The Potential of Pulsed Electric Field in the Postharvest Process of Fruit and Vegetables: A Comprehensive Perspective.

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REVIEW

The Potential of Pulsed Electric Field in the Postharvest Process of Fruit and Vegetables: A Comprehensive Perspective

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Abstract
Pulsed electric field (PEF) is a novel non-thermal treatment for quality retention of fruits and vegetables (F&V) during postharvest processing. PEF helps to microbial control and retain several attributes such as the physical and chemical of F&V. This review outlines requirements and advances in electrical systems applied in PEF for F&V. In addition, it reviews the effect of PEF application on antioxidant activity, color, texture, weight loss, and other chemical properties affecting the shelf life of F&V. Attention is also drawn to the applicability of PEF technology as a pretreatment to assist design in the case of the emergence of sustainable bio-refineries based on F&V. PEF pretreatment enhances the extraction of valuable bioactive compounds and maintains quality characteristics of F&V which include color, phytochemicals, antioxidant capacity, proteins, volatile compounds, and sensory attributes. Furthermore, the current study highlights that electroporation of the cell membrane by PEF treatment enhances mass transfer during the drying and moisture loss processes of F&V. In this context, the extraordinary rapidity of treatment applications leads to considerable reductions in processing time and total energy consumption concerning traditional methods. The adaptability and scalability of PEF secure its application in sizes varying from small-scale operations driven by supermarket demand up to food units. However, PEF has limitations in the postharvest process of F&V due to its potential for the high energy costs associated with the technology. In addition, PEF cannot guarantee the inactivation of all microorganisms, particularly the spores and certain resilient bacterial strains that cause microbial regrowth on storage. Overall, this technology can further increase the yield obtained from extraction and extend shelf life, which is essential for processing facilities and consumers' benefit.

Keywords Non-thermal processing · Waste valorization · Drying · Shelf life · Pulsed electric field

Introduction

The sustainability of the world's food supply has been of great concern to the food industries. Under this scenario, these two sectors give priority to the development of processing technologies that would both preserve and add value to the nutritional quality of fresh fruits and vegetables (F&V) by promoting the presence of bio-accessible compounds (Brito & Silva, 2024). One of the promising non-thermal methods for F&V quality maintenance is the pulsed electric field (PEF) technique. This technology is used to inactivate several microorganisms and enzymes or reduce their activities in agricultural products. It also destroys the cell membranes in the food matrix without adversely affecting the characteristics of the products (Arshad et al., 2021a, 2021b; Giannoglou et al., 2021; Younis et al., 2023).

The success of PEF in the cell membrane permeabilization depends upon (i) process parameters that include electric field strength, treatment time, specific energy, pulse shape, pulse width, frequency, and temperature; (ii) food sample characteristics that include pH and electrical conductivity of the sample; and (iii) characteristics of the target cells, such as size, shape, food matrix or structure

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membrane, and envelope structure (Arshad et al., 2020; Zhang et al., 2023a, 2023b). Recently, engineering aspects of PEF technology and its contribution to quality features of treated products have been well documented in the literature (Li et al., 2021a, 2021b; Moens et al., 2021; Palumbo et al., 2022; Salehi, 2020; Saletnik et al., 2022; Wu et al., 2020; Zhang et al., 2022a, 2022b). However, continued research is directed to enhance the PEF system and its treatment method regarding the physical, mechanical, and chemical properties of F&V through the manipulation of water activity. In F&V, water is essential for microorganism growth and enzymatic reactions (Chang et al., 2023a, 2023b; Zárate-Carbajal et al., 2024). PEF is not just a lethal action of microorganisms but also induces structural modifications that allow these processes to be used in valuable applications, such as waste valorization (Chatzimitakos et al., 2023; Faria & Silva, 2024; Naliyadhara et al., 2022).

Waste valorization is a process with enormous potential, and it is thought to bring an improvement in waste management (Giancaterino et al., 2024a, 2024b; Ramaswamy et al., 2024). PEF has been evidenced to be a valuable tool for the recovery of essential compounds from different fruit pomaces and skins in several studies (Nowacka et al., 2019a, 2019b; Andreou et al., 2020; Wang et al., 2020a, 2020, 2020b; Plazzotta et al., 2021; Shiekh et al., 2021; Macías-Garbett et al., 2022; Theagarajan et al., 2024; Rrucaj et al., 2024). Thus, PEF would be a process that would bring out benefits in terms of extracting value-added compounds. In addition, PEF application would optimize the drying process without nutrient quality loss of foods; due to the electroporation of cell membranes, enhancing mass (e.g., moisture) transfer during drying (Punthi et al., 2022). Researchers have applied PEF pretreatment followed by integrated hot air, vacuum, and freeze drying to food products such as carrots (Alam et al., 2018; Kim et al., 2023; Liu et al., 2020a, 2020b), mushrooms (Dadan et al., 2023; Li et al., 2021a, 2021b), basil leaves (Telfser and Galindo, 2019; Thamkaew & Galindo, 2020), potatoes (Shorstkii et al., 2022), kiwifruit (Llavata et al., 2024), and apple (Matys et al., 2023). These studies further reported that PEF prevents localization of high temperatures in F&V, which can lead to undesirable changes in color, flavor, and nutrition while helping to maintain an acceptable texture. It is reported to soften the tissue by lowering the turgor pressure, leading to textural changes for the ease of subsequent handling, cutting, and peeling (Koch et al., 2022; Moens et al., 2021). PEF-assisted peeling makes it possible to minimize weight loss and reduce chemical consumption and environmental pollution (Kempkes et al., 2017; Koch et al., 2022; Giancaterino and Jaeger, 2023). Thus, PEF-assisted peeling is an optimistic technique for the postharvest processing of F&V.

A number of reviews detailing the application of PEF in the sustainable food industry (Arshad et al., 2021a, 2021b), extraction escalation (Naliyadhara et al., 2022), drying (Punthi et al., 2022), and solid foods processing (Zhang et al., 2023a, 2023b) are available in the literature. However, no review (to the best of our knowledge) exclusively focuses on the potential of PEF in the postharvest process of fresh fruit and vegetables. Therefore, the current review introduces the application of PEF on the shelf life of the F&V and also describes optimum processing operation of PEF treatment of food wastes for waste valorization aims. Furthermore, the effect of PEF on the drying process of F&V and its effect on their chemical compounds, macro/microstructure, and drying kinetics are explained. This review aims to motivate researchers to gather data that is credible, replicable, and free from methodological flaws.

Mechanism

PEF technology treats the food product with short, high-intensity electrical pulses. PEF can be effectively implemented using two electrode plates, with the food material placed between them. This arrangement allows high-voltage pulses to directly act upon the food (Gomez et al., 2019). A typical PEF system comprises a treatment chamber, a high-voltage pulse generator, and a controller (Buchmann et al., 2018). The high-voltage pulse generator utilizes either a direct current power supply or alternating current from the source that is then rectified into a direct current within a particular rectifier stage. The final direct current voltage is stored in a source of capacitors as an energy reservoir. A designed high-voltage switch discharges the capacitor in controlled pulses to deliver the desired electrical treatment (Taha et al., 2022).

The pulses are produced by a high-voltage pulse generator and are targeted toward the electrodes present in the treatment chamber. The food product is placed between the electrodes and treated. Based on two categories of the physical state of the product to be treated, the treatment chamber can be classified into batch or continuous treatment chambers 2. For design of electric chamber, standard methods that affect treatment capacity include parallel, coaxial, and co-linear designs (Ramaswamy et al., 2024). Therefore, the design for the PEF chamber (parallel and co-linear designs) must provide the distribution of the electric field within the treatment area (Arshad et al., 2020).

Compared to parallel and co-linear designs, the parallel design gives the most uniform field with the lowest energy consumption and temperature increase. The co-linear design creates hot spots due to the non-uniformity of the field (Masood et al., 2018). However, the co-linear chambers will have a higher treatment capacity (Arshad et al., 2020). The choice among these designs thus fundamentally depends on the specific requirements and priorities of the application and treatment method (Arshad et al., 2020; Lombergar et al., 2024).

Figure 1a indicates the general electrical configuration of most PEF processing setups that include a treatment chamber, a pulsed power supply, and a control/monitoring system. Figure 1b describes the design steps in numerical order for calculating the process parameters for any particular application or product. The optimization of these parameters can be obtained by keeping a few constants and finding out the rest dependent parameters in this sequence of the figure (Arshad et al., 2020). Work on the development of an optimum treatment protocol is highly relevant to successful process scaling. It will also be helpful in understanding and documentation of research pertaining to this technology. The

