorter time while minimizing solvent and energy consumption. In this review, we provide a comprehensive overview of the current state of PEF technology and its implications for recovering bioactive compounds from food waste. The integration of innovative technologies like PEF in the food processing industry can play a crucial role in managing food waste sustainably, reducing environmental impact, and harnessing the full potential of bioactive compounds contained in these waste materials. The objective of this critical review is to provide an overview of the utilization of PEF pretreatment for food by-products and to conduct a comparative analysis with other extraction techniques.

Keywords: food waste; valorization; bioactive compounds; extraction; pulsed electric field; pretreatment

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1. Introduction

Food waste and by-products are prevalent in both plant and animal foods across the food supply chain. Food biomass waste is a plentiful, biodegradable, organic resource that is produced globally [1]. These waste materials are typically generated during the food manufacturing process [2]. The food processing industry is one of the most rapidly growing sectors worldwide, as it transforms agricultural ingredients into consumable, processed foods [3]. During various processes like sorting, slicing, trimming, filtering, and slaughtering, food processing generates waste or by-products such as peels, pomaces, seeds, straws, stalks, spent grains, husk, heads, viscera, and blood [3,4]. Unfortunately, much of this food waste ends up in landfills or is incinerated, leading to significant odor issues and

harmful impacts on the environment and ecosystem. Direct burning of raw food waste, for example, causes air pollution through the release of exhaust gases and ash production, which can cause respiratory problems in humans [5]. Additionally, a significant amount of wastewater is also produced by food industries. The disposal of these by-products in the environment contributes to the escalation of greenhouse gas emissions, air and water pollution, carbon footprints, and climate change [6,7]. As a result, sustainable food waste management has become more than imperative [5,8].

Given the potential of food waste valorization, efforts are being made to minimize pollution and harness biobased compounds, such as lipids, proteins, and carbohydrates [9]. Food processing by-products consist of bioactive compounds, including aroma compounds (found in fruit pomace and spice pods), pigments (found in fruit and vegetable peels), polyphenols (found in fruit and vegetable seeds and peels, as well as milling sewage), proteins (found in animal bones), and lipids (found in fish offal). Bioactive compounds are a class of chemical compounds that possess an essential part in the normal functioning of biological systems. Even though they constitute a small portion of food sources, these compounds can activate mechanisms that alter and enhance human health [10]. Bioactive compounds offer additional health benefits via antioxidant activity and therapeutic properties [11–14]. Some of these compounds, with proven health advantages like antihypertensive, anti-cancer, antioxidant, and anti-tumor properties, are utilized in drug formulation within the pharmaceutical industry [3,15]. The food industry extensively utilizes bioactive compounds derived from food processing by-products for various purposes, such as preservatives, antibrowning agents, thickeners, and colorants [16–18]. Furthermore, food waste can be transformed into biocomposites and bioplastics, and there is potential for utilizing industrial biomass waste as an environmentally beneficial energy source [19–23].

Extracting bioactive compounds from specific food wastes has been explored using various classical or conventional procedures [24]. Conventional extraction techniques include soaking, maceration, decoction, infusion, percolation, boiling, grinding, magnetic stirrer, water percolation, heat reflux, and Soxhlet extraction [25]. The efficacy of these techniques depends on the solvent type, its solvation ability, and the use of agitation and temperature [24]. Soxhlet extraction is a form of liquid extraction performed under atmospheric conditions, employing solvents at their boiling points and low pressures. This technique is employed to selectively extract specific compounds. Soxhlet extraction technique is a widely used and established technique that offers maximum efficiency in extracting carotenoids from fruits, vegetables, and microalgae [26]. Maceration was later used in the extraction of bioactive chemicals from the discarded peel of several fruits due to its adaptability to thermolabile molecules [27]. To enhance the efficiency of existing classic extraction techniques, infusion- and decoction-based procedures have been developed, building on the principle of maceration [24,28]. Percolation is another approach that has been proven to be more efficient than maceration because it is a continuous technique in which the saturated solvent, such as ethanol and water mixtures, is constantly restored by freshly generated solvent [24]. However, traditional extraction techniques suffer from deficiencies and limitations, including long processing times, low extraction yields, high solvent consumption, potential thermal degradation of thermolabile active compounds, and the use of toxic chemicals [25,29]. Furthermore, traditional extraction techniques are insufficient for selective extraction [30,31]. Moreover, these techniques may not be selective in their extraction, potentially compromising the quality of extracted products, such as proteins and polysaccharides [4].

Over the past two decades, several non-thermal extraction techniques have been introduced, overcoming the constraints of conventional techniques [32]. These novel extraction technologies include microwave-assisted extraction (MAE) [33], ultrasound-assisted extraction (UAE) [34,35], supercritical fluid extraction (SFE) [36,37], accelerated solvent extraction (ASE) [38], mechanochemical-assisted extraction (MCAE) [39], ultrahigh-pressure extraction (UHPE) [40], enzyme-assisted extraction (EAE), and pulsed electric field (PEF)-assisted extraction [41]. Among these techniques, PEF stands out as a green and

cost-effective approach for inactivating microorganisms and enhancing mass transfer in food products while also proving effective in recovering valuable bioactive compounds from food waste [30,39–42]. PEF has been widely adopted by various food industries over the last decade, providing additional incentives for businesses to reduce waste and associated environmental degradation [4,43,44].

The management of food waste and by-products is of the utmost importance throughout the food supply chain. Sustainable strategies for food waste valorization can not only minimize pollution but also unlock the potential of bioactive compounds for various applications in the food industry, pharmaceuticals, and beyond. The introduction of non-thermal extraction techniques, particularly PEF-assisted extraction, offers a promising and environmentally friendly way to recover valuable bioactive compounds from food waste, paving the way for a more efficient and sustainable future in food processing. The role of mass transfer in extraction operations from solid food is crucial. The utilization of PEF in extraction techniques has been extensively discussed in the literature (*vide infra*), particularly in the context of liquid–solid extraction [45]. Over the course of the previous decade, a multitude of investigations have been conducted regarding the utilization of PEF for the extraction of bioactive compounds from food matrices. In contrast to prior investigations, the current study on PEF-assisted extraction primarily focuses on bioactive compounds stemming from food waste. The aim of this review is to bridge the gap between the quickly developing field of PEF technology and the critical need for application for sustainable food management. We will delve into the current state of PEF technology and its implications for recovering bioactive compounds from non-conventional sources in the food industry. By conducting an in-depth analysis of existing research, we aim to shed light on how the integration of innovative technologies like PEF into the food processing industry can play a pivotal role in sustainable practices by maximizing the recovery of bioactive compounds. In light of the urgent global demand for sustainable solutions in both food production and waste management, this review endeavors to provide a comprehensive perspective on the transformative capacity of PEF technology. Moreover, we intend to compare the PEF technique with other extraction techniques and evaluate whether PEF is a superior technique for the extraction of bioactive compounds from food by-products or not. In order to enhance clarity in the comparison, a classification based on by-products rather than bioactive compounds has been employed.

2. Method Principles and Parameters Affecting Bioactive Compound Extraction

2.1. PEF Apparatus

A standard PEF processing unit consists of essential components, including a pulse generator, treatment chamber, and monitoring devices (Figure 1). The primary component generates high-voltage pulses that possess the requisite attributes in terms of duration and magnitude. The pulses that are produced are administered to a set of electrodes located within the treatment chamber, with the treated product being positioned between these electrodes [46]. Based on the type of product undergoing PEF processing (i.e., solid, liquid), treatment chambers can be categorized into two distinct classifications: batch treatment chambers and continuous treatment chambers [47]. The static treatment chamber is ideal for solid food processing. El Kantar et al. [48] developed a cylindrical static treatment chamber. The insulating material used was Teflon, while the two disk electrodes were made of stainless steel and had a 105 mm gap between them. The treatment chamber has the potential to enhance the extraction efficiency of bioactive compounds in orange, pomelo, and lemon. Liu and Esveld et al. [49] developed a method to extract bioactive compounds from fresh tea leaves using a treatment chamber with parallel plate electrodes.

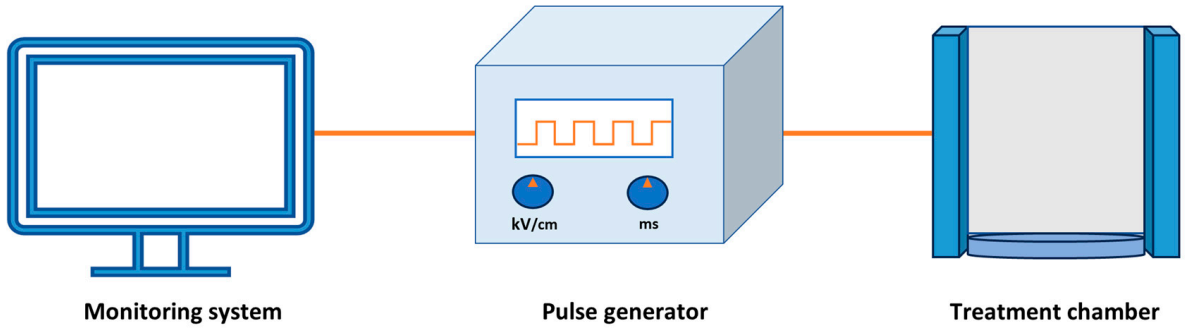

Figure 1. A typical PEF apparatus.

2.2. Solvent and Sample Characteristics

The efficiency of the PEF extraction system is influenced by various factors, including the size and location of the extracted component within the cytoplasm or vacuoles, as well as the characteristics of the solvent and sample composition (i.e., shape, size, pH level, and conductivity). Moreover, the efficiency of PEF-assisted extraction is significantly impacted by the characteristics of the tissues and cells under extraction [50,51]. In conditions of low ionic strength (i.e., 0.5 M of an aqueous salt solution), the extraction technique is more efficient. Compression and electroporation of cells, both of which involve the cytoplasm, are affected by ionic strength. However, the behavior of the electric field passing through the matrix is strongly affected by its conductivity [52].

Also important for efficient PEF extraction is the choice of solvent. Choosing the right solvent is essential for efficient PEF extraction, considering factors like solubility, conductivity, and polarity. A more conductive solvent can lead to improvements in both electroporation of cell membranes and extraction efficiency [53]. In a study [54] where several alkanes, alcohols, toluene, and dichloromethane were used as extraction solvent in extracting oil from coffee spent grounds, it was found that ethanol, the most conductive solvent, yielded the highest oil recovery.

2.3. Electric Field Strength

Electric field strength is an important parameter in calculating extraction degree since it influences the physical characteristics of the targeted molecule, such as surface tension, diffusivity, solubility, and viscosity [53]. The PEF technique employs electric waves characterized by a high amplitude of voltage. Any product positioned within the chamber is subjected to brief electrical pulses, ranging from μs to ms in duration, that exhibit high voltage levels, typically ranging from 10 to 80 kV/cm [55]. Modifications to the technique conditions, including the electric field strength, pulse frequency, pulse width, shape of the pulse wave, and exposure time (which is influenced by the flow rate and volume of fluid in the electrode chamber), can be made depending on the desired effects and the specific properties of the processed food product [56].

Porosity is a flexible characteristic; thus, electroporation can result in reversible or irreversible effects. According to Vaessen et al. [57], an electric breakdown can be reversed if the induced holes are small compared to the membrane surface area and are caused by low-intensity PEF treatment (0.5–3 kV/cm). Prolonged and intensified treatment (15–40 kV/cm) causes the development of large pores, leading to irreversible membrane rupture [56,57]. Figure 2 illustrates the electroporation process by the efficacy of membrane electroporation is dependent upon several factors, involving electric field strength, duration, membrane constitution, pulse parameters (e.g., pulse count, duration, strength, and repetition rate), treatment technique, treatment chamber arrangement, ambient medium, and cellular morphology and dimensions [58,59]. Cell disintegration is widely recognized as a straightforward approach for investigating the structural attributes of samples subjected to various processing techniques. The cell disintegration index (Z_p) presented in this study quantifies the ratio of permeabilized cells by analyzing the frequency-dependent

conductivity of intact and permeabilized plant tissues. The value of Z_p ranges from 0 for undamaged tissues to 1 for tissues in which all cells have been permeabilized [60]. The application of high-voltage impulses (e.g., 15 kV/cm) results in the disruption of the cell membrane, rendering it permeable to small molecules [61]. This happens due to the instability in the phospholipid bilayer and proteins, resulting in the formation of pores and an increase in the membrane's permeability. The cytoplasm's colloid osmotic pressure facilitates the movement of small molecules across the cell membrane, resulting in cell expansion, membrane rupture, and subsequent cell death [62]. Typically, an electric field strength ranging from 12 to 45 kV/cm is deemed sufficient for the extraction of beneficial compounds from food products. Nevertheless, the specific intensity of PEF required may vary depending on the inherent properties of the food under consideration. Likewise, the enhancement of the extraction of desired compounds is observed with an augmentation in the energy from the electric field strength, as it facilitates efficient energy transfer within the food sample [53].