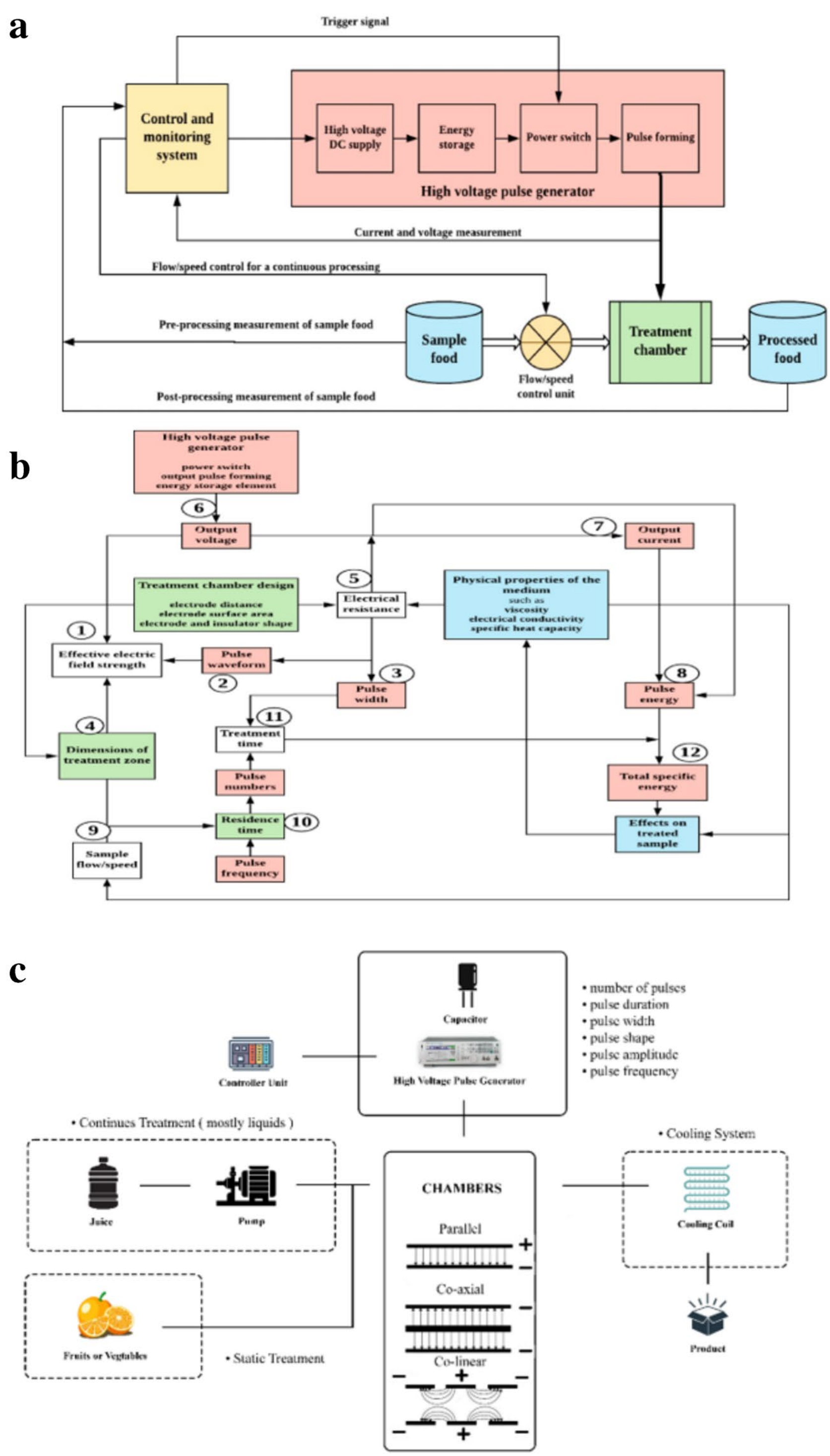

Fig. 1 (**a**) Schematic diagram of a PEF-based F&V processing system. (**b**) Flow chart describes the interdependence of PEF-based food processing parameters associated with each part (Arshad et al., 2020). (**c**) Graphical representation of the PEF process and system setup for F&V products

most common pulse shapes used in food processing with PEF are rectangular, square, exponential, oscillatory, and a combined number of narrow and wide pulse duration pulses (Qin et al., 2022).

Figure 1c illustrates a graphical presentation of PEF system. The pulsed power generator generates high-voltage pulses to the treatment chamber filled with food. A typical such generator would normally include passive discrete components. Power switches are essential apparatus in the process of energy transfer that is stored either in the capacitors or magnetic fields within inductors. Precautions should be made so that the energy transfer occurs cost-effectively, as this is going to have a great impact on the general electrical design (Arshad et al., 2020). Depending on the raw material, the feeding system can be continuous for liquids (here juice) or static (here foods and vegetables). Continuous feeding systems depend on a pump to feed the chamber continuously. Chambers can be linear, coaxial, co-linear (as addressed in most research), or in other shapes depending on desired properties. Finally, a cooling system can be utilized to cool down the final product.

Researchers mainly use the rectangular and exponential decay (ED) waveforms to treat food products (Arshad et al., 2020; Zhang et al., 2018). The waveform can effectively affect electrodes and electrolysis, and high-intensity bipolar pulses may reduce it. It was found out that the non-oscillating exponential impulse presented the best performance in a study (Qin et al., 2022). It can be observed that high-intensity bipolar pulses and non-oscillating exponential impulses can be effective in reducing electrode disappearance and electrolysis during electrical stimulation. Also, there is an inverse relationship between field strength and pulse width. Lower field intensity with a broader pulse width can have similar results to higher field intensity with a narrower pulse width. The pulse width is limited to microseconds due to local thermal effects and oxygen production by electrolysis when the electric field is high (Guionet et al., 2015; Timmermans et al., 2019). Timmermans et al. (2019) found that more long pulses were efficient in comparison to shorter pulses and also should heed to the chamber design.

The treatment chamber design is a key to realizing uniformity in the electric field distribution. Several chamber designs are beneficial concerning efficiency and temperature control. However, careful consideration must be taken to realize optimum treatment results and avoid issues such as electrode disappearance and electrolysis. It is equally essential that parameters such as pulse width, pulse shape, and pulse frequency be optimized such that the efficacy and economic feasibility of PEF treatment are related (Arshad et al., 2020; Lombergar et al., 2024). Qin et al. (2022) have proposed a PEF chamber, with BaTiO3 dielectric layers included, for the chamber to be released from electrode corrosion and work effectively. They observed that the chamber with dielectric layers successfully limited the generated iron ion in the treated yeast suspension compared with a standard chamber. Several pulse electric field setups from the literature are shown in Fig. 2.

Researchers mostly utilized cylindrical chambers for PEF treatment of the samples in liquid media. Koubaa et al. (2016) utilized a cylindrical batch treatment chamber, and two parallel stainless electrodes for the treatment of pears in a liquid solution. Most of the setups for F&V are static and consist of two parallel electrodes as the chamber (Fig. 2a). Chang et al., (2023a, 2023b) used chambers consisting of two copper plate electrodes; the setup was not protected from the air (Fig. 2c) and Chen et al. (2022) setup consisting of parallel copper electrode chambers combined with a refrigerator (Fig. 3b). The static setup with two parallel electrodes is very commonly used in treating fruits and fresh slices of it due to its simple and economic characteristics. In addition, PEF treatments coupled with refrigeration showed an innovative approach to maintaining the quality of the samples which need to be cooled throughout the treatment process. Astráin-Redín et al. (2023) used a cylindrical PEF chamber with parallel electrodes for the treatment of the carrots (Fig. 2d) and Yamakage et al. (2021) treated spinach samples between plate electrodes (Fig. 2e). Chambers with parallel electrodes are usually considered most effective in uniform electric field distribution and uniform treatment (Masood et al., 2018). Indeed, it can adapt different electrode setups to the specific features of each vegetable under treatment, ensuring effective contact and optimal PEF delivery. Such adaptability renders PEF technology versatile in food processing; hence, one should be very careful while choosing the chamber and the configuration of electrodes. Parniakov et al. (2016a) setup consists of two round electrodes for the treatment of the apple tissues (Fig. 2f). Generally, the application of PEF treatment for foods has been tested with multiple setups and configurations to obtain the best treatment effectiveness. The setup is optimized to achieve a good balance between, for example, electric field distribution, sample integrity, and process efficiency. Continuous innovation of setup design is also further needed to keep expanding the application of PEF technology within a wide variety of food matrices.

Shelf Life

PEF pretreatment enhances the shelf life of F&V by disrupting cell membranes, which reduces microbial load and enzymatic activity while preserving nutritional and sensory qualities. This non-thermal technology is particularly effective as a pre-processing step, extending freshness and improving the efficiency of subsequent preservation methods. Changes in physical and chemical properties provoke changes in the F&V appearance and quality. Treatment is expected to extend shelf

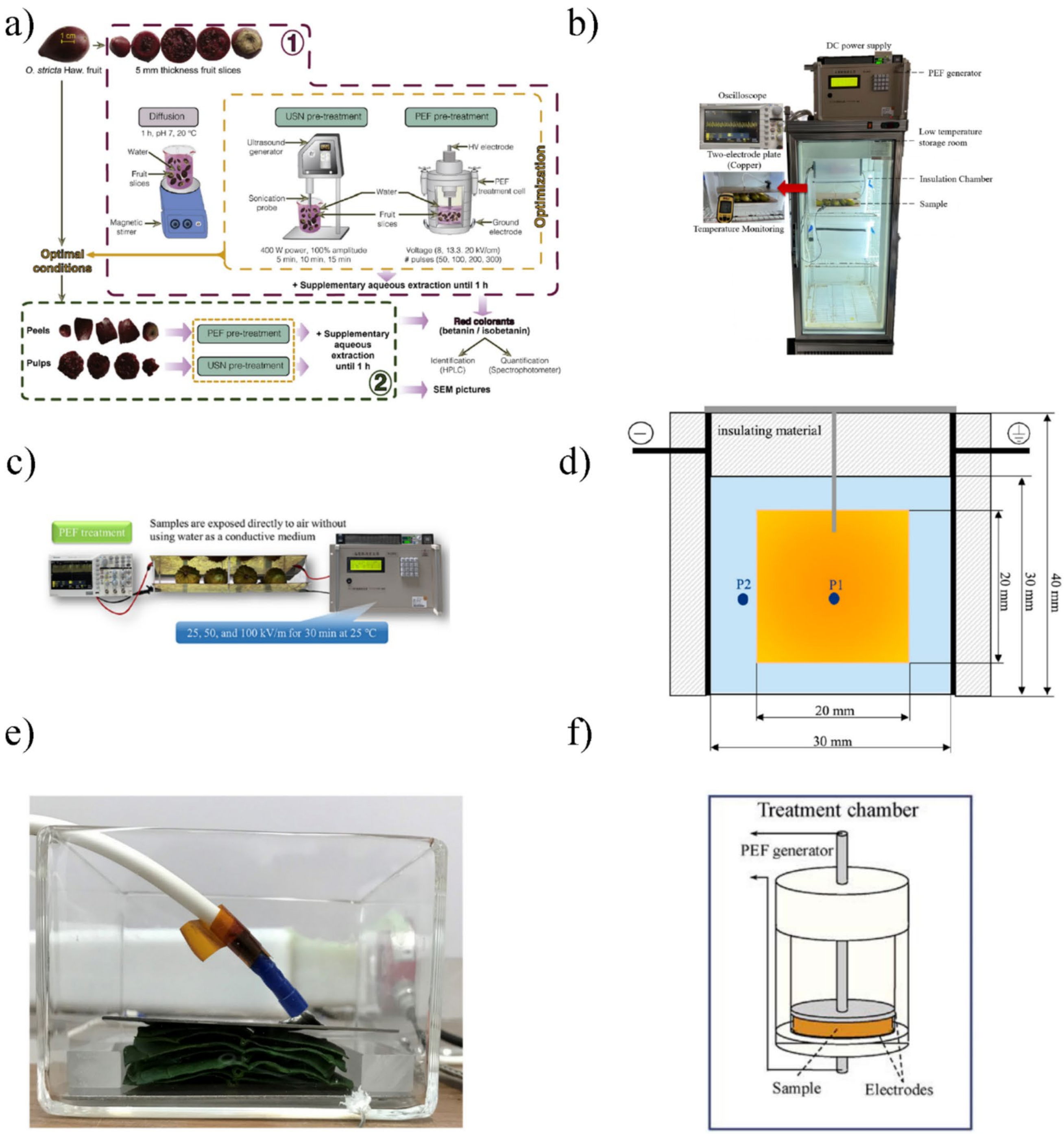

Fig. 2 (**a**) Experimental setup of PEF and fusion by other non-thermal systems (Koubaa et al., 2016, (**b**) PEF processing system and storage device (Chen et al., 2022). (**c**) The process of PEF processing Atemoya (Chang et al., 2023a, 2023b). (**d**) Schematic of a longitudinal section of the treatment chamber together with the carrot sample during application of the PEF treatment. P1 and P2 refer to the area where the carrot and treatment medium temperature were measured, respectively (Astráin-Redín et al., 2023). (**e**) Picture of reactor in PEF system (Yamakage et al., 2021). (**f**) The scheme of PEF-assisted vacuum cooling (Parniakov et al., 2016a, 2016b)

life and retain F&V properties during storage (Arshad et al., 2021a, 2021b). Using PEF as a non-thermal way of inhibiting microorganisms leads to the retention of several physical and chemical attributes of the F&V (Guo et al., 2022). Several results have indicated the efficiency of PEF on the antioxidant, color, texture, weight loss, and other chemical properties that are responsible for the shelf life of the F&V.

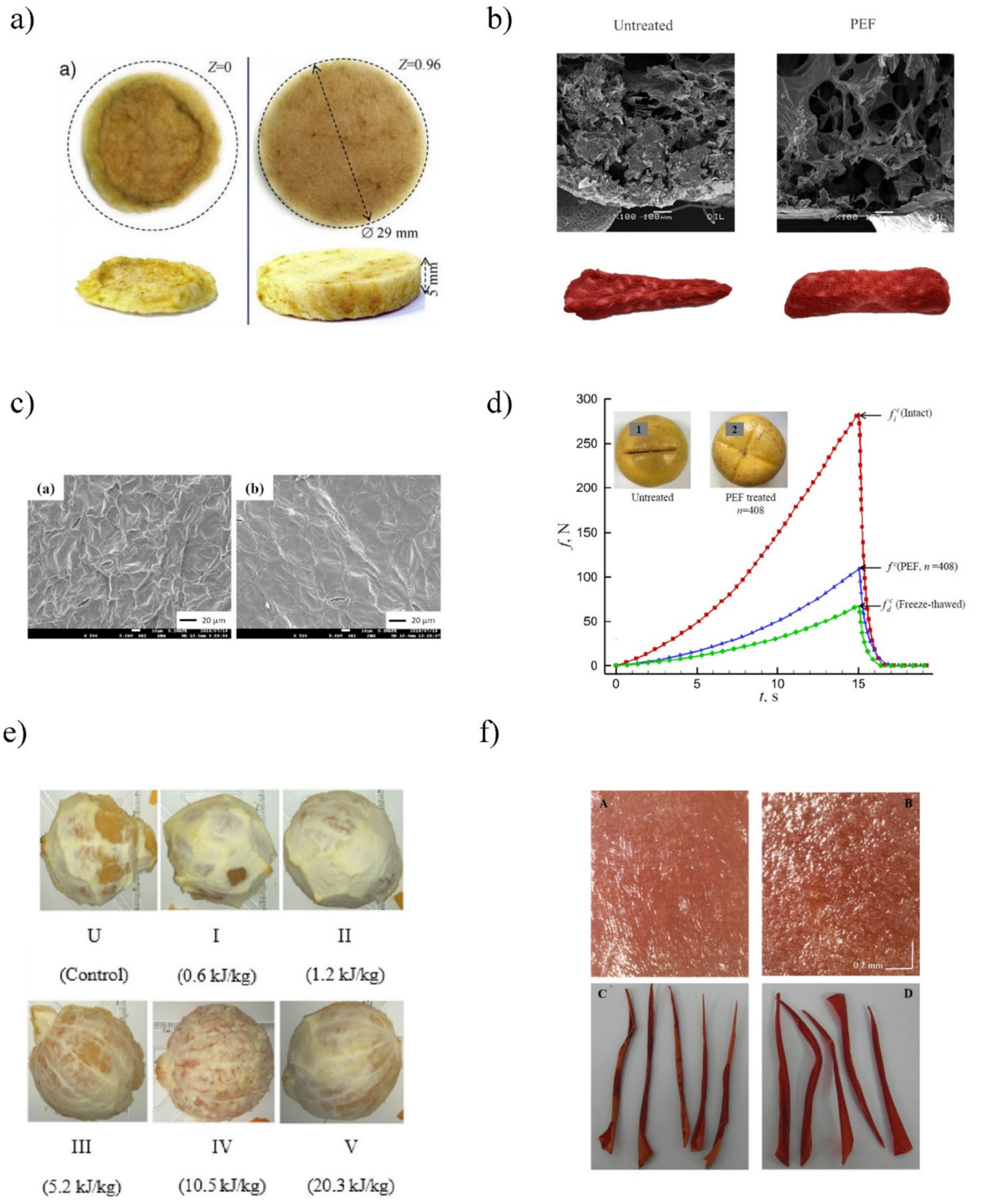

Fig. 3 Application of PEF on the **a** microstructures of the surface of dried samples (Yamakage et al., 2021). (**b**) Macroscopic photos of untreated and treated samples (Parniakov et al., 2016a, 2016b). (**c**) Homogeneous surface color of red pepper (Won et al., 2015). (**d**) Albedo residues of oranges (Koch et al., 2022). (**e**) Chemical properties of the sample (Bobinaitė et al., 2015). (**f**) Force versus the time for the cutting tests of pomelo whole fruit (El Kantar et al., 2018)

Antioxidant Properties

Researchers have discovered the PEF technology to be effective in maximizing the beneficial health effects such as the antioxidant properties (Souli et al., 2023; Liu et al., 2024a, 2024b). Antioxidants enhance well-being by scavenging the reactive substances that could cause adverse metabolic effects. The extraordinarily high levels of detrimental free radicals and reactive oxygen species (ROS) indicate that raising the concentrations of antioxidants may reduce chronic disease risks (Morales-De la Peña et al., 2021; Ali et al., 2024).

Research reported an increase in the antioxidant capacity of apples after PEF treatment applied 0.4–2 kV cm^{-1} (0.008–1.3 kJ kg − 1) as total specific energy input to the apple samples. A significant increase in antioxidant activity, by 43%, was obtained at 0.008 kJ kg^{-1} energy level after 12 h of storage at 4 °C, in comparison with untreated samples and other energy level treatments, and 15% after 24 h at 22 °C. The same tendency was observed for phenolic content: at an energy level of 0.008 kJ kg^{-1}, the optimum increment in total phenolics was reached after 24 h in storage at 22 °C, by 13% (Soliva-Fortuny et al., 2017). Similarly, Giannoglou et al. (2021) showed a rapid rise in phenolic content, which results in the release of antioxidant compounds after pulsed electric medium field (PEMF) treatment at 240 V, 96 J per pulse, 300 MHz. Researchers reported an increased amount of phenolic content in samples treated with PEMF and stored for 14 days. Both studies noticed an increase in phenolic content after applying the respective treatments and also low electric fields and pulsed electromagnetic fields seem to be effective. Although the initial rise could be immediate, enhanced phenolic content appears to be maintained over long storage periods.

The browning index is a critical quality parameter for evaluating food products, as it quantifies color changes that may result from enzymatic or non-enzymatic browning reactions. Studies have demonstrated a positive correlation between the antioxidant potential of fruits and vegetables and their contents of vitamin C and phenolic compounds, including phenolic acids and flavonoids (Dermesonlouoglou et al., 2018; Li et al., 2023a, 2023b, 2023c). Chen et al. (2022) examined the effects of pulsed electric fields (PEF) on the phenolic compounds of atemoya fruit during extended storage and observed a decline in total phenolic compounds in untreated samples. In contrast, PEF treatment enhanced the antioxidant content and nutritional value of fruits and vegetables. Nevertheless, further investigation into the underlying mechanisms and the optimization of PEF parameters for different food matrices is necessary. Additionally, comprehensive long-term studies are crucial to assess the efficacy of PEF in boosting antioxidant capacity and its synergistic potential with other preservation methods.

Textural Impact

Texture analysis reveals the firmness of fruits and vegetables, which is a crucial factor in their resistance to mechanical impacts. PEF destroys the cell membranes, through which the cell sap runs out and reduces the turgor pressure, hence the initial softening of the fruit (Giancaterino & Jaeger, 2023; Koch et al., 2022). In addition, activation of enzymes, including pectinases and cellulases, by PEF treatment degrades cell wall components and thus causes softening (Li et al., 2023a, 2023b, 2023c).