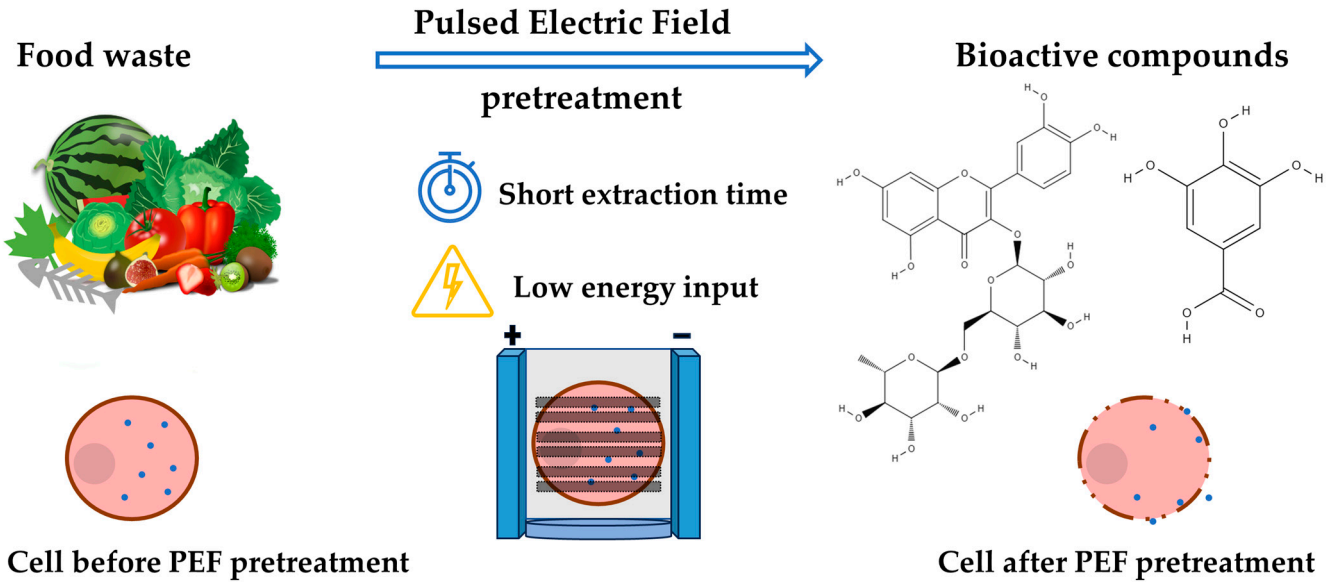

Figure 2. Electroporation of cell membrane from food by-products due to employment of PEF. Bioactive compounds are extracted from the extraction solvent.

2.4. Temperature and Time of PEF Extraction

Temperature is a key factor that influences the technique of PEF extraction. Due to the nonthermal nature of PEF extraction technique, it is often performed at ambient temperatures. Elevated temperatures (>90 °C) typically lead to a reduction in the viscosity of liquid solvents, thereby detrimentally impacting the extraction technique [63].

The duration of treatment, including the number of pulses and the width of each pulse, is an additional parameter that can be used to assess the effectiveness of PEF. However, an extended duration of treatment may result in an elevation of the product's temperature [52]. For instance, it was found that polyphenol extraction from fresh tea leaves was maximized when longer pulses were applied at intensities of 0.9 kV/cm for a duration of 0.5 s and 1.1 kV/cm for a duration of 3 s [64].

3. Applications of PEF in Food Waste

3.1. Fruit Waste

3.1.1. Grapes

Grape by-products usually consist of peels, seeds, marc, stems, pulp, and pomace. Corrales et al. [65] investigated the valorization of grape by-products (skins, stems, and seeds) by extracting the bioactive compounds polyphenols and anthocyanins. They combined conventional extraction (stirring) at 70 °C with emerging novel pretreatment technolo-

gies like ultrasonication (US) (at 35 KHz), high hydrostatic pressure (HHP) (at 600 MPa), and PEF (at 3 kV/cm) in order to maximize the anthocyanin extraction. A pulse voltage of 9 kV was employed, leading to an electric field strength of 3 kV/cm. A series of 30 pulses was administered in order to achieve a targeted energy input of 10 kJ/kg. The overall temperature rise after the pretreatment was below 3 °C. The pulse repetition rate utilized in the experiment was 2 Hz, while the total duration of the treatment was 15 s. The results showed that total polyphenol content (TPC) was measured at ~200 μmol GAE/g dm. Both the pretreatments of US and PEF resulted in a ~75% increase in TPC, while HHP led to a 50% increase from the control extraction (~200 μmol GAE/g dm). In antiradical activity (A_{AR}), the conventional extraction recorded ~200 μmol TE/g dm. The extractions performed using PEF showed a four-fold increase, HHP resulted in a three-fold increase, and the US led to a two-fold increase compared to the control extraction. Regarding anthocyanins extraction, PEF pretreatment was the most efficient technique to extract anthocyanins monoglucosides and acylated anthocyanins monoglucosides, recording a total ~77% increase from the conventional extraction, ~81% from US, and ~25% from HHP. However, the extraction of some acylated anthocyanins was more efficient with HHP pretreatment. HHP has the potential to lower the pH level due to the deprotonation of the extracted compounds. This decrease in pH level results in a better extraction of these compounds since, at pH < 4, they are in a more stable form. This study proved that the utilization of efficient extraction technologies and cost-effective raw materials can eliminate the need for large quantities of organic solvents and extended extraction periods, thereby circumventing conventional extraction procedures.

In another study, Medina-Meza et al. [66] explored the effectiveness of two different processing configurations of PEF and UAE of bioactive compounds on plum and grape peels. The impact of these technologies on peel extraction was evaluated, considering factors such as treatment chamber diameter and temperature. PEF parameters were flow 290 L/h, 25 kV voltage, 10 Hz frequency, and 6 μs pulse width. The difference between PEF-I and PEF-II was in the treatment chamber diameter, 25 and 7 mm, respectively. The temperature in both treatments did not surpass 3 °C. US was also tested in two different temperatures at 25 and 50 °C as potential environmentally friendly alternatives to water extraction at 70 °C for extracting bioactive compounds (polyphenols including flavonoids and anthocyanins, ascorbic acid) from plum and grape peels. Among the techniques, PEF I and ultrasound at 50 °C were the most effective by increasing the corresponding yield in bioactive compound extraction. The higher temperature during US treatment resulted in significantly increased yields in grape peels. The larger diameter of the chamber in PEF-I resulted in greater success for the technique. Compared to the water extraction at 70 °C, PEF-I increased the total polyphenol yield by ~205% in plums peels, and in grape peels, the increase of extraction yield was ~80% in total flavonoids and ~300% in anthocyanins. US at 50 °C was also found to be an effective way to extract anthocyanins and ascorbic acid from plum peels. Compared to PEF-I, the US 50 °C technique enhanced the extraction of the above bioactive compounds from plum peels by above 500% and ~71%, respectively. The overall superiority of PEF-I of the techniques mentioned was also confirmed with the measurement of DPPH A_{AR}. Both fruit by-products recorded ~850 μM Trolox equivalent, higher by ~13%, at least, than any other technique. However, all of the abovementioned processes had negative effects on ascorbic acid extraction from grape peels. The production of radical species is regarded as the most plausible mechanism for elucidating the reduction of ascorbic acid beyond its thermal instability. Sonication leads to a reduction in dissolved oxygen, a crucial factor that significantly impacts the stability of ascorbic acid. Further investigations should be conducted in order to shed light on why all these processes did not affect ascorbic acid in plum peels.

Ntourtoglou et al. [67] examined the potential impact of PEF pretreatment on the efficiency with UAE of polyphenols and volatile compounds from grape stems. An electric field strength of 1 kV/cm for a total duration of 30 min was used. The pulse duration for the treatment was 1 ms, and the pulse frequency was 1 Hz. They also analyzed the impact

of various solvents (water and 50% methanol) in the pretreatment technique. Grape stem extracts were prepared utilizing US treatment. Furthermore, samples pretreated with PEF using various solvents were subjected to US treatment and then compared. The results revealed that the use of PEF treatment of grape stems can increase the yield of polyphenols and volatile compounds in the extracts. The absence of US during the use of PEF results in only a 4% increase in TPC when 50% methanol is used as an extraction solvent. However, TPC was highly affected with both PEF and US treatments and led to a 17% increase with 50% methanol and a 35% increase with water as solvent. Furthermore, PEF treatment of grape stems prior to US increased the total volatile compounds by 234%.

In another study regarding the valorization of grape pomace, Carpentieri et al. [68] examined the effectiveness of pretreating white grape pomace with PEF in order to enhance the extraction of bioactive compounds, specifically total polyphenols and flavonoids, which possess strong antioxidant properties. Water and ethanol were the solvents used for extraction. The extracts obtained from both untreated and PEF-treated samples were analyzed using HPLC-PDA analysis. To optimize the PEF treatment along with the extraction technique, response surface methodology was used in each case. Under optimal conditions (electric field strength 3.8 kV/cm and energy input 10 kJ/kg) before solid–liquid extraction at a fixed temperature of 50 °C using 50% ethanol enhanced the extraction yield of bioactive compounds. The extracts obtained from samples treated with PEF exhibited significantly higher TPC by 8%, total flavonoid content by 31%, and ferric-reducing antioxidant power (FRAP) values by 36% compared to the control extraction. Epicatechin, *p*-coumaric acid, and quercetin were identified as the major phenolic components recovered by HPLC analysis. Furthermore, no degradation occurred as a result of the PEF application.

Supercritical carbon dioxide (SC-CO_2) and PEF-assisted SC-CO_2 oil extraction from Graševina (*Vitis vinifera* L.) white grape seeds were compared to the traditional technique of cold pressing (CP) by Curko et al. [69]. The SC-CO_2 extraction conditions had a temperature set at 45 °C and a flow rate of 45 g CO_2/min. PEF treatment condition required an electric field strength at 5 kV/cm and a pulse frequency of 120 Hz. Response surface methodology was used to determine the optimal parameters of SC-CO_2 pressure (35 MPa for SC-1 and 50 MPa for SC-2) and of PEF duration (5 min for PEF-1 and 1 min for PEF-2). CP resulted in a lower extraction yield (~67 g/kg), but it extracted at least ~12% higher polyphenolic antioxidants, ~26% tocochromanols, and ~2% linoleic acid. Both PEF pretreatments and SC-CO_2 extraction significantly increased extraction yield (up to 81.8 g/kg) and allowed for more selective extractions, specifically targeting sterols and nonflavonoids (such as phenolic acids and trans-resveratrol) compared to CP. In particular, larger quantities of these compounds were obtained with extended PEF pretreatment (PEF-1), followed by extraction at 35 MPa (SC-1), generating higher extraction by ~38% in sterols, by ~31% in *trans*-resveratrol and by ~165% in gallic acid compared to CP. The utilization of these pretreatment techniques led to the selective recovery of target compounds. In addition, the implementation of PEF treatment prior to SC-CO_2 was vital for the extraction of total polyphenols, flavonoids, and tocochromanols, achieving statistically significant figures ($p < 0.05$) than sole SC-CO_2.

In another study exploring the potential of using SC-CO_2 extraction, Salgado-Ramos et al. [70] combined the above technique with PEF treatment to extract lipidic and glycosylated compounds from exhausted grape marc. This raw material was initially treated with PEF, generating liquid fraction I (LF-I). The conditions for PEF treatment required an electric field strength of 3 kV/cm, frequency of 2 Hz, specific energy of 100 kJ/kg, and pulse duration of 100 ms. The solid fraction was further treated with SC-CO_2, producing liquid fraction II (LF-II). The conditions for SC-CO_2 were pressure ranging from 15 MPa, total flow set at 25 mL/min (10% ethanol at 2.5 mL/min, and 90% CO_2), temperature set at 50 °C, and total procedure time of 60 min. The above fractions were compared to a control soaking sample, which was prepared with a 24 h extraction with 50% ethanol at room temperature. Statistically significant differences ($p < 0.05$) were observed between the three samples in antioxidant assays. In TEAC, the control sample recorded ~35 μmol TE/g dw,

but LF-I and LF-II recorded ~14% and ~28% higher values, respectively. In ORAC, the control sample recorded ~210 μmol TE/g dw, whereas LF-I and LF-II had higher values by ~41% and ~95%, respectively. However, statistically non-significant differences ($p > 0.05$) were observed in TPC, with the three samples recording approximately 21 μmol TE/g dw. Liquid chromatography mass spectrometry analysis revealed that LF-II glycosylated antioxidants such as Quercetin-3-*O*-glucuronide and Quercetin-7-*O*-glucoside ranged from 0.27–9.78 mg/L and were statistically significantly lower ($p < 0.05$) than LF-I antioxidants, in which antioxidants ranged 79.73–450.45 mg/L. Nuclear magnetic resonance analysis additionally demonstrated the potential of PEF in combination with supercritical fluid extraction (SFE) for the selective recovery of free sugars (primarily glucose, but also sucrose and fructose) and lipidic high-added-value components, such as oleic and linoleic acid using SC-CO_2. SC-CO_2 with PEF "enabled" the sample, so PEF could be combined with other techniques for the enhancement of valuable bioactive compound extraction.