The firmness level can be controlled by being very sensitive to the intensity, time, and frequency of electric pulses. Chen et al. (2022) studied PEF treatment of bananas after storage for 20 days. The peel toughness increased during storage, registering the highest value on the 10th day after PEF treatment. Firmness of the PEF-treated group was significantly lower than that of the untreated group throughout the storage period. Chen et al. (2022) treated atemoya fruit using optimized PEF system with different energy 25, 50, and 100 kV/m and they reported the moderate PEF treatment leads to a lower firmness loss. In contrast, Giannoglou et al. (2021) and Li et al., (2023a, 2023b, 2023c) assessed firmness of strawberries and apple under PEF treatment. Both of them reported there were no significant differences in firmness between the tested and control samples during the storage time. The effect of PEF on food firmness had a different inflection from the leveraged perspective, as indicated by the contradictory inducible responses to PEF found in various studies. While in treatment with PEF-softened potato samples, no effect on firmness was observed in apples (Li et al., 2023a, 2023b, 2023c).

The color of F&V is an appearance characteristic of their quality for consumers and can indicate underlying chemical changes. Color is influenced by several factors, including the antioxidants they contain. The browning index (BI) is used to measure overall color changes and reflects brown color purity in the presence of sugar-content food samples. Enzymatic browning could be measured by biochemical indices such as polyphenol oxidase activity or physical indices, including surface color.

Since some phenolic compounds are color contributors of a fruit, color change measurements can provide information on a quantitative level of the amount of the phenolic under PEF treatments. Chen et al. (2022) showed the optimal properties for reducing browning in bananas were 32 kV m^{-1}, frequency 278 Hz, treatment time 32 min, and width 600 µs, inhibiting the degree of browning by 131.6%. During storage at 7 °C for 20 days, PEF treatment showed a better performance of postponing browning by about 5 days. The obtained findings revealed that the PEF pretreatment offered a promising rise in lightness of kiwifruits and also showed the fastest speed of color shifting among other properties utilized.

Li et al., (2023a, 2023b, 2023c) and Chen et al. (2022) confirmed that PEF-treated samples had a slower increase in the browning index compared with the untreated control sample during the storage time at various temperatures. They claimed that PEF can delay browning on the F&V and 50 kV/m treatment was the most effective, reducing the browning index considerably compared to the untreated group.

Weight Loss

There are some doubts about the effect of PEF on weight loss. On the one hand, some researchers reported that the PEF treatment can reduce microbial activity with less breakdown of the produce and, consequently, less weight loss during storage (Chang et al., 2023a, 2023b; Dadan et al., 2020; Li et al., 2023a, 2023b, 2023c; Lin et al., 2024). Li et al., (2023a, 2023b, 2023c) observed a 15% reduction in weight loss during 10 days of storage at 4 °C in five different apple variety samples. Similarly, Chen et al. (2022) investigated weight loss of PEF-treated bananas (with various properties) compared to untreated samples. The samples were stored at 7 c for 20 days. During the first 5 days, no significant difference was observed. However, after 10 days, the treated sample retained their weight better than the control samples.

On the other hand, some researchers claimed PEF causes structural changes in F&V, which might lead to shrinkage and weight loss (Rahaman et al., 2019; Trusinska et al., 2023; Wu et al., 2020). Giannoglou et al. (2021) investigated the effect of PEF on quality attributes of strawberry storage at various temperature levels as observed in the weight loss of strawberries significantly increased with storage time and temperature during the storage period. Although the results obtained highlighted the potential for the prevention of weight loss in some F&V, more research is required to ascertain the desired inactivation mechanism and to investigate the applicable tune-in of various F&V.

PEF treatment creates short bursts of high-voltage electric fields, permeating cell membranes. It has several effects on F&V enzymes, including polyphenol oxidase. PPO is an enzyme that causes fruits to go brown when cut or damaged. In this way, PEF application can inactivate PPO, hence lowering enzymatic browning in fruit. This maintains the color, flavor, and nutritional quality of the fruit (Evrendilek & Özkan, 2024; Li et al., 2023a, 2023b, 2023c; Liu et al., 2024a, 2024b).

The effect of different PEF treatments on the PPO during storage time in apples has been evaluated by Li et al., (2023a, 2023b, 2023c). PEF-treated groups maintained PPO activity significantly lower than control during storage, reflecting the effectiveness of the inactivation of the PPO enzyme. The significant effect of PEF treatment on the modulation of PPO activity was confirmed again using storage. Almost the same results were gotten in another experiment on similar products. The results show that the POD activity of PEF treatment during storage is significantly less than in the control group. Although the POD activity of all PEF groups is lower, the group 3 kV/cm has the most pronounced effect. These findings confirmed PEF as a feasible approach to reduce browning reactions in apples by decreasing both PPO and POD activity. It seems that PEF decreases PPO and POD activity by inducing structural changes in these enzymes, which can lead to their inactivation or reduced functionality during storage. Additionally, PEF treatment disrupts cellular integrity, limiting the interaction between enzymes like PPO and POD with their substrates, thereby reducing the enzymatic browning reactions in apples.

Also, the permeability of cell membranes in F&V can lead to an increase in the measured total soluble solid (TSS). Younis et al. (2023) evaluated the effect of PEF treatment on the TSS of Barhi dates. At first, as more intense PEF and exposure time, TSS decreased, maybe due to enzyme inactivation or water loss. At the highest PEF settings, however, this trend reversed. In contrast, a further increase in the number of pulses during the process with PEF treatment raised TSS to a critical value, after which TSS decreased. These results indicate that PEF parameters have to be well chosen to obtain the desired TSS reduction in Barhi dates during storage. Although the PEF treatment appears to be effective in reducing enzymatic browning in some F&V, the underlying mechanisms need more study. Similarly, the effects of PEF on the chemical properties were complex. Table 1 summarizes the performed research to assess the application of PEF treatment on the shelf life parameters of the various F&V.

Waste Valorization

PEF pretreatment facilitates waste valorization of F&V by enhancing the extraction of valuable bioactive compounds, such as polyphenols, antioxidants, and pigments, from by-products. This energy-efficient, non-thermal technology optimizes the recovery of high-value components from waste streams, contributing to sustainable processing and circular economy practices. In the pursuit of deriving end products from F&V, various components such as trimmings, peels, seeds, unused flesh, shells, leaves, and stems often end up being discarded as waste (Jara-Quijada et al., 2023; Okuthe, 2024). The primary sources of food waste are predominantly the by-products generated during the production of oil, starch, sugar, and juice. The prevalence of this type of practice carries a big challenge, especially in the era of modern industrial processing, for the requirements of sustainable development and environmental protection. These essential components have great potential to be removed from food waste and applied later in postharvest processing because of their significant biological activities (Arshad et al., 2021a, 2021b; Zhang et al., 2023a, 2023b). Various non-thermal

Table 1 Potential of PEF on the shelf life of various F&V

Product	Treatment process	Assessed parameters	Effect on the shelf life	Reference
Apple	0.008–1.3 kJ kg^{-1}	Total phenolic content, flavonoid, and flavan-3-ol content, antioxidant capacity	The antioxidant was increased. Antioxidant capacity of apples was with enhanced by 43% respect to that of untreated with the mildest PEF treatment after 12 h at 4 °C and by 15% after 24 h at 22 °C	Soliva-Fortuny et al. (2017)
	i) 0.4 kV cm^{-1}, 5 pulses (0.01 kJ kg^{-1}, 20 µs total treatment time); ii) 2.0 kV cm^{-1}, 35 pulses (1.8 kJ kg^{-1}, 140 µs total treatment time), and iii) 3.0 kV cm^{-1}, 65 pulses (7.3 kJ kg^{-1}, 260 µs total treatment time)	Total phenolic, flavonoid and flavan-3-ol contents, antioxidant capacity, color, firmness, solid soluble	PEF induced important quality changes, mainly discoloration and firmness loss, while overall phenolic contents decreased, except those of flavonols. Total phenolics and total flavan-3-ols contents increased	Ribas-Agustí et al. (2019)
	1, 3, 5 kV/cm, 200 µs, 500 Hz	PPO activity, POD activity	Enzymatic activity related to browning was reduced. Fruit quality and appearance were maintained. Shelf life was enhanced by inhibiting enzymatic browning reactions	Li et al., (2023a, 2023b, 2023c)
Carrot	5 pulses of 350 kV m^{-1} (580 ± 80 J kg^{-1})	Respiratory, pectinmethylesterase, polygalacturonase, polyphenol oxidase, peroxidase, and phenylalanine ammonia-lyase activities	Production of volatile compounds and more CO2 during storage was promoted. Activity of the key enzyme involved in phenolic biosynthesis was increased. Pectinmethylesterase was increased and polygalacturonase was decreased	López-Gámez et al. (2020)
Mushroom	50 Hz	Firmness, malondialdehyde and total phenolic content, enzymes activity, and polyphenol oxidase	Significantly prevented the accumulation of malondialdehyde (MDA), delayed loss of total phenolic, enhanced the superoxide dismutase (SOD) and catalase (CAT) activity, and had the better microstructure	Yan et al. (2020)
	600 kV/m, 50 Hz, 120 min	Browning, electrolyte leakage, malondialdehyde, total phenolic content, activity of polyphenol oxidase and lipoxygenase	Browning of oyster mushrooms was reduced by 40% after 12 days of storage, and the effect was closely related to the inactivation of polyphenol oxidase, the delay of electrolyte leakage, and lower malondialdehyde levels	Hsieh et al. (2020)
Tomato	40, 120, and 200 kV m^{-1} and number of pulses: 5, 18, and 30 pulses	Respiratory activity, total carotenoids, lycopene, lipophilic antioxidant capacity, color, firmness, pH, soluble solids	Antioxidant and carotenoid content was increased. Respiratory activity was differently influenced depending on the PEF conditions and PEF affected the physico-chemical quality of tomato fruit	González-Casado et al. (2018)
Potato	50 Hz, 0.2 to 1.1 kV/cm, 1 to 10 kJ/kg	Ion leakage, cell viability, microstructure,	PEF induced cellular damage leading to ion loss and subsequent loss of cell turgor	Faridnia et al. (2015)
Banana	25, 50, 75, 100, 150, 200, and 250 kV m^{-1} (fixed width, frequency, and treatment time of 600 µs, 50 Hz, and 30 min	Weight loss, firmness	Degradation was reduced compared to untreated. The texture and firmness were improved	Chen et al. (2022)