Carpentieri et al. [71] employed response surface methodology to examine the efficacy of the PEF technique in enhancing the extraction of essential intracellular components, including total polyphenols, tannins, anthocyanins, and flavonoids from red grape pomace. The extraction conditions of both PEF-treated and untreated samples were a solid-to-liquid ratio of 1:10, temperature set at 50 °C, 50% ethanol as a solvent, and 300 min extraction time. The results revealed that applying PEF at the optimum processing conditions (electric field strength of 4.6 kV/cm and energy input of 20 kJ/kg) significantly increased the permeability of the cell membrane in grape pomace tissues. This led to improved extraction of TPC by 15%, flavonoid content by 60%, total antioxidant capacity by 23%, total carbohydrates by 42%, and FRAP values by 31% compared to the control (PEF-untreated sample) extraction. The most prevalent polyphenols, namely epicatechin, *p*-coumaric acid, and peonidin-3-*O*-glucoside, were identified through the application of HPLC-DAD. This observation remained consistent irrespective of the utilization of PEF treatment. Furthermore, no degradation of these specific compounds was observed following PEF treatment.

Based on the information presented in the studies above, it can be concluded that the utilization of low voltage (ranging from 1 to 5 kV/cm) demonstrates efficacy in the recovery of polyphenols from grape processing by-products. The observed improvement leads to the enhancement of the antioxidant properties of the extracts, thereby transforming the by-products into value-added compounds. PEF has actually proved to be the best extraction technique in grapes waste. Meini et al. [72] implemented enzymatic extraction on grape pomace in acetate buffer using three different enzymes: pectinase, cellulase, and tannase. The TPC they obtained were 0.76 and 0.74 mg GAE/g grape pomace in the case of cellulase and tannase, respectively. In another study conducted by Pintać et al. [73], six solvents were evaluated in moderate shaking in order to evaluate their efficacy. The best one was proved to be 80% methanol, which resulted in a higher yield. Caldas et al. [74] evaluated UAE and MAE, along with conventional extraction. UAE was found to be the best extraction technique, 80 mg GAE/g. Up until now, PEF seems to be a more effective pretreatment technique, increasing the recoveries of the target compounds, but not to a great extent.

3.1.2. Citrus Fruits

Orange, lemon, and Satsuma mandarin belong to the *Citrus* genus. Commonly, their main by-products are their peels, which can be divided into albedo and flavedo. Luengo et al. [75] investigated the effect of PEF treatment on the extraction of polyphenols and flavonoids from orange peel by pressing. The highest Z_p was achieved with a treatment time of 60 μs (20 pulses of 3 μs) at the various electric field strengths tested. The results showed that a PEF treatment of 5 kV/cm increased the amounts of naringin from 1 to 3.1/100 g fw and of hesperidin from 1.3 to 4.6 mg/100 g fw, respectively. Furthermore, the overall extraction yield of polyphenols was quantified to be 34.80 mg/100 g fw. Notably, the application of PEF at an electric field strength of 1, 3, 5, and 7 kV/cm resulted in a respective increase of 20, 129, 153, and 159% in the extraction yield of polyphenols from

orange peel. PEF treatments of 1, 3, 5, and 7 kV/cm improved the antioxidant activity of the extract by 51, 94, 148, and 192%, respectively, as compared to the untreated sample. The measured total polyphenol yield in orange peel waste was substantially lower than found in other studies using stirred-tank extraction with organic solvents [75] or UAE [76]. However, the primary advantages of the PEF technique compared to other techniques for enhancing polyphenol extraction from orange peels through pressing are its ability to avoid sample dehydration and its utilization of water as a solvent. Furthermore, it is a cost-effective and environmentally feasible alternative to conventional extraction techniques, which require the product to be dried, use large amounts of organic solvents, and need long extraction times.

Athanasiadis et al. [77] aimed to analyze and improve the key factors impacting the extraction of ascorbic acid, carotenoids, and polyphenols from orange peels (albedo and flavedo). They employed US or PEF as pretreatment steps for bioactive compound extraction using ethanol and water mixtures as the extraction solvents. The pulse duration was 10 µs, the period was 1 ms (frequency: 1000 Hz), and the electric field strength was adjusted to 1 kV/cm. The extraction time (15–180 min) and temperature (20–80 °C) were investigated, whereas response surface methodology was used to maximize the extraction yield. Hesperidin concentration (16.26 mg/g dw), TPC (34.71 mg GAE/g dw), and total carotenoids (52.98 µg CtE/g dw) were all enhanced by using PEF treatment, except for ascorbic acid determination (1228.93 mg/100 g dw), where the optimized pretreatment was the use of US. One potential restriction of this research could be in the limited investigation of a single cultivar of oranges. However, the suggested pretreatment techniques utilizing PEF exhibit potential practical applications on an industrial scale. These applications span various industries, including beverage production, cosmetics manufacturing, pharmaceutical preparation, and the substitution of synthetic pigments with natural pigments.

Afifi et al. [78] conducted a comprehensive comparison of four extraction techniques: conventional, US, HHP, and PEF. The aim was to determine the most effective technique for extracting bioactive compounds from the orange peels. The investigation demonstrated that the extracts derived from this waste product contain a diverse range of bioactive compounds, with a particular focus on polymethoxy flavones. The antioxidant activity of the flavedo samples was found to be significantly higher when subjected to extraction techniques involving PEF and HHP, thereby demonstrating superior effectiveness compared to alternative extraction techniques. The ethyl acetate extract had the most notable antioxidant properties among the albedo samples. The aforementioned phenomenon can be ascribed to the distinctive qualitative composition of the compounds, as opposed to merely possessing larger quantities of identical metabolites. The study determined that the most effective processing conditions for extracting albedo using HHP and PEF were observed at a pressure of 200 MPa and an energy input of 15 kJ/kg, with a voltage of 10 kV/cm. The results showed that the most efficient conditions for extracting flavedo were achieved by subjecting the sample to HHP at a moderate pressure level of 400 MPa in conjunction with PEF treatment at an energy input of 15 kJ/kg and an electric field strength of 3 kV/cm. The analysis yielded a collective count of 57 metabolites, wherein 15 metabolites were found to be significantly present in both the flavedo and albedo. This finding suggests a noteworthy qualitative convergence of dispersed flavonoids. The chemometric analysis of the dataset indicates that orange flavedo can be considered a dependable source of soluble polyphenols, specifically polymethoxy flavones.

Kalompatsios et al. [79] applied a simple extraction technique in water solvent in orange peel waste and resulted in a relatively high TPC yield. However, UAE on orange peels in an ethanolic solvent led to a 60% higher recovery than simple maceration, as established by Razola-Diaz et al. [80]. Based on the findings of the aforementioned studies, it is evident that the utilization of PEF in ethanolic solvents for the pretreatment of orange peels has enhanced efficacy as an extraction strategy. Although the effectiveness of PEF is obvious, Lachos-Perez et al. [81] demonstrated in their research that the most effective way to extract flavanones from orange peel waste is through subcritical water extraction (SWE).

Peiró et al. [82] examined the impact of varying intensities of PEF (3–9 kV/cm and 0–300 µs treatment time pulses) on the extraction of total polyphenols from lemon (*Citrus limon*) peel residues through pressing. Z_p determined that the optimal treatment duration for increasing permeability is 30 pulses of 3 µs (total 90 µs) and electric field strength of 7 kV/cm, as statistically non-significant ($p > 0.05$) differences were found between 7 and 9 kV/cm. In contrast to the control samples, the impact of PEF was found to be unrelated to the size of lemon residue (1, 2, and 3 cm) in polyphenol extraction yield. However, PEF treatment significantly increased TPC, as an average of ~160 mg GAE/100 g of dw was an up to ~60% increase from the control sample, whereas 3 cm lemon peels were selected as optimal. The concentrations of hesperidin and eriocitrin, which are the predominant polyphenols present in lemon residues, were observed to exhibit a notable increase in response to the application of pressure and electric field. This resulted in an approximate 300% increase, yielding maximum observed values of hesperidin (84 mg/100 g fw) and eriocitrin (176 mg/100 g fw).

Another study on a *Citrus* species was conducted by Hwang et al. [83]. They determined whether the combination of PEF and SWE could enhance the efficiency of extracting hesperidin and narirutin from Satsuma mandarin (*Citrus unshiu*) peels. The samples underwent treatment with PEF at an intensity of 3 kV/cm for either 60 or 120 s. The subsequent SWE was performed at various extraction temperatures (110–190 °C) for a duration of 3 to 15 min. The highest concentration of hesperidin was observed to be 46.96 mg/g of dry peel following the application of PEF treatment for 120 s, in combination with steam explosion treatment at 150 °C for 15 min. Similarly, the concentration of narirutin reached its peak at 8.76 mg/g after PEF treatment for 120 s, followed by SWE treatment at 190 °C for 5 min. The levels of both hesperidin and narirutin exhibited an increase in concentration as the duration of PEF treatment was extended. The application of PEF for 120 s resulted in a significant increase in the extraction yields of hesperidin and narirutin by 22.1 and 33.6% compared to the control sample, respectively. This study showcases the potential of PEF pretreatment in augmenting the SWE efficiency of flavonoids from Satsuma mandarin peel.

According to the results from the mentioned studies, PEF pretreatment of citrus fruits seems to enhance the recovery of polyphenols, flavonoids, and anthocyanins. Electric field strength ranging from 3 to 10 kV/cm seems to be sufficient for optimal extraction of the bioactive substances. However, a combination of PEF with other techniques, such as US or HHP, is likely to increase the performance of the compounds to a greater extent.

3.1.3. Olives

The main by-products from olive trees are leaves, kernels, and olive mill wastewater. Roselló-Soto et al. [84] explored the possibility of enhancing the recovery of intracellular valuable bioactive compounds from olive (*Olea europaea*) kernels. Pretreatments such as high-voltage electrical discharges (HVED), PEF, and US were employed prior to extraction. The study examined the impact of energy in HVED with varying input levels (0–109 kJ/kg), pH values (2.5–12), and ethanol concentrations (0–50%) on extraction efficiency. PEF conditions required an electric field strength of 13.3 kV/cm, pulse length of 10 µs, and pulse rate of 10 Hz. Total polyphenols, proteins, antioxidant activity, and pigments were all determined in the extracts produced following corresponding pretreatments. The superiority of HVED treatment over US and PEF in terms of energy input and effective treatment time for the extraction of polyphenols and proteins was demonstrated. In the same energy input of 109 kJ/kg, the TPC was found to be 255 mg GAE/L for high-voltage electrical discharges, while for US and PEF, it was 140 mg GAE/L and 146 mg GAE/L, respectively. One potential hypothesis is that the fragmentation of treated particles of olive kernels occurs when electrical discharges are applied to various biological materials. This fragmentation might be caused by the propagation of shock waves and the subsequent explosion of cavitation bubbles. This technique is thought to enhance the extraction of polyphenols, as suggested by Ohsima et al. [85]. Furthermore, polyphenols can form complexes with proteins, starch, cellulose, minerals, and various other compounds. The protein content was measured at

~250 mg/L for HVED and ~150 mg/L for the other two techniques. The results of multiple optimizations indicated that the TPC (626.60 mg GAE/L), protein content (225 mg/L), and antioxidant capacity [TEAC (9.80 mM TE) and DPPH (7.61 mM TE)] of the sample were maximized through HVED pretreatment at an energy input of 66 kJ/kg and pH level of 2.5, followed by extraction in 49% ethanol. Consequently, the utilization of HVED treatment was superior and could exhibit considerable potential as a technological advancement for enhancing the extraction efficiency of valuable compounds from olive kernels. It is a sustainable extraction technique that has low energy requirements, typically ranging from 60 to 80 kJ/kg. Nevertheless, the viability of implementing HVED technology at pilot or industrial levels remains uncertain.

Pappas et al. [86] assessed the efficacy of the PEF technique in extracting polyphenols from olive leaves. The study encompassed a range of environmentally friendly solvents, specifically water, ethanol, and various combinations of the two at a 25% incremental gradient. PEF conditions required an electric field strength of 1 kV/cm with 30 min total extraction time. Additionally, several pulse duration values were examined (10–100 μs). The outcomes derived from the PEF-treated extracts were contrasted with untreated extracts. The most significant effect of PEF was observed when utilizing an aqueous ethanol solution with a concentration of 25% v/v, employing a pulse duration of 10 μs. The total polyphenols measured at ~21 mg/g dw exhibited a notable increase of 31.85%, whereas the specific metabolites demonstrated a substantial increase of 265.67%. The evaluation of changes in the oxidative stability of the samples was conducted using differential scanning calorimetry. According to the findings, the peak oxidation temperature was 569 °C. A high peak oxidation temperature may indicate sample resistance to oxidation. This notable temperature was attained through the application of a pulse duration of 100 μs and a pulse period of 1000 μs to the samples. Regarding the main metabolite luteolin-7-*O*-glucoside, it is worth noting that there was a significant increase of 71.87%, resulting in a total of 0.82 mg/g dw using the above PEF parameters. However, oleuropein was the only molecule that exhibited the highest extraction yield under a 100 μs pulse.