Table 1 (continued)

Product	Treatment process	Assessed parameters	Effect on the shelf life	Reference
Atemoya	25, 50, 100 kV/m	Browning index, firmness	Browning time compared to untreated was delayed. PEF-treated groups maintained a better visual appearance. The firmness retention was improved	Chen et al., 2022
Strawberries	240 V, 96 J per pulse, 300 MHz	Phenolic content, color stability	antioxidant capacity was increased. Color stability and phenolic retention were improved and led to prolonged freshness and quality retention	Giannoglou et al. (2021)
Blueberries	2 kV/cm 1 µs pulse width, and 100 pulses per second for 2, 4, and 6 min	Native microbiota and artificially inoculated *Escherichia coli* K12 and *Listeria innocua* populations, color, texture, anthocyanins, and total phenolic compound concentrations	Up to 3 log reduction of *E. coli* and *Listeria* as well as 2 log/g reduction of native microbiota. PEF treatments did not cause any changes in color and appearance of the blueberries. Cause the blueberries to soften in texture. Anthocyanins and phenolic compounds in blueberries increased by 10 and 25%	Jin et al. (2017)
Date	10–40 kV/cm, 40–160 ms, 50–150 pulses	Total soluble solids	TSS levels were modulated effectively. Storage stability and quality retention were enhanced	Younis et al. (2023)

methods such as high-pressure processing (Eslami et al., 2024; Li et al., 2022), ultrasound (Nabi et al., 2024), cold plasma (Zargarchi et al., 2024), and PEF (Faria & Silva, 2024; Jara-Quijada et al., 2024) have been used to optimize waste valorization process.

Several research on the suitability of PEF technology as a pretreatment option to enable the designing of sustainable bio-refineries of F&V have been performed (Andreou et al., 2020; del Carmen Razola-Díaz et al., 2024; More et al., 2022; Nirmal et al., 2023; Plazzotta et al., 2021). Many benefits of PEF technology have had a turn in extensive application in the valorization of by-products derived from apple (Wang et al., 2020a, 2020, 2020b), kiwi fruit (Shorstkii et al., 2023), pomegranate (Faria and Silva, 2024), millet (Lohani & Muthukumarappan, 2016), berries (Bobinaitė et al., 2015; Medina-Meza et al., 2016), tomatoes (Andreou et al., 2020), and beetroot (Nowacka et al., 2019a, 2019b). For this reason, PEF is a favorable method compared to conventional extraction of fruits' by-products.

Since peels are the major part of fruits' by-products and are a good source of phytochemicals such as phenols and anthocyanins, they are popular in waste valorization. Medina-Meza and Barbosa-Cánovas (2015) observed PEF with 290 L/h flowrate, 25-mm chamber diameter, 26-mm gap, 25 kV voltage, 10 Hz frequency, and 6 µs pulse width was successful at enhancing the extraction of anthocyanins and flavonoids from grape peels. Leaves are also among other waste parts of F&V that contain a significant amount of valuable compounds. The extraction of the compounds with the assistance of PEF showed enhanced values of them. Shiekh et al. (2021) assessed the potential of PEF in the custard apple leaf extraction using 6 kV/cm, 300 pulses, and 142 kJ/kg for 5 min. The study's findings suggest that PEF's enhancement of extraction efficiency resulted in reduced bactericidal content. Overall, there is a good potential for research on the effect of PEF on leaves and future studies can focus on this issue.

PEF can be a complementary method that increases yield extraction of other methods. The increased surface area and intracellular spaces due to the PEF treatment enhanced the pectin yield compared to the traditional process. PEF, when combined with complementary methods like ultrasound, intensifies cell disruption, promoting the release of intracellular components. This synergistic approach significantly enhances pectin extraction efficiency from fruit waste powder, demonstrating its effectiveness as a method that maximizes yield while minimizing heat application (Murakonda & Dwivedi, 2022; Faria and Silva, 2024; del Carmen Razola-Díaz et al., 2024).

Several studies have claimed that PEF treatment successfully decreases extraction time (Table 2). The highlighted studies revealed that the optimal extraction conditions depend on the type of by-product and its target compounds. These results further call for extraction conditions to be matched with by-product characteristics and compound targets. In another view, efficient recovery of high-added value compounds benefits waste valorization because it changes by-products into valuable resources by supporting sustainable practices.

To maximize extraction yield, it is essential to identify and assess the key factors involved in the extraction process. Electroporation is a key factor in PEF performance as it makes PEF applicable to various F&V. Electroporation through PEF increases plant cell permeability, leading to the enhancement of waste valorization of F&V (Andreou et al., 2020). Also, Wang et al., 2020a, 2020, 2020b) and Andreou et al. (2020) found that the extraction efficiency of different bio-compounds from various fruit peels can depend on the disintegration index and the applied value of PEF intensity.

Although PEF demonstrated better extraction yields than other non-thermal treatment methods in some cases (Barba et al., 2015a, 2015b; Parniakov et al., 2016a, 2016b), its performance was not better in the recovery of intracellular valuable compounds compared to other products (Macías-Garbett et al., 2022; Roselló-Soto et al., 2015). Roselló-Soto et al. (2015) explained that the application of electrical discharges to different biological materials results in the fragmentation of treated particles of F&V sample due to the propagation of the shock waves and explosion of cavitation bubbles, thus facilitating the extraction of phenolic compounds. Furthermore, phenolic compounds can form complexes with proteins, starch, cellulose, minerals, and other substances. Therefore, the application of various non-thermal methods can affect phenolic binding thus increasing the extractability of these compounds. This shows that the initial concentration of F&V waste can affect the superiority of one extraction method over another alongside the target valuable compounds (Arshad et al., 2021a, 2021b; Faria and Silva, 2024).

Dryers

PEF is one of the promising technologies recommended for industrial use as a pretreatment of drying operations (Shorstkii et al., 2022). Several scientific studies have revealed the effect of PEF on plant cell membranes, providing explanations for the processes of pore formation under external electric fields. The latter caused an increase in membrane permeability and, hence, an increment in mass transport in plant tissue matrices (Fauster et al., 2020; Giancaterino et al., 2024a, 2024b; Punthi et al., 2022). The treatment involved bears all the benefits of efficient food production processes with raised production efficiency and product quality from the reduction of mass transfer resistance (Boateng, 2024; Lammerskitten et al., 2019; Matys et al., 2022; Rahaman et al., 2024).

Due to its ability to provoke electroporation of the cell membrane, it therefore increases mass transfer, hence promoting moisture removal during drying. It relieves such constraints to ease processing temperatures and time to the optimal drying protocols (Naveed Arshad et al., 2021a, 2021b; Zhang et al., 2023a, 2023b). Thus, PEF becomes a proper solution to add value during drying. Understanding these mechanisms and their variants of PEF treatment and its influence on the quality and structural attributes of various F&V becomes imperative to gauge its efficacy comprehensively.

Mass Transfer

Water mass transfer velocity, an indispensable feature of the drying process, depends on cell permeability as one of the critical factors (Rahaman et al., 2021). PEF treatment, through the exerted non-thermal effect on the membranes of plant cells, leads to damage to their anatomy and integrity (Shorstkii et al., 2022). It has been notified that electroporation of cell membranes resulting from the PEF treatment contributes toward enhanced mass transfer throughout the drying and moisture evacuation processes (Ali et al., 2024; Zhang et al., 2023a, 2023b). Disintegration index of cells and the diffusion coefficient of water are most important parameters for performing massive mass transfer of the F&V (Mohammed et al., 2024; Punthi et al., 2022).

The cell disintegration index reflects the extent of disruption or breakdown of the cell structures of the produce. In contrast, the water diffusion coefficient will depict the ease of movement of the water molecules through the cellular matrix (Rahaman et al., 2021; Wang et al., 2023). Rahaman et al. (2019) revealed that the increasing value of electric field intensity substantially increased the index of cell disintegration. In addition, Liu et al. (2022) and Kim et al. (2023) reported that the disintegration of cells is mainly increased, leading to an increase in the rate of mass transfer during drying.

On the other hand, some studies showed that PEF treatment alone might not be so effective. For example, del Carmen Razola-Díaz et al. (2023) observed insignificant changes in the mass loss of strawberries and kiwifruits treated with PEF. Similarly, Dermesonlouoglou et al. (2018) and Dermesonlouoglou et al. (2018) studied PEF pretreatment of kiwifruit and goji berries, respectively. They claimed initial drop in OD (osmotic dehydration) did not go hand in hand with the difficulty of the OD technique in measuring the mass change, a problem that was mainly ascribed to the high resistance of cellular membranes. Using PEF combined with OD led to a faster initial loss in moisture; thus, a mass transfer can be effectively achieved before entering the drying process.

The positive effect of the fusion of PEF and other high-tech systems has encouraged researchers to combine PEF and other non-thermal methods such as ultrasound to achieve better performance. Further, Rahaman et al. (2021) used ultrasound treatment to develop cavitation by forming a

Table 2 PEF extraction of by-product from various F&V wastes

Intended compounds	By-product	Treatment condition				Observation	Reference
		Field strength	Energy Input	Pulses	Time		
Carotenoid	Tomato juice residues	1 kV/cm	28.5 kJ/kg	500		Carotenoid extraction yield increased by up to 56.4% after PEF treatment	Andreou et al. (2020)
Lycopene		1 kV/cm	28.5 kJ/kg	500		Lycopene extraction increased from 9.84 mg/100 g to 14.31 mg/100 g tomato residue with PEF treatment at 1.0 kV/cm for 7.5 ms	
Total phenolic content		2 kV/cm	22.8	700		Total phenolic compounds concentration doubled to 56.16 mg gallic acid/kg with a 2 kV/cm, 700 pulses treatment	
Antioxidant capacity		4 kV/cm	11.4	50		Increased antioxidant capacity correlated with higher carotenoid concentration	
Total phenolic content	Sorghum flour	2 kV/cm	6.96 kJ/kg		875 µs	TPC increased by 24.8% compared to control. Higher concentrations of salicylic, ferulic, p-hydroxybenzoic, and caffeic acids. Optimal TPC observed as 79.7 mg GAE/100 g DW and 178.8 µmol TE/100 g DW	Lohani and Muthukumarappan (2016)
	Apple pomace		3 kJ/kg		500 µs	TPC increased by 37.4% compared to control. Higher concentrations of protocatechuic, chlorogenic, and salicylic acids. Optimal TPC observed as 416.3 mg GAE/100 g DW and 815.8 µmol TE/100 g DW	
Total anthocyanins	Grape pomace	13.3 kV/cm	564 kJ/kg			At $Z = 0.8$, PEF increased the extraction yield of total anthocyanins by 22% compared to US and by 55% compared to HVED Z index used to discuss mechanisms, compare efficiencies, and predict yields. Physical treatments were effective in recovering soluble bio-compounds in an aqueous medium	Barba et al., (2015a, 2015b)
Flavonoids	Raspberry purees			3.9	66 µs	Non-enzymatic browning inhibited, with PPO inactivation achieved significantly by US and combined methods ($p < 0.01$)	Medina-Meza et al., (2016)
Anthocyanin	Blueberry purees					High recovery of flavonoids (+20%) in raspberry and anthocyanins (+30%) in blueberry purees	
Anthocyanins	Grape peels			25.2	151.2 µs	PEF with large chamber facilitated higher anthocyanin (+400%) and flavonoid (+200%) extraction from grape peels but reduced ascorbic acid content	Medina-Meza and Barbosa-Cánovas (2015)
Total phenols				9.7	58.2 µs		
Total phenols	Plum peels			25.2	151.2 µs	US enhanced anthocyanin and flavonoid extraction in plum peels, although PEF was more effective for total phenols (+300%)	
Total polyphenol content	Apple peels	480–1200 kV/cm		50	100 µs	Higher PEF intensities (E = 1200 V/cm) with Zc (electrical conductivity) ≈ 1 significantly enhanced TPC extraction efficiency Lower PEF intensities (480–800 V/cm) at fixed Zc exhibited higher improvements in TPC, indicating differential extraction efficiencies based on PEF intensity and protocol details	Wang et al., (2020a, 2020, 2020b)
Steroidal alkaloids	Potato peels	0.75 kV/cm	18.47 J/kg		600 µs	Significantly increased total steroidal alkaloid yield by 99.9% compared to untreated peels. Higher PEF intensities reduced steroidal alkaloid recoveries, indicating optimal conditions for PEF efficacy	Hossain et al. (2015)
Total phenolic content	Mango peels	13.3 kV/cm	1000 kJ/kg	2000	8.3 µs	PEF followed by supplementary aqueous extraction (+SE) at 50 °C, pH 6 for 3 h enhanced TPC yields by 400% at neutral pH conditions	Parniakov et al. (2016b)
Antioxidant compounds Proteins						PEF and HVED combined with mild temperature aqueous extraction showed feasibility in recovering antioxidant compounds and proteins from mango peels without solvent use, preserving functional properties of high-added value components	
Total phenolic content Total flavonoid content Total anthocyanin content Vitamin C	Dried peach pomace		0.0014 kJ/kg	4	16 µs	Maximum concentration of bio-compounds and antioxidant activity was achieved in 40 min by CTT and 0.0014 kJ/kg by PEF in 16 µs (+57.3%, +409%, 1080%, and +77% increase in the extraction of total phenolic content, total flavonoid content, total anthocyanin content, and vitamin C, respectively)	Plazzotta et al. (2021)
Total phenolic content	Potato peels	1 kV/cm	5 kJ/kg			PEF confirmed effective as a cell disintegration technique using impedance measurements and SEM. PEF pretreatment resulted in 10% higher total phenolics yield compared to control	Frontuto et al. (2019)
Total free phenolic content Total bound phenolic content	Brewers' spent grains	2.5 kV/cm	18.75 kJ/kg	1500	10	Optimal PEF conditions led to concentrations of total free and bound phenolic compounds 2.7 and 1.7 times higher, respectively, than extraction without PEF. PEF improves cell membrane permeability, enhancing bioactive compound extraction	Martín-García et al. (2020)

Table 2 (continued)

Intended compounds	By-product	Treatment condition				Observation	Reference
		Field strength	Energy Input	Pulses	Time		
Bioactive Compounds	Custard Apple Leaves	6 kV/cm	142 kJ/kg	300	15	Extraction yield increased by 5.2% compared to untreated (13.28%). PEF improved yield and bioactivities of extracts without negatively impacting TPC	Shiekh et al., 2021
Pectin Polysaccharide	Jackfruit Waste	11.99 kV/cm				Increased cell rupture and severing observed in SEM images. Optimal conditions led to 18.24% yield with lower energy consumption (0.0986 kW-h). Improved color, solubility, viscosity (39.86 cp), and gelling properties	Lal et al., 2021
Catechin Coumaric acid Chlorogenic Acid Neochlorogenic Acid Quercetin	Thinned Peaches	5 kV/cm	3.85 kJ/kg	30	3 µs	Water as solvent increased total bioactive compounds and individual phenols (+45% in chlorogenic acid, 60% in coumaric acid, and + 28%neochlorogenic acid) when PEF was applied. Also, a 33% increase in Quercetin and a 16% decrease in Catechin extraction yield have been observed	Redondo et al., 2018
Lycopene	Industrial Tomato Peels	5 kV/cm	5 kJ/kg			PEF significantly enhanced lycopene extraction rate (27–37%), yield (12–18%), and antioxidant power (18.0–18.2%) in both solvents compared to untreated samples	Pataro et al., 2020
Total Carotenoids	Tomato Peels	0.5 kV/cm	1 kJ/kg			PEF induced significant damage at the cuticular level, increasing total carotenoids yield (up to 188%) compared to untreated peels. Lycopene was the main carotenoid extracted with no degradation or isomerization observed	Pataro et al., 2018
Phenolic compounds, Flavonoids, Anthocyanins	Red-fleshed apple residues	35 kV/cm			258 µs	Significantly lower degradation of total polyphenols (3.74%), flavonoids (10.05%), and anthocyanins (14.75%) compared to conventional thermal treatments. Strong correlation between bioactive compounds and antioxidant activity	Katiyo et al., 2018
Polyphenols, Ellagic acid, Gallic acid	Pomegranate peels	10 kV/cm	90–100 kJ/kg			High Voltage Electrical Discharge (HVED) enhanced recovery of polyphenols by ≈3 times compared to Ultrasound, and ≈1.3 times compared to PEF. PEF selectively extracted and enhanced the recovery of ellagic acid (≈740 µg/g DM), while HVED intensified gallic acid extraction (≈345 µg/g DM)	Rajha et al., 2019
Total Phenols, Hesperidin, Eriocitrin	Lemon peel residues	7 kV/cm	7.6 kJ/kg	30	0–300 µs	PEF at 7 kV/cm increased polyphenol extraction efficiency by 300%. Maximum values were 84 mg of hesperidin and 176 mg of eriocitrin per 100 g FW. PEF combined with pressing improved TPC	Peiró et al., 2019
Phenolic compounds, Flavonoid Content,	White grape pomace	3.8 kV/cm	10 kJ/kg			reduced solvent consumption (3–12%) and extraction time (23–103 min) prior to solid–liquid extraction (SLE). TPC increased by 8% and Flavonoid Content by 31%. No degradation of main phenolic compounds (epicatechin, p-coumaric acid, quercetin) was observed	Carpentieri et al., 2022
Phenolic compounds, Flavonoids, Anthocyanins, Tannins	Grape pomace	4.6 kV/cm	20 kJ/kg			PEF significantly enhanced the extractability of TPC (+15%), FC (+60%), and Total Anthocyanins Content (TAC) (+23%), compared to control. Main phenolic compounds identified included epicatechin, p-coumaric acid, and peonidin 3-O-glucoside with no degradation	Carpentieri et al., 2022
Polyphenols, Ascorbic Acid, Hesperidin, Carotenoids	Orange peels	1 kV/cm			10 µs	Orange peels were found to be an excellent source of bioactive compounds. Extracts contained hesperidin (16.26 mg/g dw), total polyphenols (34.71 mg GAE/g dw), ascorbic acid (1228.93 mg/100 g dw), and total carotenoids (52.98 µg CtE/g dw). Pretreatment techniques significantly increased extraction yield	Athanasiadis et al., 2022
Flavonoids (Polymethoxy Flavones, other flavonoids), Antioxidants	Orange peels (Flavedo)	15 kJ/kg				PEF and High Hydrostatic Pressure (HHP) treated flavedo showed higher antioxidant activity compared to other methods	Afifi et al., 2023
	Orange peels (Albedo)					Ethyl acetate extract exhibited highest antioxidant effects in albedo	
Hesperidin, Narirutin	Citrus unshiu peel	3 kV/cm			120 s	Highest hesperidin concentration: 46.96 ± 3.37 mg/g peel (dry basis) after PEF 120 s + subcritical water extraction (SWE) at 150 °C for 15 min. Peak narirutin concentration: 8.76 ± 0 mg/g peel	Hwang et al., 2021

Table 2 (continued)