The same research team, Pappas et al. [87], evaluated the olive leaves valorization by maximizing polyphenol extract concentration by using PEF. They conducted a thorough investigation into the optimization of key parameters in PEF technology for the extraction of olive leaves. They focused on the extraction chamber geometry, electric field strength, pulse duration, pulse period (and frequency), and extraction duration. Through their experiments, they were able to gain insights into the optimal PEF assistance span for static solid–liquid extraction of olive leaves. PEF-treated extracts were compared to extracts obtained without the use of PEF. The results showed that the contribution of PEF on the extractability of total polyphenols (25.35 mg GAE/g dw) showed an increase of ~38% from the control sample. Furthermore, specific metabolites exhibited a remarkable increase of ~117%. This optimal contribution was observed when using a rectangular extraction chamber, a solvent mixture of 25% v/v ethanol, an electric field strength of 0.85 kV/cm, a pulse period of 100 μs with a pulse duration of 2 μs, and an extraction duration of 15 min. Regarding oxidative stability of the samples tested with differential scanning calorimetry, samples treated with a pulse duration of 10 μs, pulse period of 1000 μs, electric field of 0.85 kV/cm, and a time of extraction of 30 min exhibited the highest oxidation peak at 488 °C, which was higher by ~16% compared to the control sample. These findings highlighted the significant impact of PEF assistance on extraction performance and physicochemical properties enhancement, which were influenced by the specific parameters chosen.

There are so many different studies on the recovery of bioactive compounds from olive tree residues. Martínez-Patiño et al. [88] studied and optimized the UAE of olive mill leaves using an ethanolic solvent. Although UAE seems a promising technique, PEF pretreatment is an apt option for the extraction of bioactive compounds from olive leaves as it leads to higher yields. Furthermore, Da Rosa et al. [89] examined the potential of MAE as a pretreatment to ultrasonication, which has proved to be a favorable technique, but not as much as PEF pretreatment. Nevertheless, the most effective extraction technique from

olive leaves is cloud point extraction, as illustrated by Stamatopoulos et al. [90], which yielded in their study recoveries from various polyphenols up to 100%.

3.1.4. Blueberry

Berry fruit by-products mainly consist of skins and seeds. They also contain their pomace and their press cake. Bobinaitė et al. [91] examined the application of PEF pretreatment in order to enhance the permeability of cell membranes in fresh blueberry (*Vaccinium myrtillus* L.) tissue prior to pressing. The ultimate goal was to improve both the quality and quantity of the obtained juice that came from mechanical pressing, as well as to increase the extraction yield of bioactive compounds from the by-products of blueberry processing (press cake). The impact of varying combinations of electric field strengths (1, 3, and 5 kV/cm) and total specific energy input (1, 5, and 10 kJ/kg) on the Z_p of blueberry juice yield and tissue was investigated. PEF treatment intensity of 1 kV/cm and 5 kJ/kg yielded the lowest Z_p (0.61). The strongest treatment (5 kV/cm and 10 kJ/kg) boosted Z_p to 0.87, and this specific energy input value was chosen for further procedures. In blueberry juice, PEF treatment at 1 or 3 kV/cm increased the extraction yield by ~38% compared to untreated samples. Electric field strength variation showed statistically non-significant differences ($p < 0.05$) in TPC, as PEF-treated samples averaged ~110 mg GAE/100 mL of juice, but this value was considerably higher than the control sample (~46%). The same pattern was observed in both total anthocyanin content (TAC) and FRAP, with PEF-treated samples increasing this content by ~60% and ~33% compared to the control sample, respectively (~25 mg/100 mL of juice and ~4.5 μmol TE/mL of juice). In blueberry press cake, however, the results revealed the statistically significant ($p < 0.05$) impact in each electric field strength value of all the above values per gram or 100 g of press cake. Comparing the PEF-treated sample at 10 kV/cm with the control sample, TPC, TAC, and FRAP recorded an increase up to ~79% (~1800 mg GAE/100 g of press cake), ~106% (~1600 mg/100 g of press cake), and ~62% (~60 μmol TE/g of press cake), respectively. This study showed that PEF treatment could also be utilized for solid waste, which had better results compared to liquid samples.

In another investigation, Zhou et al. [92] focused on the use of PEF for anthocyanin extraction from by-products of blueberry processing (pomace and juice). The utilization of response surface techniques was employed by the authors to identify the optimal parameters for the extraction of anthocyanin from blueberry waste. The optimal conditions for anthocyanin extraction were determined to be a solvent containing 60% ethanol acidified with 0.1% (v/v) of hydrochloric acid, a liquid-to-liquid ratio of 1:6 (v/v), a pulse number of 10, and an electric field strength of 20 kV/cm. The extracted anthocyanin yield was measured at 223.13 mg/L of blueberry by-products. In comparison to US extraction, the emerging technology of PEF treatment demonstrated enhanced anthocyanin extraction yield (~1% higher yield) at reduced extraction temperature (from 40 °C to room temperature) and duration extraction time (from 60 min to ~15 min). In the present study, it was revealed that PEF is a fast and efficient technique for the extraction of bioactive compounds. Also, it was proved that low-temperature maintenance is feasible, and efficient extraction of thermolabile compounds is achieved.

Pataro et al. [93] also assessed the utilization of PEF treatment in blueberry by-products (press cake). The electric field strength was increased to 3 kV/cm, and the energy input (1–10 kJ/kg) was modified prior to pressing in order to enhance both the quantity and quality of the expressed juice from blueberry fruits. Additionally, anthocyanins were extracted from the by-products of blueberry pressing, specifically from the press cake, using solid–liquid extraction techniques. The juice obtained from the pretreated sample, subjected to PEF treatment at an energy level of 1 kJ/kg, exhibited a significant increase of ~32% when compared to the untreated sample, which had a juice output of 42.7 g/100 g of fw. The application of higher energy input, specifically 10 kJ/kg, resulted in the most favorable outcome in terms of the largest increase in anthocyanin content by ~55%. Additionally, the antioxidant capacity, as determined by FRAP and DPPH assay, exhibited an increase

of approximately ~36% and ~41%, respectively, in the juice. The extracts derived from the press cake of blueberries treated with PEF at an input energy of 10 kJ/kg exhibited higher anthocyanin content (~75%) and antioxidant capacity (determined by FRAP and DPPH tests at ~71% and ~109%, respectively) compared to extracts obtained from untreated blueberries. There was no significant degradation of individual anthocyanins following the application of PEF. HPLC analysis revealed that the predominant types of anthocyanins found were glycosides of delphinidin, cyanidin, petunidin, peonidin, and malvidin. The findings of the study indicate that the application of PEF as a pretreatment technique for blueberries and their by-products (press cake) shows promising results in facilitating the extraction of juice and antioxidants.

The studies discussed above on the recovery of anthocyanins from blueberry by-products indicate that a PEF pretreatment at high electric field strength values (10–20 kV/cm) is a favorable step. Furthermore, PEF treatment does not negatively affect the targeted compounds.

3.1.5. Prunus Fruits

Cherry, peach, and apricot belong to the *Prunus* genus. Their main by-products are their pomace, peels (or skin), kernels (seeds), and leaves. In the case of almond, which also belongs to the *Prunus* genus, its main waste is its hull. The research conducted by Pataro et al. [94] focused on investigating the impact of PEF pretreatment on the extraction yield and antioxidant properties of juice obtained from the "Duroni Nero" variety of sweet cherry (*Prunus avium* L.) fruits. Additionally, the study examined the extraction of bioactive compounds from cherry by-products (specifically, press cake). PEF pretreatment was carried out with a specific energy input of 10 kJ/kg and electric field strength (0.5–3 kV/cm) before a pressure of 1.64 bar was applied for 5 min. The application of PEF with an electric field strength of 1 kV/cm resulted in a significant enhancement in juice extraction, with a notable increase of 40% in juice yield. Furthermore, the PEF-assisted pressing technique exhibited a substantial improvement of 80% in anthocyanin content and a 27% increase in antioxidative activity when compared to untreated samples. The application of PEF to press cake extracts resulted in a significant increase of 38% in anthocyanin content and 21% in antioxidant activity compared to untreated samples. This enhancement was observed at an electric field strength of 0.5 kV/cm. PEF treatment of juice and press cake extracts did not result in the degradation of certain anthocyanins. Overall, the findings of this study revealed the potential of PEF as a moderate technique to increase the efficiency of industrial cherry fruit processing.

Redondo et al. [95] assessed the potential of PEF as a technique for improving the extraction of polyphenols and flavonoid compounds from freshly thinned peach (*Prunus persica*) by-products. The aim was to reduce the reliance on methanol in the extraction technique. PEF treatments were administered with pulses ranging from 10 to 50, each pulse lasting 3 μs (30–150 μs). The electric field strength varied from 0 to 5 kV/cm. Furthermore, the optimal conditions for PEF treatment have been determined using response surface methodology, with the solvent identified as the primary influencing factor. The electric field strength of 5 kV/cm and 35 °C were found to be the optimal conditions. In summary, using 80% methanol at 35 °C and no PEF treatment, the values of total polyphenol yield (~83 mg GAE/100 g fw), total flavonoid yield (~54 mg CE/100 g fw), and A_{AR} (~57% scavenging activity) were measured. However, with the use of PEF at 5 kV/cm, the results were significantly decreased by 0% methanol at 35 °C (~48 mg GAE/100 g, ~12 mg CE/100 g fw, and ~17% scavenging activity). The promoting effect of PEF on the enzymatic oxidation of polyphenols may provide an explanation for this observed phenomenon. In the untreated sample, there was minimal or no influence on enzymatic oxidation effects. This technique led to a decrease in the overall quantity of polyphenols in the thinned fruits, consequently reducing the extractable number of polyphenols.

In a study regarding the valorization of peach (*Prunus persica*) pomace, Plazzotta et al. [96] aimed to investigate the recovery of bioactive compounds from peach waste through the

application of PEF or thermal treatment. They explored the recovery of bioactive extracts using 70% ethanol from frozen or dried peach pomace, which was increased using either conventional thermal treatment at 50 °C for up to 90 min or PEF with electric field strength from 0.8 to 10 kV/cm, energy input from 0.0014 to 2.88 kJ/kg, with 4–30 monopolar pulses with a duration of 4 μs each, at a frequency of 0.1 Hz. In relation to the effectiveness of PEF extraction, they determined the minimum input energy that resulted in the maximum concentration of the target compound. Regarding the control samples of frozen and dried peach pomace, it was found that they had TPC values of 204 and 416 mg GAE/100 g dm, respectively. It is likely that the matrix drying treatment is accountable for these observed results. The drying process enhances the porosity of the matrix, thereby improving its extractive surface. Both treatment techniques were found to degrade bioactive compounds such as ascorbic acid in maximum energy input value (~89 kJ/kg), so it would be more beneficial to be compared in the lowest possible energy input value (~0.06 kJ/kg). In conventional thermal treatment, the frozen and dried pomaces had TPC values of 212 and 411 mg GAE/100 g dm, respectively. The corresponding values of PEF-treated samples were measured at ~371 and ~386 mg GAE/100 g dm. A similar pattern was observed in the measurement of total flavonoids, anthocyanins, and ascorbic acid. The current study revealed that the extraction efficiency of bioactive compounds is significantly influenced by the physical state of the by-product. Frozen PEF-treated samples retained polyphenols compared to dried samples. Furthermore, it is important to highlight that the PEF technique exhibited greater efficiency compared to conventional thermal treatment with low energy input values (0.0014–2.88 kJ/kg). This was evident not only in terms of achieving higher extraction yields of bioactive compounds but also in reducing the overall extraction time (40 min compared to some μs).

Makrygiannis et al. [97] investigated the valorization of defatted biomass of apricot (*Prunus armeniaca)* kernels to generate extracts with high polyphenol content. PEF was evaluated as an independent extraction technique and as an addition to the prior extraction technique, utilizing water as solvent. Deep eutectic solvent (DES) and PEF integration were examined to increase extraction yield. The samples underwent PEF treatment for a total duration of 15 min, utilizing an electric field strength of 1 kV/cm. The pulses lasted for 10 μs and occurred at a frequency of 1000 μs. The defatted apricot kernel biomass was stirred for 15 min with water or deep eutectic solvent (glycerol:choline chloride 2:1 *w*/*w*), and the samples underwent PEF treatment for 15 min, either with extraction for 3 h at 60 °C or PEF + extraction. The results indicated that applying PEF prior to the extraction procedure resulted in an 88% increase in TPC. Similarly, the utilization of DES resulted in an approximately 70% increase in TPC. The combination of the two approaches resulted in a 173% increase (~12 mg GAE/g dw). DES with PEF prior to extraction was found to be the most effective way to extract bioactive compounds from defatted apricot kernels. Thus, a similar pattern was observed in total flavonoid content (TFC), FRAP, and A_{AR}. Consequently, by implementing the above parameters, TFC, P_R, and A_{AR} were measured at ~10 mg RtE/g dw, ~18 μmol AAE/g dw, and ~12 μmol AAE/g dw. The corresponding increases were ~150%, ~80%, and ~71% compared to the control extraction with water, respectively. This study highlighted that low-voltage PEF treatment could be employed with several green solvents, such as deep eutectic solvents, in order to increase bioactive compound extraction.

A study on the extraction of lipids, carbohydrates, and antioxidants from almond (*Prunus amygdalus*) hull biomass was conducted by Salgado-Ramos et al. [98]. More specifically, they examined the combination of PEF followed by SC-CO_2. The parameters for PEF pretreatment were 100 kJ/kg specific energy output at a field strength of 3 kV/cm, the duration of the pulse was 100 ms, and the frequency was 2 Hz. As for the fluid extraction and SC-CO_2, the maximum pressure utilized was 15 MPa, at a flow rate of 25 mL per min, for one hour at 50 °C. The combined PEF and SC-CO_2 improved the efficacy of this technique by ~77% for total antioxidant capacity and by ~20% for polyphenols recovery, compared to ordinary soaking. Carbohydrate-soluble and lipidic fractions were

also identified by nuclear magnetic resonance analysis and preferentially extracted by PEF and SC-CO_2, respectively. Finally, differential thermogravimetric curves showed several contemporaneous valorization procedures for almond hull fractions, but scanning electron microscopy showed surface pores after PEF and fiber compaction after fluid extraction.

3.1.6. Quince

Quince by-products include its peels and leaves. Athanasiadis et al. [99] studied the recovery of bioactive compounds from quince peels. Firstly, they investigated the effects of various extraction parameters such as solvent composition, temperature, and time, as well as techniques such as PEF and US, either separately or in conjunction. Then, they optimized these parameters using response surface methodology, aiming to enhance the extraction of bioactive compounds. The PEF conditions utilized were an electric field strength of 1 kV/cm, a pulse duration of 10 µs, a pulse period of 1 ms, and a frequency of 1000 Hz. The US treatment was carried out in a bath, operating at 3 kHz, at 30 °C for 20 min. The most effective extraction technique proved to be simple, economical stirring at a relatively high temperature of 65 °C for 120 min. Following the application of principal component analysis and partial least squares analysis, it has been determined that quince peels exhibit notable quantities of various compounds. These include total polyphenols (43.99 mg gallic acid equivalents/g dw), total flavonoids (3.86 mg rutin equivalents/g dw), chlorogenic acid (2.12 mg/g dw), and ascorbic acid (543.93 mg/100 g dw). Additionally, the antioxidant activity of the quince peels has been measured to be 627.73 µmol AAE/g dw and 699.61 µmol DPPH/g dw through the employment of FRAP and DPPH assays, respectively. Nevertheless, PEF pretreatment of the samples appeared to enhance the DPPH radical scavenging value, thus increasing the antioxidant properties of the extracts.

3.1.7. Papaya

An investigation conducted by Parniakov et al. [100] focused on comparing the efficiency of PEF and HVED in extracting papaya (*Carica papaya*) peels for their antioxidant and nutraceutical components. In this study, the influence of varying pH levels (2.5–11) and temperatures (20–60 °C) on the extraction efficiency of nutritionally advantageous compounds was explored. Furthermore, a two-step extraction technique was utilized, wherein the sample was initially subjected to PEF treatment, followed by a subsequent aqueous extraction technique known as supplementary aqueous extraction (SAE), conducted at a relatively low temperature of 50 °C. The variation in extraction temperature or the use of a basic medium with a pH of 11 did not consistently result in higher yields or TEAC values. The protein content and TEAC values at pH levels of 7 and 11 exhibited a significant decrease when the temperature rose from 50 to 60 °C. The extraction of high-value chemicals using HVED demonstrated superior performance compared to PEF-assisted extraction. The protein concentrations utilized in the HVED- and PEF-assisted extractions were 60 and 20 mg/L, respectively. The experiments were performed under specific conditions, including a pH of 7, a temperature of 20 °C, and an extraction time of 45 min. The utilization of electrical discharges, turbulence, and pill fragmentation has been found to significantly enhance the efficiency of HVED-assisted extraction. Chemical by-products can be produced through the process of electrolysis and the generation of reactive free radicals resulting from electrical discharges. The aforementioned by-products possess the ability to decompose compounds that possess a significant amount of nutritional value. The combination of PEF treatment and subsequent aqueous extraction at 50 °C resulted in enhanced yields of papaya peel components and increased antioxidant capacities, even when the pH conditions were neutral.

3.1.8. Mango

Parniakov et al. [101] implemented PEF pretreatment in order to recover bioactive compounds from mango peels. In their work, they examined the efficacy of traditional extraction at various pH values, ranging from 2.5 to 11, and various temperatures, varying

between 20 and 60 °C. Then, they investigated the extraction aided by PEF or HVED of compounds identified in mango peels that are nutritionally valuable. For PEF and HVED treatments, exponential decay pulses with initial electric field strengths of 13.3 kV/cm and 40 kV/cm, respectively, were utilized. The aqueous extraction of proteins and carbohydrates was not influenced by temperature. Aqueous extraction at 60 °C and pH 6 yielded the highest concentrations of antioxidant and nutritionally valuable compounds, but the extracts were not stable. The use of the two-stage PEF and supplementary aqueous extraction approach proved to be the most effective technique. The first step included PEF pretreated extraction. The second step was a supplementary extraction at pH 6, at 50 °C, for 3 h. The combination of the two provided an exceptional increase in the yields of TPC (~400%) even at normal pH levels.

3.1.9. Pomegranate

In their study, Rajha et al. [102] employed various extraction techniques, including infrared (IR), US, PEF, and HVED, to facilitate the recovery of polyphenols, flavonoids, and tannins from pomegranate peels. The temperature remained constant at 50 °C for each extraction, whereas electric field strength was set at 10 kV/cm. The temperature increase observed during the PEF treatment did not surpass 5 °C and was effectively regulated through the implementation of a cold-water bath. The specific energy input for the PEF treatment ranged from 90 to 100 kJ/kg, while the energy delivered per pulse was measured to be 0.29 kJ. While the utilization of HVED-assisted extraction resulted in a 1.3-fold increase in the recovery of polyphenols compared to PEF-assisted extraction, the latter technique exhibited a higher recovery of ellagic acid. After a duration of 7 min, the phenolic extractable fraction by PEF exhibited a mean value of 39 ± 2 mg GAE/g DM. This measurement was found to be 15.22% lower than the HVED treatment. However, it was observed to be 168.97% higher than the ultrasonic US treatment, 387.5% higher than the IR treatment, and 680% superior to the water bath treatment. This study demonstrates the considerable effectiveness of both HVED and PEF treatments in extracting polyphenols from pomegranate peels. The effectiveness of PEF in recovering polyphenols is lower compared to HVED. However, PEF is characterized by less damage and a higher level of selectivity in its treatment technique when compared to HVED.

In a broad sense, it appears that HVED treatment is a more beneficial technique for extracting bioactive compounds from food by-products in comparison to PEF treatment. This assertion is substantiated by the research conducted by Rajha et al. [102] on pomegranate peels and the study conducted by Parniakov et al. [101] on mango peels, as previously mentioned.

3.1.10. Custard Apple

Ahmad Shiekh et al. [103] investigated the effects of employing a PEF-assisted technique on the production of custard apple leaf extract using ethanol (70% v/v). Various electric field strengths (2–6 kV/cm), pulse numbers (100–300 pulses), and specific energy (45–142 kJ/kg) were utilized for a duration of 2.5–5 min. The application of PEF at an electric field strength of 6 kV/cm, with a total of 300 pulses and an energy input of 142 kJ/kg for a duration of 5 min, resulted in a higher cell disintegration index in the custard apple leaf extract sample, measured at ~0.75. The extraction yield exhibited a significant increase of 5.2% when compared to the untreated counterpart, which had a yield of 13.28%. The PEF treatment resulted in enhanced radical scavenging activities as evaluated through the DPPH (~84.88%), ABTS (~145%) radical scavenging assays, and FRAP (~203%) analysis. The inhibition of the growth of *Staphylococcus aureus* and *Escherichia coli* was also found to be effective. However, the levels of chlorophyll A and B in PEF-pretreated custard apple leaf extract were found to be insignificant compared to the untreated sample (~300 lower in total). The main compounds observed in the samples treated with PEF were rutin and purpureacin 2, as determined through LC-MS analysis. Therefore, these extracts have the potential to serve as natural additives for the purpose of food preservation.

3.1.11. Jackfruit

The combination of PEF with another extraction technique seems to be gaining popularity since it gives satisfactory extraction results of bioactive compounds. To that end, the methodology employed by Lal et al. [104] included a synergistic approach involving the utilization of PEF and MAE for the extraction of pectin from jackfruit waste. The optimal operating conditions through the technique of desirability analysis were as follows: electric field strength of 11.99 kV/cm and treatment duration of 5.47 min. The pectin that was obtained was subjected to analysis in order to evaluate its structural and functional properties in comparison to the pectin that was conventionally extracted. The highest pectin yield (~18%) was achieved when the sample was subjected to an electric field strength of 10 kV/cm for a duration of 4 min, coupled with a microwave power density exposure of 550 W/g for 10 min compared to control extraction (~17%). The combined techniques could save up to ~330% min than conventional extraction (~45 min The findings of this study demonstrate that the application of a PEF in conjunction with other methodologies enhances the retrieval of bioactive compounds. Moreover, this approach holds significant economic implications for the food industry, as it offers both time and financial savings.

3.1.12. White Mulberry

The objective of the study conducted by Chaiyana et al. [105] was a comparative analysis of the composition and biological activity of white mulberry (*Morus alba* L.) leaf extract obtained from three local farms located in Thailand (Chiang Mai, Sakon Nakho, and Buriram). They compared the extract obtained using PEF with 95% *v*/*v* ethanol to a control extract obtained through the conventional maceration technique. The technique of maceration was conducted for a duration of 24 h and repeated for a total of 3 cycles. In contrast, PEF treatment was applied for a single session lasting 20 min. The employment of PEF treatment required an intensity of 10 kV/cm at a frequency of 5 Hz, with a pulse width of 1 µs, over a duration of 20 min. The results indicated that the PEF extract from white mulberry leaves from Buriram exhibited similar ABTS scavenging activity as L-ascorbic acid and comparable anti-tyrosinase activity as kojic acid. Specifically, the measured yield (~8%) was significantly higher than the samples from the other two regions (~1%). Increased values were also observed in several antioxidant assays, such as TPC (~40%), DPPH (~14%), ABTS (~20%), and FRAP (~30%). In contrast, the PEF extract of white mulberry leaves obtained from Sakon Nakhon demonstrated a notably elevated level of anti-hyaluronidase activity, which was found to be comparable to the level of the positive control, oleanolic acid (~80%). According to the authors, it is recommended to employ PEF as a viable technique for extracting white mulberry leaves in order to obtain natural cosmetic ingredients with whitening and anti-aging properties.

3.2. Vegetables

3.2.1. Tomato

Commonly, tomato waste includes peel, pulp, and seeds. Luengo et al. [106] investigated the impact of applying PEF with varying intensities (3–7 kV/cm) and durations from 0 to 300 µs on the extraction of carotenoids from both tomato peel and pulp. The extraction technique was conducted using 50:25:25 *v*:*v*:*v* hexane:acetone:ethanol. Based on the Z_p, it has been determined that the most favorable duration for the permeabilization process of tomato peel and pulp is 5 kV/cm and 90 µs (30 pulses of 3 µs). Moreover, Z_p in PEF-treated pulp increased from 0 to 0.7 with increasing treatment time (0–300 µs) and was almost twice that of the Z_p in PEF-treated peels. However, a switch from 5 to 7 kV/cm led to a statistically non-significant ($p > 0.05$) increase in carotenoid extraction of tomato peels. Compared to the untreated sample, PEF treatment at 5 kV/cm led to a 39% increase in the carotenoid extraction efficiency of tomato peels using the abovementioned solvent mixture. The inclusion of acetone in the solvent mixture did not yield a significant improvement in carotenoid extraction when tomato peels were subjected to PEF treatment. The employment of response surface methodology to assess the efficacy of PEF treatment in reducing the

proportion of hexane within a hexane:ethanol mixture facilitated a decrease in the hexane concentration from 45 to 30% while maintaining the carotenoid extraction yield and keeping it unaffected. The correlation between the carotenoid concentration and the antioxidant capacity of the extracts derived from tomato peel was observed, while the application of PEF treatment did not have any significant impact on the antioxidant capacity.

Pataro et al. [107] investigated the impact of PEF pretreatment on the recovery yield of lycopene from industrial tomato peel residues. Specifically, the effects of different field strengths (1–5 kV/cm) and energy inputs (5–10 kJ/kg) were examined. The solvents used in the recovery process were acetone or ethyl lactate. The samples were further extracted with the abovementioned extraction solvents, with a 1:40 constant solid-to-liquid ratio at 25 °C in an orbital incubator. PEF treatment was employed with an electric field strength of 5 kV/cm and energy input of 5 kJ/kg and resulted in a notable increase in the extraction rate (27–37%), lycopene yields (12–18%), and antioxidant power (18.0–18.2%) of both acetone and ethyl lactate extracts when compared to untreated samples. Nevertheless, it was observed that acetone yielded the highest amount of lycopene. The results obtained from the high-performance liquid chromatography analyses indicated that the predominant carotenoid extracted was all-*trans* lycopene. Furthermore, no instances of degradation or isomerization were observed during the extraction technique.

Andreou et al. [108] evaluated PEF treatment in tomato processing stages in order to boost productivity, product quality, and waste utilization without major line adjustments. For the recovery of bioactive compounds, the condition of PEF was electric field strength from 1 to 5 kV/cm. The application of PEF with an electric field strength of 1 kV/cm for a duration of 7.5 ms resulted in a significant enhancement in lycopene extraction from tomato waste, with a lycopene yield of 14.31 mg/100 g of waste, representing a ~45% increase compared to the control (untreated) sample. The polyphenol compound extraction from tomato waste was observed to increase twofold (56.16 mg GAE/kg) under PEF conditions of 700 pulses and with an electric field strength of 2 kV/cm, which verified PEF potential to enhance the mass transfer phenomena that occur during the extraction process. Furthermore, the release of intracellular protein under PEF treatment was evaluated. The concentration of the protein that was released exhibited a positive correlation with both the magnitude of the electric field and the duration of exposure. This study highlighted that PEF treatment not only enhanced protein extraction but also maintained the protein content of the extracts.