Intended compounds	By-product	Treatment condition				Observation	Reference
		Field strength	Energy Input	Pulses	Time		
Polyphenols	Olive leaves (OLL)	1 kV/cm			10 µs	Total polyphenols increased by 31.85% with PEF treatment compared to conventional extraction methods. Specific metabolites increased by 265.67% with PEF treatment, indicating enhanced extraction efficiency. PEF-assisted extraction in 25% ethanol solution showed optimal results, achieving higher polyphenol yields	Pappas et al., 2021
Polyphenols	Apricot kernel biomass (AKB)	1.0 kV/cm			10 µs	TPC) increased by 70% with Deep Eutectic Solvents (DES), 88% with PEF, and 173% with combined PEF-DES treatments. Other parameters like total flavonoid content (TFC), ferric-reducing power, and antiradical activity also increased	Makrygiannis et al., 2023
Purpureacin 2, Rutin	Custard apple leaf extract (CALE)	6 kV/cm	142 kJ/kg	300		Extraction yield increased by 5.2% compared to untreated CALE. Increased abundance of purpureacin 2 and rutin in PEF-treated CALE	Shiekh et al., 2021
Phenolic content	Morus alba L. leaf extract					PEF significantly enhanced phenolic content and various biological activities compared to conventional maceration	Chaiyana et al., 2020
Quercetin, Quercetin glucosides	Dried onion skin	2.5 kV/cm				Optimal extraction achieved with PEF at 2.5 kV/cm for 15 s + SWE at 145 °C for 15 min (19.25 ± 0.77 mg/g). PEF treatment enhanced quercetin yield by 33.22% compared to untreated samples. PEF facilitated better solvent penetration during SWE, improving quercetin extraction	Kim et al., 2022
Polyphenols, Flavonoids	Asparagus officinalis root (AR)	1.6 kV/cm			20 µs	Higher extraction yield compared to conventional solvent extraction, but lower antioxidant activity	Symes et al., 2023

sponge-like matrix within the product. The co-application of ultrasound with PEF shows a better development in mass transfer during plums drying. It has been observed that increasing the intensity of the PEF enhances the removal of moisture removal.

While the improvement of mass transfer effectiveness due to PEF is quite well described, a gap is observed in some of the more recent works concerning a more detailed discussion related to the dynamics of mass transfer. Considering numerical modeling as an advanced method in studying physical processes, Zhang et al., (2023a, 2023b) proposed using it to explain the mechanism of the effect of PEF treatment on drying and changing laws of heat and mass transfer. Correspondingly, Shorstkii et al. (2022) developed such a model for drying potato, onion, and carrot tissues pretreated by PEF with an error of the mean below 4%. Consequently, it has been inferred that this model enables the prediction of moisture potential transfer progress and, consequently, the drying behavior of PEF-treated material at various levels of electroporation.

The model presented in the literature offers a comprehensive elucidation of PEF pretreatment, laying a strong foundation for its potential application in the drying of F&V. As recommended, applied models could be effectively utilized in the candying process to optimize PEF pretreatment to produce F&V characterized by high dehydration levels and reduced sugar content. Future research may thus focus on the optimal PEF parameters to allow for targeted drying but exclude adverse effects on product quality that are usually unfavorable to the treated produce. It would be interesting for both industry and academia to investigate further how the PEF treatment affected the rehydration properties, nutritional content, and sensory attributes of dehydrated F&V during long-term storage.

Quality Characterizations

The preservation of key parameters is the main part of PEF-pretreated F&V as the importance of healthy and hygienic postharvest processing. Calín-Sánchez et al. (2020) stated that quality parameters of dried F&V include color, bulk density, porosity, shrinkage, phytochemicals, antioxidant capacity, sugars, proteins, volatile compounds, and sensory attributes. Polyphenol content, energy aspects, texture, and shrinkage parameters have been also mentioned by Akter et al. (2022), and Li et al., (2023a, 2023b, 2023c). Many research has claimed these parameters for ascertaining the nutritional values, stability during the shelf life period, and sensory appeal of understanding in an overall manner the consumer acceptance of F&V (Calín-Sánchez et al., 2020; Rajoriya et al., 2021).

Liu et al., (2020a, 2020b) revealed although PEF could be attributed to a shorter drying time, it had negative effect on the color of dried sample. Further research into optimum drying time for different PEF-pretreated F&V that minimizes the adverse effect of PEF on the color of the products should be carried out since, from the above discussion, PEF-pretreated samples indicated lower total color changes at shorter drying times. It should be noted that PEF-treated samples exhibit higher residual moisture during the initial drying stages. Due to the increased surface water content after PEF treatment, less vaporization can be achieved. It is also evident that higher PEF intensities do not lead to a decreased drying time (Punthi et al., 2022; Zhang et al., 2023a, 2023b). Therefore, relevant to establish the magnitude of energy consumed within the PEF treatment as well as further drying processes in the method that is used to evaluate further the justifiably sustainable and cost-effective nature of the research method. Overall, the effect of the PEF on the drying process of various F&V has been interesting for researchers and their finding has shown that the PEF had a positive effect (Table 3).

PEF treatment has shown notable enhancements in the quality of dehydrated F&V. When it comes to drying rate, PEF speeds up the process, cutting down drying durations for items such as parsnips by as much as 28% at 70 °C and carrots by 27–49% (Alam et al., 2018). Color retention in both carrots and apples is influenced by PEF, with carrots showing higher redness and apples displaying increased lightness (Lammerskitten et al., 2019). The texture advantages are significant, as PEF-treated samples are often crunchier and more brittle because of increased porosity, as seen in freeze-dried apples and red beet (Ammelt et al., 2021; Lammerskitten et al., 2019).

Another benefit is the retention of bioactive compounds, leading to notable enhancements in phenolic levels in fruits such as mangoes (Lammerskitten et al., 2020) and apples (Lammerskitten et al., 2019). Nevertheless, there may be a decrease in antioxidant activity, indicating the necessity for parameter optimization. Rehydration ability is typically enhanced, as demonstrated in apples and red beet, pointing to enhanced structural integrity (Ammelt et al., 2021). PEF also leads to positive alterations in the microstructure, including increased pore size (Parniakov et al., 2016a, 2016b) and decreased shrinkage (Yamakage et al., 2021), improving texture and rehydration characteristics. Even though there are advantages, the impact of PEF can differ between various F&V, stressing the need for customized PEF settings for each item.

Total phenolic content (TPC) indicates the potential health benefits of products. It influences the taste, color, and shelf life of F&V (Mikulic-Petkovsek et al., 2020). Lammerskitten et al. (2019) reported that PEF treatment significantly increased the TPC of freeze-dried apples. During PEF processing, biochemical reactions can take place, and new compounds can be formed. The changes found for the TPC of mangos dried using PEF were also investigated by Lammerskitten et al. (2020). Both conventional and vacuum drying enhanced TPC retention when PEF pretreatment was applied. This enhancement effect resulted from a reduced thermal impact and enabled accelerated water evaporation.

Also, PEF treatment significantly affected the antioxidant activity of F&V (Niu et al., 2021; Surano et al., 2022). del Carmen Razola-Díaz et al. (2023) reported that the application of PEF treatment affected the antioxidant activity and capacity of strawberries and kiwifruits differently. For strawberries, a higher electric field strength (200 V/cm) increased antioxidant capacity and activity by 13.6% and 11.5%, respectively. On the other hand, for kiwifruits, an even better outcome was obtained with the lower electric field strength of 100 V/cm, which increased antioxidant capacity and activity by 7.0% and 15.6%, respectively; these are meaningful results in terms of the bioactive potential of this fruit. Morales-De la Peña et al. (2021) and Pashazadeh et al. (2020) reported that some F&V showed higher antioxidant capacity and activity than others, most probably due to a higher content of polyphenols and a protective role of sucrose in strawberries. In contrast, though ascorbic acid was found to be sensitive to environmental factors, it displayed a lower antioxidant capacity and activity, which should be ascribed to increased exposure of some F&V to the treatments (Pérez-Lamela et al., 2021; Su et al., 2024; Zhang et al., 2021, 2023a, 2023b).

Macro/Microstructural Analysis

PEF-treated dried F&V are affected in their microstructures significantly. PEF makes the shape more uniform, maintains volume better, and improves visual quality about the processed material (Li et al., 2023a, 2023b, 2023c; Shams et al., 2024). The assessments also showed the distribution to be more homogeneous, with an increased pore thickness representing the main difference from the corresponding controls (Lammerskitten et al., 2020). PEF treatment minimizes the phenomena of shrinkage, enhances the rehydration capacity, and improves the mechanical properties of FD products, hence reducing the volume losses and improving firmness (Giancaterino & Jaeger, 2023). In addition, processing with the PEF affects the Tg of solid products and raises the molecular mobility within the system, which induces a less stable matrix that can be detected in various F&V such as in apple, carrot, and potato tissues (Castagnini et al., 2020; Iaccheri et al., 2022; Liu et al., 2023; Bao et al., 2024). PEF has shown promise as a non-thermal technology to enhance the microstructure and shape of dried F&V during processing.

Shapes of dried fruit influence sensory expectations and consumer preferences. Parniakov et al., (2016a, 2016b) and Liu et al., (2020a, 2020b) reported that PEF-pretreated samples could almost return to their original shape and size. The untreated dried samples exhibited noticeable deformation and shrinking of the macro-shape, homogenization of the tissue structure, and the absence of visible micro-pores. By contrast, PEF treatment before drying maintained the macro-shape well, not causing shrinkage. Furthermore, Ali et al. (2024) reported that the electroporated samples showed that more excellent pores were developed, indicating the PEF treatment favored maintaining the structural integrity while increasing the porosity during the drying process. PEF pretreatment was observed to reduce the microstructural changes in dried samples significantly. Micrographs from PEF-pretreated samples were better than those from untreated samples. This effect was very well correlated with the PEF treatment, which mostly maintained the tissue structure of the cells during drying (Giancaterino et al., 2024a, 2024b; Liu et al., 2020a, 2020b; Trusinska et al., 2023).