The study of Kumar et al. [109] aimed to utilize several advanced techniques for the extraction of lycopene from the by-product of tomato processing in the industrial setting, specifically the peel. These techniques involved PEF-assisted extraction (PAE), low-temperature MAE, power UAE, combined low-temperature microwave-power ultrasound-assisted extraction (MUAE), and combined ultrasound-PEF-assisted extraction (UPAE). In this study, a solvent mixture consisting of ethanol and ethyl acetate in a volumetric ratio of 2:3 was employed for the purpose of lycopene recovery. UPAE treatment exhibited the highest extraction yield, with a lycopene yield of 3.56%. This was closely followed by the MUAE treatment, which yielded 3.49% of lycopene. The UPAE technique exhibited the highest antioxidant capacity, as evidenced by its DPPH value of 87.09%, surpassing other techniques under investigation. Additionally, the lycopene that was obtained was encapsulated within an oil-in-water emulsion in order to create a lemon juice beverage that is enriched with this compound.

The application of PEF pretreatment on tomato peels, specifically at an electric field intensity of 5 kV/cm, appears to be the most effective technique for the extraction of lycopene. Extensive study [110–113] has been conducted to determine the optimal methodology for extracting bioactive compounds from tomato waste. Various techniques, including the utilization of liquid and supercritical carbon dioxide, high hydrostatic pressure extraction, UAE, and cloud point extraction, have been subjected to experimentation and evaluation. Among the several strategies considered, it is evident that cloud point extraction (CPE) exhibits the most notable performance, surpassing the others significantly. However, the PEF

technique appears to be the most suitable approach, as it demonstrates higher percentages, surpassing even the CPE technique. Conducting a study on the integration of these two strategies and analyzing the outcomes would be a compelling endeavor.

3.2.2. Potato

Hossain et al. [114] the influence of PEF pretreatment and pulsed light pretreatment on the recovery of steroidal alkaloids (glycoalkaloids and aglycone alkaloids) from potato peels via solid–liquid extraction. An electric field strength of 0.75 kV/cm and a total duration of 600 μs resulted in a maximum recovery of total steroidal alkaloids that was increased by ~99.9% compared to the untreated (control) peels. However, electric field strength higher than 0.75 kV/cm diminished steroidal alkaloid recoveries during treatment periods ranging from 150 to 1500 s. The quantities of glycoalkaloids and aglycone alkaloids in potato peels were likewise enhanced by pulsed-light treatments, reaching a plateau at fluences of 7.86 and 9.38 J/cm^2, respectively. However, PEF treatment increased extraction yield more than pulsed-light-treated peels. For instance, α-solanine and solanidine were measured at ~80 and ~1300 μg/g dw, respectively. The corresponding values from pulsed light treatment for the above compounds were ~70 and ~600 μg/g dw, respectively.

Frontuto et al. [115] examined the most effective PEF-assisted extraction conditions to enhance the extraction of polyphenols with significant antioxidant properties from potato peels. The effect of several combinations of electric field strengths among 1, 3, and 5 kV/cm and the total specific energy input among 1, 5, and 10 kJ/kg were examined. Under optimal conditions, which were 5 kV/cm fields strength and 10 kJ/kg specific energy output, 52% ethanol as a solvent, 230 min extraction duration, and 50 °C for the subsequent solid–liquid extraction, extracts from PEF pretreated samples measured at 1295 mg GAE/kg fw in total polyphenol yield (+10% from the control).

In the above studies on potato peel valorization, it appears that a significantly lower electric field strength was required for the extraction of steroidal alkaloids than for the extraction of polyphenols.

3.2.3. Carrot

Roohinejad et al. [116] assessed the recovery of β-carotene from carrot pomace via oil-in-water, utilizing a PEF pretreatment. The optimum conditions for PEF treatment were determined as an electric field strength of 0.6 kV/cm with a constant frequency of 5 Hz, a treatment duration of 3 ms, and a pulse width of 20 μs. The results showed that the β-carotene content of PEF-treated carrot pomace extracted using microemulsions was greater than that of untreated carrot pomace. To forecast the ideal extraction conditions employing transparent microemulsions with high β-carotene loading, low polydispersity index, and small microemulsion particle size, a mathematical model was developed. The model indicated that the optimum conditions were a temperature of 52.2 °C, an extraction time of 49.4 min, and a ratio of 1:70 w/w carrot/microemulsion. The extract would yield microemulsions with a polydispersity index of 0.27, a particle size of 74 nm, and α-carotene loading of 19.6 μg/g at these conditions. The results of this study support the use of oil-in-water microemulsions for the extraction of β-carotene.

3.2.4. Corn

Corn silk is known as the main agricultural corn by-product. Zhao et al. [117] implemented a response surface methodology in order to enhance the recovery of polysaccharides from corn silk via PEF pretreatment. There were three tested parameters: the electric field intensity, the pulse duration, and the liquid-to-raw solid material ratio. The experimental values of the electric field intensity were 25, 30, and 35 kV/cm. The pulse duration was between 4, 6, and 8 μs. The liquid-to-raw-solid material ratio varied between 45, 50, and 55. These independent variables were statistically analyzed, and the optimum conditions were proved to be electric field intensity of 30 kV/cm, 6 μs pulse duration, and a ratio of liquid-to-solid raw material of 50:1. Under these conditions, the yield of the

polysaccharides was 2.36%, and of the crude protein was 0.14%. It has become clear that increasing the polysaccharide recovery depends on the PEF intensity. The yield of extracted polysaccharides increases as the electric field intensity under 30 kV/cm elevates.

3.2.5. Onion

Skin is the main onion by-product. In a study valorizing onion, Kim et al. [118] studied the most effective extraction conditions for obtaining quercetin from dehydrated onion skin and investigated the potential enhancement of yield by combining pretreatment with PEF treatment and SWE. Onion skin samples were treated with PEF with varying electric field strengths (0.5–2.5 kV/cm) and durations (5–120 s). SWE was subsequently conducted using a 15 min extraction duration and several temperatures (105–185 °C). The highest yield of total quercetin was observed when pretreated with PEF at 2.5 kV/cm for 15 s, followed by SWE at 145 °C for 15 min (19.25 mg/g onion skin dw). The inclusion of PEF resulted in a decrease in the optimal extraction temperature (at 145 from 165 °C) and a ~31% increase in the yield of quercetin (from 14.60 mg/g dried onion skin). The results indicate that pretreating onion skin with PEF has the potential to enhance flavonoid extraction.

3.2.6. Asparagus

The root of *Asparagus officinalis* is known to possess beneficial bioactive compounds. Symes et al. [119] conducted a study in which the primary objective was to increase the efficacy of polyphenol and flavonoid extraction from green asparagus roots through the utilization of two innovative methodologies, namely PEF and ionic liquids. The A_{AR} of the acquired extracts was also assessed. The study involved the determination of TPC, total flavonoid content (TFC), and A_{AR} using various assays, including DPPH, oxygen radical absorbance capacity (ORAC), and FRAP assays. The utilization of PEF under optimal conditions, namely electric field strength of 1.6 kV/cm, pulse width of 20 μs, and frequency of 200 Hz, led to a greater extraction yield in comparison to the conventional solvent extraction technique. The PEF-treated samples showed an overall increase in all assays and yield compared to untreated samples, bar ORAC. The corresponding percentage changes are shown in brackets: Yield (+23%), TPC (+5%), TFC (+6%), DPPH (+60%), ORAC (−11%), and FRAP (+4%). However, the use of ionic liquids was found to be more effective than PEF treatment. For instance, the TFC acquired by the use of ionic liquids was measured at 122 mg RE/g. This value was ~80 times higher compared to the TFC obtained through the use of PEF treatment. Despite the superiority of ionic liquids compared to PEF in asparagus root samples, it would be imperative to conduct additional research to ascertain the safety of ionic liquids in the food industry.

3.2.7. Chicory

Chicory's basic by-products are its roots and root fibers. Zhu et al. [120] investigated the industrial conditions for the extraction of inulin from PEF-treated chicory roots. The special pilot extractor previously developed by Loginova et al. [121] was employed. This extractor facilitates the countercurrent flow of cossettes and extracting juice, serving the intended purpose. This study examined the impact of PEF parameters, specifically the electric field strength set at 0.6 kV/cm, 100–500 pulses, and treatment duration (10–50 ms), as well as the diffusion temperature (30–80 °C), on the kinetics of soluble matter extraction, inulin content of juice, and pulp exhaustion. The optimum conditions had 0.6 kV/cm and 50 ms duration. The utilization of PEF treatment has been found to enhance the extraction technique of inulin at a typical diffusion temperature of 80 °C. In that temperature range, inulin was measured at ~12 g/100 mL of juice compared to ~11.5 g/100 mL measured in the control sample. Furthermore, it has been observed that the diffusion temperature can be lowered by 10–15 °C while maintaining a comparable concentration of inulin in the juice. However, 30 °C was the optimal temperature in pulp, where inulin was measured ~30 g/100 g of pulp compared to the ~15 g/100 g of pulp at 70 °C. The reduction of diffusion temperature following PEF treatment of chicory roots yields significant advantages,

primarily in terms of minimizing PEF electrical energy consumption. Additionally, there is potential for economic gain, specifically in relation to the diffusion step, with an estimated profit of 34.76 EUR/ton of inulin.

3.3. Other

3.3.1. Coffee and Cocoa

Cocoa bean shell is the most common cocoa by-product. As for coffee seeds, their most well-known by-products are their silverskin and their parchment, which consists of their skin and pulp. Barbosa-Pereira et al. [122] implemented PEF as a new pretreatment technique in order to enhance polyphenol recovery from two food by-products, coffee silver skin, and cocoa bean shell. The optimal PEF conditions were established by a response surface methodology as 1.74 kV/cm electric field strength and 991 pulses in 11.99 µs. Then, a solid–liquid extraction followed utilizing ethanol 39.15% as a solvent for 118.54 min. The findings revealed the potential of PEF pretreatment to increase the extraction of bioactive compounds from cocoa bean shell and coffee silver skin as a greener alternative extraction option compared to traditional extraction techniques with industrial-scale use. Appropriately chosen PEF pretreatment extraction parameters customized to each matrix can increase the yield of bioactive compounds in cocoa bean shell and coffee silver skin samples by 20 and 21.3%, respectively, when compared to untreated samples and may be adopted to produce extracts with high nutritional specific phytochemical profiles.

Macías-Garbett et al. [123] developed a green extractive technique that employs PEF pretreatment and MAE to extract bioactive compounds (polyphenols) from coffee parchment and two types of pulp (yellow and red pulp), with short processing times and water as the single solvent. The pretreatment operating parameters were established at a total treatment time of 5 min, electric field strength of 6 kV/cm, and pulse frequency of 5 Hz. MAE was then performed on PEF-pretreated samples. The combined PEF pretreated and microwave-assisted extracted samples outperformed treatment controls in terms of total phenolic content and radical scavenging activity in all examined residues. Regarding TPC values in coffee parchment waste, the control sample measured recorded ~195 mg GAE/100 g of material. Samples treated with both MAE and PEF led to a high TFC value (~164 mg RtE/100 g of coffee parchment). This value was ~92% higher than the control sample and ~18% higher than the sole MAE-treated samples. The same pattern was also observed in all coffee waste samples in other antioxidant assays (DPPH, ABTS, FRAP). This study also presents a novel application of MAE + PEF for the revalorization of coffee processing waste. The technique involves the extraction of polyphenols using short processing times and minimal reagent requirements. Consequently, this approach holds promise as a valuable addition to a coffee biorefinery strategy.

Carpentieri et al. [124] investigated how PEF pretreatment affected the recovery of target aromas and bioactive compounds, such as theobromine and caffeine from cocoa bean shells, vanillin from vanilla pods, linalool from vermouth mixture, and limonene from orange peels. The extraction was carried out in green solvents, water and ethanol mixtures, and propylene glycol. The efficiency of PEF as a cell disintegration technique was proved using impedance measurements over a ranged electric field strength (1–5 kV/cm) and energy input (1–40 kJ/kg), and the results were used to optimize PEF pretreatment conditions of each plant tissue prior to the subsequent solid–liquid extraction technique. The optimal PEF conditions for cocoa bean shells and vanilla pods were determined as an electric field strength of 3 kV/cm and a specific energy output of 20 kJ/kg, enabling the highest cell disintegration index at 0.82. In the case of the vermouth mixture, the highest cell disintegration index was 0.77, and it was achieved through 3 kV/cm electric field strength and 15 kJ/kg specific energy input. As for orange peels, the electric field strength was 5 kV/cm, and the specific energy input was 40 kJ/kg, leading to the highest cell disintegration index of 0.55. More specifically, in ethanolic extracts, a 14% increase in vanillin, 25% increase in theobromine, 34% increase in caffeine, 114% increase in linalool, and 33% increase in limonene were observed. These results suggest that recovering clean labels and nutrients

from aromatic plants and food by-products using PEF treatment prior to solid–liquid extraction with green solvents may be an approach with long-term sustainability.

3.3.2. Rapeseed

The main residue of rapeseed is its stems. Rapeseed (*Brassica napus* L.), a seasonal oilseed plant cultivated during winter or spring, ranks as the third most extensively cultivated variety of vegetable oil globally, following palm and soybean oil. Yu et al. [125] investigated the recovery of bioactive compounds, such as polyphenols and proteins, from rapeseed stems and leaves. The thermocouple-controlled temperature elevation during PEF treatment did not rise above 5 °C. The maximum polyphenol recovery was obtained after treatment at 5 kV/cm. More specifically, the polyphenols extraction yield reached 52% after 1 h of extraction with the mild PEF treatment (electric field strength 0.80 kV/cm, energy input 6.4 kJ/kg, and Z_p 0.7), but under the same conditions, protein yield was not significantly improved. The findings also demonstrate that the polyphenol and protein content of rapeseed stems and leaves varied depending on the maturity of the plant, which may help to pinpoint the ideal harvest period for by-product valorization.

3.3.3. Drumstick Tree

Bozinou et al. [126] investigated the employment of PEF treatment in freeze-dried drumstick tree (*Moringa oleifera*) leaves. The comparative analysis involved evaluating the efficacy of PEF extraction in relation to other established techniques, including MAE and UAE, simple boiling water extraction, and plain maceration (serving as the control). The control sample was prepared by employing equal amounts of freeze-dried leaves, which remained in double-distilled water at ambient temperature and immersed in water for a period of 40 min, which corresponded to the duration of the PEF procedure. Electric field strength was constant at 7 kV/cm. The variables examined in this study encompassed the pulse duration (PD), which denotes the duration of time in which the electric field is administered, and the pulse interval (PI), which represents the duration between two consecutive pulse applications. Pulse duration ranged from 10–100 ms, whereas pulse interval ranged from 25–100 μs. PEF-treated samples had eight different combinations of PD and PI. Regarding TPC, the PEF-5 sample (20 ms PD and 100 μs PI) was the most effective way by extracting 40.24 mg GAE/g dw, achieving ~45% more than the control sample. The same pattern was also observed in other antioxidant capacity assays, such as % scavenging activity and FRAP, as expected. Other PEF-treated samples with high PI (100 μs) and increasing PD (from 50 to 100 ms) had decreasing TPC. Hence, it should be highlighted that a combination of low PD and high PI is the optimal condition for the extraction of total polyphenols from freeze-dried *M. oleifera* leaves.

3.3.4. Flaxseed

Flaxseed sole by-product is the seed hulls. An interesting study regarding hull valorization was conducted by Boussetta et al. [127]. The authors assessed the feasibility of extracting polyphenols from flaxseed hulls through the application of PEF treatment. They examined the impact of various operating parameters on the extraction of polyphenols, specifically focusing on the duration of the treatment (1–10 ms), the electric field strength (10–20 kV/cm), the composition of the solvent (including ethanol: water mixtures, 0.05–0.3 M citric or sodium hydroxide), and the duration of product rehydration (0–60 min). Flaxseed hulls underwent acidic or alkaline extraction with the solvents above while being agitated at 20 °C prior to PEF. The utilization of 50% ethanol resulted in a more efficient extraction of polyphenols (~300 mg GAE/100 g dm), achieving an increase of ~42% compared to extraction of 20%. However, the authors declared that industrial PEF applications should not exceed this ethanol level (20%), so this level was used as optimal. The findings of the study revealed that the optimum conditions of a PEF treatment were at 20 kV/cm for 10 ms, with an energy output of 300 kJ/kg, after 40 min of rehydration at 150 rpm. The use of 0.3 M citric acid obtained ~270 mg GAE/100 g of dm, whereas the

use of 0.3 M sodium hydroxide obtained ~1000 mg GAE/100 g of dm. The control sample with no sodium hydroxide obtained ~200 mg GAE/100 g of dm instead. The use of PEF produced satisfactory results in the recovery of antioxidant compounds; however, it would be interesting to recover proteins from this by-product.

3.3.5. Sage

Leaves and stems are the two by-products of sage. The study conducted by Athanasiadis et al. [128] had as its primary objective to assess the efficacy of PEF-assisted extraction in obtaining phytochemicals from the leaves of sage (*Salvia officinalis* L.). The experimental conditions involved a range of parameters, specifically the pulse duration of the PEF, which was set at either 10 or 100 μs for a duration of 30 min. They also investigated the use of various "green" extraction solvents, namely pure water, ethanol, and their mixtures at concentrations of 25–75% v/v. The extracts that were obtained as a result were assessed in comparison to reference extracts that were obtained without the use of PEF. The extraction efficiency was evaluated by determining the levels of total polyphenols, individual polyphenols, volatile compounds, and oxidation resistance. The optimal conditions involved a 25% v/v aqueous ethanol solvent with a pulse duration of 100 μs and electric field strength of 1 kV/cm, which led to the highest PEF contribution to both total and individual polyphenols, as well as rosmarinic acid extractability. This led to a significant increase of up to 73.2 and 403.1%, compared to reference extract, respectively. The findings were also validated by the differential scanning calorimetry technique. The PEF-treated extracts exhibited an average increase in oxidation temperature of 61.5% compared to the reference extracts (182 °C). Finally, the primary compounds were detected in both the extracts treated with PEF and the reference extracts, comprising approximately equal proportions of the total composition (65.51 and 67.58%, respectively). These results showed that the application of low energy intensities may result in minor alterations to the aroma of the examined extracts via PEF.

3.3.6. Rosemary and Thyme

Rosemary and thyme by-products are plant tissue. Tzima et al. [129] explored the feasibility of valorizing rosemary and thyme by-products (stems and leaves). In order to achieve cellular permeabilization, these were subjected to PEF treatment, followed by ultrasonic treatment using an aqueous ethanol solution. The evaluation of the impact of low-energy PEF-induced permeabilization on the extraction of specific intracellular polyphenols was conducted using the Z_p as a measure before any optimization was performed. A fixed sample size was subjected to each treatment, consisting of a series of 167 bipolar pulses with a pulse duration of 30 μs and an applied electric field strength of 1.1 kV/cm. The combined and individual impacts of the two methodologies were assessed through the utilization of TPC antioxidant capacity (DPPH and FRAP) assays. In both rosemary and thyme samples, the employment of US led to statistically significant ($p < 0.05$) differences between the PEF-treated samples. The higher the duration of US, the higher the values of the above assays. However, the combination of the two techniques turned out to be the most effective way to extract bioactive compounds from these samples. For instance, the rosemary PEF-treated sample recorded ~40 mg GAE/100 g fw, whereas US treatment for 12.48 min led to ~220 mg GAE/100 g fw, and the combination of the two treatments resulted in ~300 mg GAE/100 g fw. A similar pattern was observed in the thyme samples, where the combination of the two techniques led to ~400 mg GAE/100 g fw. In addition, the application of PEF as a pretreatment technique resulted in an elevation in the levels of certain key polyphenols found in rosemary and thyme. Rosmanol, epirosmanol, and carnosol were the major polyphenols, with rosmarinic and carnosic acid found to be considerably lower in content. Previous research has demonstrated a potential correlation between the reduced concentration of carnosic acid and its degradation into carnosol. A previous study [130] has demonstrated a potential correlation between the reduced concentration of carnosic acid and its degradation into carnosol. Regarding thyme extracts,

the application of PEF pretreatment led to the production of extracts with distinct phenolic profiles in comparison to those obtained solely through US treatment. The predominant polyphenols found in thyme were luteolin-7-*O*-glucoside, luteolin-7-*O*-glucuronide, and rosmarinic acid. The results obtained indicated that PEF pretreatment could be employed as a disintegration technique prior to solid–liquid extraction procedures, as it has been observed to yield advantageous outcomes even when low levels of energy are applied.

3.4. Seafood

The main by-products of fishery and seafood consist of viscera, skin, bones, fins, and heads, and in the case of shrimps, their main by-product is their side streams. The utilization of fishery by-products is significant due to their abundance of biologically active compounds, such as proteins and astaxanthins. Therefore, it is crucial to employ environmentally friendly and efficient extraction techniques to retrieve these valuable compounds. To that end, a study conducted Wang et al. [131] utilized the head, skin, and viscera of rainbow trout and sole as the focal matrices. Two extraction techniques, namely accelerated solvent extraction (ASE) and PEF, were employed. ASE was conducted at temperatures ranging from 45 to 55 °C for a duration of 15 min, with pH levels between 5.2 and 6.8 and pressure set at 103.4 bars. PEF, on the other hand, involved applying electric field strength ranging from 1 to 3 kV/cm, with energy levels between 123 and 300 kJ/kg, and a duration of 15 to 24 h. The parameters of PEF were dependent on the part of the fish studied. The results of the study indicated that the utilization of both ASE and PEF treatments had ~80% protein extraction efficiency of fish by-products. The SDS-PAG electrophoresis revealed that the application of ASE and PEF treatments resulted in alterations to the molecular size distribution of the protein present in the extracts. The findings of the study indicated that the application of ASE and PEF treatments resulted in a significant enhancement of the antioxidant capacity (ORAC) in extracts obtained from the skin and head of rainbow trout and sole fish ($p < 0.05$). However, ASE treatment was found to be the most effective way to extract antioxidant compounds in both fish species. ASE treatments in the skin of rainbow trout and in the viscera of sole recorded ~43 and ~50% higher values than the corresponding PEF-treated samples. On the other hand, PEF was found to be more effective in ABTS assay. The utilization of PEF has proven advantageous for the extraction of soluble proteins from by-products. This technique not only serves as a substitute for the environmental pollution caused by organic reagents in conventional extraction techniques but also effectively preserves the antioxidant properties of bioactive compounds. This aligns with the demands of contemporary industry and environmental progress and is poised to significantly contribute to the future transformation and exploitation of aquatic resources.

Shrimp by-products serve as a significant ecological reservoir of astaxanthin. The optimization of the extraction technique for astaxanthin from shrimp side streams holds significant importance in the valorization of crustacean by-products and the advancement of astaxanthin-based products. The study conducted by Pinheiro et al. [132] aimed to assess the individual and combined impacts of two advanced extraction techniques, namely PEF and ASE, on the extraction of astaxanthin from two distinct shrimp species. The electric field strength was 3 kV/cm, the specific energy was 100 kJ/kg, and the total number of pulses was 74. Additionally, the study investigated the potential benefits of employing a sequential approach by combining these technologies and utilizing two different solvents (DMSO and ethanol). The species *A. antennatus* exhibited the highest recovery (585.90 μg/g, ~200% increase from control) when the solvents DMSO were utilized in conjunction with the combined application of PEF and ASE. The same pattern was observed in *M. kerathurus* species, where ASE and PEF treatments with DMSO as solvent led to the highest astaxanthin content (~240 μg/g, ~150% increase from control). It was also observed that ASE treatment resulted in higher astaxanthin extraction compared to PEF treatment in all cases. In this study, both techniques proved to be effective for extracting antioxidant-rich carotenoids, i.e.,

astaxanthin, from by-products of shrimp processing. All the above studies are illustrated in Table 1.

Table 1. Application of PEF on food by-products and the treatment effects.

Type of By-Product	Target Bioactive	PEF Conditions	Treatment Effect	Reference
Grape skin, stem, seed	Polyphenols, anthocyanins	3 kV/cm, 30 pulses, 10 kJ/kg, 15 s, 2 Hz	Polyphenols: 75% increase when combined with US Anthocyanins: 77% increase compared to conventional extraction, 88% compared to US, 25% compared to HHP	[65]
Plum and grape peels	Polyphenols, flavonoids, anthocyanins	I: 25 kV, 6 µs pulse, 10 Hz, flow 290 L/h, 25 mm chamber diameter II: 25 kV, 6 µs pulse, 10 Hz, flow 290 L/h, 7 mm chamber diameter	I: 205% increase in polyphenols, 80% increase in flavonoids, 300% increase in anthocyanins	[66]
Grape stems	Polyphenols and volatile compounds	1 kV/cm, 1 ms pulse, 1 Hz, 30 min	PEF combined with US led to TPC 17% increase (methanol 50%), 35% increase (water), volatile compounds 234% increase	[67]
White grape pomace	Polyphenols, flavonoids	3.8 kV/cm, 10 kJ/kg	8% increase in TPC, 31% in flavonoids, 36% increase in antioxidant power compared to control extraction	[68]
White grape seeds	Polyphenols, tocochromanols, linoleic acid	SC-CO_2-assisted PEF: I: 5 kV/cm, 120 Hz, 5 min, flow rate 45 g CO_2/min, 45 °C II: 5 kV/cm, 120 Hz, 1 min, flow rate 45 g CO_2/min, 45 °C	I: 38% increase in sterols, 31% in *trans*-resveratrol, 165% in gallic acid	[69]
Exhausted grape marc	Lipidic and glycosylated compounds	SC-CO_2-assisted PEF: 3 kV/cm, 100 kJ/kg, 2 Hz, 100 ms pulse duration, 15 MPa, flow 25 mL/min, 1 h duration	14% and 28% increase in liquid fraction, 41% and 95% increase in ORAC	[70]
Red grape pomace	Polyphenols, flavonoids, tannins, anthocyanins	4.6 kV/cm, 20 kJ/kg, 300 min, ethanol 50%	8% increase in TPC, 31% in flavonoids, and 36% in FRAP, all compared to the control extraction	[71]
Orange peels	Polyphenols, flavonoids	1-3-5-7 kV/cm, 60 µs,	20%, 129%, 153%, and 159% increase in TPC, 51%, 94%, 148%, and 192% increase in antioxidant capacity	[75]
Orange peels	Polyphenols, ascorbic acid, carotenoids	1 kV/cm, 10 s pulse duration, 1000 Hz	PEF increased the yields from all the targeted compounds except for ascorbic acid, which was increased only by US	[77]
Orange peels	Polymethoxy flavones	3 kV/cm, 15 kJ/kg, 10 kV,	PEF-assisted high hydrostatic pressure extraction was the optimal condition; 15 out of 57 recognized metabolites were present in significant amounts	[78]

Table 1. *Cont.*

Type of By-Product	Target Bioactive	PEF Conditions	Treatment Effect	Reference
Lemon peels	Polyphenols	7 kV/cm, 30 pulses of 3 μs,	60% increase in TPC, 300% increase in hesperidin and eriocitrin	[82]
Satsuma mandarin peels	Hesperidin, narrirutin	PEF-assisted subcritical water extraction, 3 kV/cm for 60 and 120 s	At 120 s PEF treatment, 22.1% and 33.6% increase was observed in hesperidin and narirutin, respectively	[83]
Olive kernels	Polyphenols	13.3 kV/cm, 10 μs pulse duration, 109 kJ/kg, 10 Hz	HVED was proved a more favorable technique than PEF and US	[84]
Olive leaves	Polyphenols	1 kV/cm, 10 μs pulse duration, extraction time 30 min in an aqueous ethanol solution	31.85% increase in TPC	[86]
Olive leaves	Polyphenols	Optimization of previous study, 0.85 kV/cm, 2 μs pulse duration, 100 μs duration, 15 min extraction duration, 25% *v*/*v* ethanol	38% increase in TPC under optimum conditions	[87]
Blueberry juice and press cake	Polyphenols and anthocyanins	5 kV/cm, 10 kJ/kg	79 and 106% increase in TPC and TA, respectively	[91]
Blueberry pomace and juice	Anthocyanins	20 kV/cm, 10 pulses, 60% ethanol with 0.1% hydrochloric acid, 15 min extraction duration at room temperature	PEF pretreatment demonstrated higher TA values than US in lower temperature and extraction duration	[92]
Blueberry press cake	Anthocyanins	3 kV/cm, 10 kJ/kg	55% increase in TA, 36 and 41% increase in FRAP and DPPH values, respectively	[93]
Cherry press cake	Anthocyanins and antioxidant power	1 kV/cm	40% juice output increase, 80% increase in TA, 27% in antioxidant power	[94]
Freshly thinned peach by-products	Polyphenols and flavonoids	5 kV/cm, 3 μs pulse duration	80% methanol, 35 °C, and no PEF treatment were the optimal conditions, yielding 57% scavenging activity and higher TPC and TFC values	[95]
Frozen and dried peach pomace	Polyphenols	0.8–10 kV/cm, 0.0014–2.88 kJ/kg, 4–30 pulses, 4 μs pulse duration, 0.1 Hz	In low energy input (0.06 kJ/kg), PEF increased 81.86% the TPC yield of frozen pomace	[96]
Apricot kernels defatted biomass	Polyphenols	1 kV/cm, 10 μs pulse duration, 1000 μs frequency, 15 min treatment duration, solvents were water and DES glycerol:choline chloride 2:1 *w*/*w*	The combination of DES and PEF pretreatment yielded a 173% TPC increase	[97]
Almond hull	Lipids, carbohydrates, and antioxidants	3 kV/cm, 100 kJ/kg, 100 ms pulse duration, 2 Hz	77% increase in antioxidant activity and 20% for TPC	[98]

Table 1. *Cont.*

Type of By-Product	Target Bioactive	PEF Conditions	Treatment Effect	Reference
Quince peels	Bioactive compounds	1 kV/cm, 10 µs pulse duration, 1ms pulse period, 1000 Hz	PEF did not maximize the bioactive compounds yield, but it enhanced the DPPH radical scavenging value, increasing the antioxidant activity of the extract	[99]
Papaya peels	Nutraceuticals and antioxidant compounds	Comparison of PEF and HVED, pH ranging from 2.5 to 11, temperature from 20 °C to 60 °C	Optimal conditions were PEF pretreatment, pH value 7, temperature 50 °C, and extraction time 45 min	[100]
Mango peels	Bioactive compounds	Two-stage PEF, 13.3 kV/cm and 40 kV/cm	400% TPC yield increase	[101]
Pomegranate peels	Polyphenols, flavonoids, and tannins	10 kV/cm, 90–10 kJ/kg, 0.29 kJ	PEF TPC yield was 168.97% higher than US, 387.5% higher than IR, but 15.22% lower than HVED	[102]
Custard apple leaves	Bioactive compounds	6 kV/cm, 142 kJ/kg, 300 pulses, 5 min treatment duration	5.2% increase in extraction yield	[103]
Jackfruit waste	Pectin	PEF-MAE 10 kV/cm, 4 min treatment duration	18% increase in pectin extraction	[104]
White mulberry leaves	Bioactive compounds	10 kV/cm, 1 µs pulse width, 5 Hz, 20 min treatment, 95% *v*/*v* ethanol, 20 min duration	40% increase in TPC, 14% in DPPH radical scavenging, 20% in ABTS scavenging, 30% in FRAP	[105]
Tomato peel and pulp	Carotenoids	5 kV/cm, 90 µs duration,	39% increase in carotenoids extracted from tomato peels	[106]
Tomato peels	Lycopene	5 kV/cm, 5 kJ/kg,	12–18% increase in lycopene, acetone as a solvent yielded a higher recovery than ethyl lactate	[107]
Tomato industrial processing residues	Lycopene	1 kV/cm, 7.5 ms duration	45% increase in lycopene recovery	[108]
Tomato peels	Lycopene	Utilization of PEF, MAE, UAE, MUAE, UPAE	UPAE showed 3.56% lycopene yield and 87.09% DPPH value	[109]
Potato peels	Steroidal alkaloids	0.75 kV/cm, 600 µs treatment duration	99.9% increase compared to untreated samples	[114]
Potato peels	Polyphenols	5 kV/cm, 10 kJ/kg,	10% increase in TPC yield and 9% in antioxidant activity	[115]
Carrot pomace	β-carotene	0.6 kV/cm, 20 µs pulse width, 3 ms treatment duration, 5 Hz	The application of PEF treatment enhanced the extractability of β-carotene in carrot pomace (19.6 µg/g) compared to the untreated samples	[116]
Corn silk	Polysaccharides	30 kV/cm, 6 µs pulse duration	2.36% increase of polysaccharides	[117]

Table 1. *Cont.*

Type of By-Product	Target Bioactive	PEF Conditions	Treatment Effect	Reference
Onion skin	Quercetin	2.5 kV/cm, 15 s treatment duration, and 145 °C for 15 min	31% increase in quercetin yield	[118]
Asparagus roots	Polyphenols and flavonoids	1.6 kV/cm, 20 µs pulse width, 200 Hz	23% extraction yield increase, 5%, 6%, 60%, and 4% increase in TPC, TFC, DPPH radical scavenging, and FRAP yields, respectively, and 11% decrease in ORAC yield	[119]
Chicory roots	Inulin	0.6 kV/cm, 100–500 pulses, 50 ms treatment duration	4.34% increase in the yield of juice extract at 80 °C, 100% increase in the yield of pulp at 30 °C	[120]
Cocoa bean shell and coffee silver skin	Polyphenols	1.74 kV/cm, 991.27 pulses, 11.99 µs treatment duration	20 and 21.3% increase in cocoa bean shell and coffee silver skin, respectively	[122]
Coffee parchment and pulp	Polyphenols	6 kV/cm, 5 Hz, 5 min treatment duration	MAE and PEF yielded 64% increase in polyphenols and 92% increase in flavonoid quantities	[123]
Vanilla pods, cocoa bean shells, vermouth mixture, and orange peels	Vanillin, theobromine, caffeine, linalool, and limonene	3 kV/cm, 20 kJ/kg for vanilla pods and cocoa bean shells, 3 kV/cm and 15 kJ/kg for vermouth mixture, 5 kV/cm and 40 kJ/kg for orange peels, ethanol-water, and propylene glycol as two different solvents	In ethanolic extracts, there was a 14% increase in vanillin, 25% in theobromine, 34% in caffeine, 144% in linalool, and 33% in limonene	[124]
Rapeseed stem and leaves	Proteins and polyphenols	5 kV/cm, 6.4 kJ/kg	52% increase in TPC yield	[125]
Drumstick tree leaves	Polyphenols	7 kV/cm, 20 ms pulse duration, 100 µs pulse interval	45% increase in TPC yield	[126]
Flaxseed hulls	Polyphenols	20 kV/cm, 300 kJ/kg, 10 ms treatment duration, 0.3 M sodium hydroxide as solvent	400% increase in TPC yield	[127]
Sage leaves	Phytochemicals	1 kV/cm, 100 µs pulse duration, 30 min treatment duration, 25% *v*/*v* aqueous ethanol	73.2 and 403.1% increase in polyphenols and rosmarinic acid yield, respectively	[128]
Rosemary and thyme stems and leaves	Polyphenols	1.1 kV/cm, 167 bipolar pulses, 30 µs pulse duration	Rosemary leaves: PEF combined with US showed 650% increase in TPC yield compared to only PEF Thyme leaves: PEF combined with US 700% increase in TPC yield compared to only PEF	[129]

Table 1. *Cont.*

Type of By-Product	Target Bioactive	PEF Conditions	Treatment Effect	Reference
Fishery by-products	Bioactive compounds	1–3 kV/cm, 300 kJ/kg, 15 to 24 h treatment duration	80% increase in protein extraction, 26% increase in ABTS for PEF treatment, ASE was proved a more efficient pre-treatment technique in general	[131]
Shrimp by-products	Astaxanthin	3 kV/cm, 100 kJ/kg, 74 pulses, DMSO	PEF and ASE yielded 150% and 200% increases compared to control in astaxanthin content at *M. cerathurus* and *A. antennatus*, respectively	[132]

4. Conclusions and Future Perspectives

This review aimed to assess the effectiveness of PEF as an extraction technique and to compare its outcomes with those of other extraction techniques in order to determine whether it offers superior performance. PEF technology recovers bioactive compounds, including polyphenols, pigments, and macronutrients, from food processing wastes utilizing low-energy and concentrated solvents. It may also be used to recycle waste products from various food processing industries. The primary problem with PEF applications is that the efficacy of the treatment can be affected by PEF device parameters and external factors such as conductivity, pH, and the concentration of the treated solution. Until definitive pathways are established, further investigation into the thermal, chemical, and biophysical effects of PEF on protein structures is necessary. It is also critical that authors supply all necessary experimental details so that similar studies can be carried out and outcomes can be compared. Furthermore, more research is required to clarify the clinical implications. Additionally, researchers are investigating the influence of integrating these techniques on a variety of dietary components. To maximize the extraction of bioactive compounds from wasted spices and oilseed residues, it would be beneficial to optimize PEF treatment conditions. Similarly, PEF technology can be used to isolate bioactive compounds in the wastewater from industries engaged in the processing of dairy products, meat, and seafood, thereby enabling these sectors to economically valorize their wastewater. In order to evaluate the safety and quality of the extracts, it would be helpful to conduct in-depth research into how PEF technology affects the extract's color, pH, conductivity, mineral content, and in vitro protein digestibility. A comprehensive study on the effects of PEF would be useful for consumers and food companies, and the technology can be expanded to valorize wastes from the production of dairy, spices, and condiments.

There are still numerous obstacles in the PEF pretreatment technique that should be overcome in the future. The extraction mechanisms of PEF should be verified, and models of extraction kinetics should be developed and tested. A better understanding of the mechanism and the development of a scientific model of mass transfer are required for its future practical application. PEF continuous extraction technology has been improved in design. Further study is needed to optimize the geometry of PEF treatment chambers and scale up the extraction technology for use in industrial settings. The continuous PEF is commonly executed on a laboratory scale with high efficacy. The ongoing development of the extraction system will enhance its suitability for industrial applications. The anticipation is that in the future, continuous PEF will be a competitive technique in the extraction of bioactive compounds. The application of PEF on fruits has resulted in a significant increase in juice yield. However, it is important to note that the use of PEF has also led to a decline in the quality of fruit juices due to the release of enzymes that affected their overall quality. Likewise, in the context of oilseeds, the qualitative attributes such as free acidity and peroxide value of the oil were adversely affected, too. Nevertheless, the alterations in these

metrics fell within the established standard thresholds, but these are obstacles that need to be overcome. Further investigation is necessary to expand the knowledge regarding novel functional foods derived from the by-products of food processing. These residues may be promising candidates for the development of new functional foods. As a result, research on novel functional foods from food-processing wastes should continue, with substantial support from the PEF continuous extraction approach.

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