Also, to assess the rehydration capability, it is recommended to evaluate the dependent parameter of rehydration such as the cell disintegration index (Parniakov et al., Ammelt et al., 2021; 2016; Rahaman et al., 2024). Parniakov et al., (2016a, 2016b) reported that the deformations and remarkable shrinkage were observed in untreated samples, and micropores were not easily visible so the value for rehydration capacity would be around one such that it would be wholly rehydrated. By contrast, the PEF-treated samples kept their macro-shape and seem to prevent the shrinkage, hence higher rehydration capacity. Such an "over-rehydration" phenomenon may indicate an increase in pore size because of the PEF treatment and an improvement in the ability of the tissue to rehydrate rapidly and efficiently (Chauhan et al., 2018; Kim et al., 2023). Additionally, rehydration significantly enhances the efficiency of electroporation by restoring the cell membrane's fluidity, making it more susceptible to electrical pulses. Hence, the effect of PEF on electroporation should be assessed (Demir et al., 2023).

The electroporation in the PEF may effectively modify the molecular structure, which will be influenced by Tg. Kempkes et al. (2017) found that PEF makes lower Tg for F&V. This effect of the decrease in the Tg, as was demonstrated in the underlying research, is a highly significant effect that must be taken into account given the application of PEF treatment to F&V. Research has shown that the protein structure has been altered in the F&V, which has a change in the TgII, which has also changed the secondary protein structure: α-helix and β-sheets. Such a phenomenon will be argued to have given satisfaction in both the effectiveness of the drying and the quality characteristics of the products obtained in the end (Dadan et al., 2020; Iaccheri et al., 2022;Guo et al., 2024a, 2024b; Shams et al., 2024).

There exist intensive ruptured structures of cells during the electroporation phenomenon provoked by PEF; in this case, water removal rises during drying, which in turn might influence the protein structure of those products that get dried. This emphasizes that PEF treatments are needed to induce changes in protein structure in dried F&V; hence, it is a valuable tool to maintain quality and inherent characteristic products during drying. In addition, the literature revealed that electroporation facilitates the peeling of fruit by creating microscopic pores in the skin, which weakens its structural integrity. This technique enhances the efficiency of peeling processes, resulting in smoother and faster removal of the fruit's outer layer (Koch et al., 2022; Giancaterino and Jaeger, 2023; Shorstkii et al., 2022). Figure 3 shows the potential of PEF on the micro/macrostructure of the F&V during the drying and peeling processes.

The dried control spinach (Fig. 3a) displayed numerous wrinkles caused by shrinkage in the surface microstructure. In contrast, the dried PEF-pretreated samples exhibited significantly fewer wrinkles, indicating that shrinkage was inhibited. The macroscopic images of untreated and PEF-pretreated apple samples after vacuum freeze drying are shown in Fig. 3b. The initial apple disc–shaped samples had a diameter of 29 mm and a thickness of 5 mm before drying. The data indicate significant deformation and shrinkage in the untreated freeze-dried samples. In contrast, PEF pretreatment before vacuum freeze drying resulted in good retention of the macro-shape and inhibition of shrinkage. By contrast, visual inspection of red pepper immediately after PEF treatment revealed no significant differences in shape and structure between the control and PEF-pretreated samples (Fig. 3c). However, after the drying process, a notable difference in surface color was observed. The control red pepper exhibited several white spots on the surface, while the PEF-pretreated sample displayed a very homogeneous surface color.

The variations in peeling ability, skin weight, and skin size could be attributed to the individual conditions and quality of the fruit. These factors seem to have a more significant impact on the values observed than the PEF treatment itself. The presence and thickness of the albedo (white spongy layer) are crucial, as a thicker albedo layer makes peeling more difficult. This aligns with the subjective peeling ability analysis, where oranges treated with 5.2 kJ/kg displayed less albedo (Fig. 3d) and were easier to peel (Koch et al., 2022). Similarly, Fig. 3e illustrates the effect of PEF on the cutting and peeling ability of pomelo. The same blade displacement in the fruit, the untreated pomelo was cut, whereas the PEF-treated pomelo remained intact. This outcome is due to the softening effect of PEF treatment, which allows the product to deform without being cut. Consequently, the resistance of the pomelo to the blade displacement is reduced (El Kantar et al., 2018). Overall, a considerable impact of PEF treatment on the preservation of shape in dried F&V has been discerned. Nevertheless, there exists a discernible lacuna in comprehending the precise influence of individual PEF parameters on this preservation aspect, thus necessitating additional research.

Table 3 Impact of PEF treatment on various quality parameters of F&V during drying process

Product	Drying method	PEF treatment	Observation	Reference
Apple	Osmotic dehydration + freezing/thawing	800 V/cm, 10 pulses, 100 ms, 12 ± 0.6 kJ/kg	Accelerated freezing/thawing processes, improved texture characteristics, texture after defrosting comparable to fresh apples at optimum conditions	Parniakov et al., (2016a, 2016b)
	Freeze drying	1.07 kV/cm, 0.5 s, 2 Hz, 10 ms pulse width	Higher crystallinity of PEF-treated samples (35.5%) compared to untreated (11.0%). Improved reconstitution properties were observed in PEF-treated apples, with higher water absorption ability and unchanged loss of soluble solids compared to untreated samples	Lammerskitten et al. (2019)
	Vacuum freeze drying	800 V/cm, disintegration index $Z = 0.96$	Preserved sample shape, prevented shrinking, and increased tissue pores. High rehydration capacity observed (≈1.3). Increased pore size by ≈86%	Parniakov et al., (2016a, 2016b)
	Freeze drying	1.07 kV/cm, 0.5, 1, and 5 kJ/kg	Reduced residual moisture content by up to 82%, Good macro-shape, inhibition of shrinkage, development of large pore, Higher polyphenolic content by up to 47%, crunchier and more brittle texture compared to untreated, which was harder and crackly	Lammerskitten et al. (2019)
	Vacuum drying	4 kJ/kg, 1.07 kV/cm	A shift in Tg II to a lower temperature (from 45.12 to 43.37 °C at 0.22 aw), indicating increased mobility and less stable matrix	Iaccheri et al. (2022)
Kiwifruit	Osmotic dehydration	At 100 V/cm and 200 V/cm	Increased water loss, decreased solid gain with sucrose, improved color, increased antioxidant capacity and activity, strong antimicrobial effect with sucrose	del Carmen Razola-Díaz et al. (2023)
	Hot air drying (50, 60, 70 °C)	PEF at 200 V/cm and/or osmotic dehydration	Improved drying kinetics and firmness, better color retention, and high overall acceptability, especially at 70 °C	Castagnini et al. (2022)
	Osmotic dehydration	0.7, 1.1, 1.8 kV/cm, 15 µs, 300 Hz	Increased water and solute transfer during osmotic dehydration (OD), leading to increased water loss (WL) and solid gain (SG), and higher effective diffusivity coefficients	Dermesonlouoglou et al. (2018)
	Vacuum drying	100 V/cm, 200 V/cm, 100 pulses	PEF at 100 V/cm generally preserved cell viability and increased metabolic heat production, while 200 V/cm caused irreversible electroporation and tissue breakdown	Nowacka et al. (2019)

Table 3 (continued)

Product	Drying method	PEF treatment	Observation	Reference
Strawberry	Osmotic dehydration	200 V/cm	Increased water loss, no change in solid gain, improved color, increased antioxidant capacity and activity, increased antimicrobial activity	del Carmen Razola-Díaz et al. (2023)
	Simulated digestion	100 or 200 V/cm	Maintained/enhanced anthocyanin stability, higher recovery of cyanidin-3-O-glucoside after digestion	Oliveira et al. (2019)
	100 V/cm, 100 pulses	Enhanced mass transfer during osmotic dehydration (OD), leading to increased water loss and textural breakdown	Nowacka et al. (2019)	
Carrot	Vacuum drying	0.6 kV/cm, tPEF = 0.1 s	Lower ΔE for PEF-pretreated samples, indicating that the color of PEF-pretreated samples were not as affected as that of the untreated samples	Liu et al. (2020a)
	Convective drying	1.07 kV/cm	Tg shift to lower temperatures, Tg I shift of about 7–9 °C and Tg II shift, indicating increased mobility after PEF treatment	Iaccheri et al. (2022)
Blueberry	Simulated digestion	100 or 200 V/cm + edible coating	Maintained/enhanced anthocyanin stability, higher recovery of malvidin-3-O-glucoside after digestion	Oliveira et al. (2019)
	Conventional hot air or vacuum drying (45, 60, 75 °C)	2 kV/cm, 2 µs, 200 pulses per second, 96 ms of total time	Reduced drying time significantly with vacuum drying (from 6 to 4 h at 75 °C, 10 to 7 h at 60 °C, and 70 to 40 h at 45 °C). No significant impact on nutritional values before drying. Minimal impact on nutritive quality of dried samples at 75 °C	Yu et al. (2018)
Potato	Convective drying	1.07 kV/cm	Tg shift to lower temperatures, Tg I shift of about 2–7 °C and Tg II shift, indicating increased mobility after PEF treatment	Iaccheri et al. (2022)
	Vacuum drying (40, 50, 60, 70 °C)	600 V/cm, 100 pulses	Retained texture and microstructure's shape, with most free water evaporating at relatively low temperatures (18–27 °C). Improved cutting force and capillary impregnation behavior	Liu et al. (2018)
Red pepper	Industrial drying by a convection drying oven at 45 °C	2.5 kV/cm, 100 Hz, 4 s	More than 10% increase in b* value	Won et al. (2015)
Goji berry	Air drying	2.8 kV/cm, 750 pulses	Increased effective diffusivity coefficients and drying rate	Dermesonlouoglou et al. (2018)
Parsnip	Thermal drying (50, 60, 70 °C)	0.9 kV/cm, 20 µs, 50 Hz, 65.8 ± 1.6 kJ/kg + 195 g of KCl salt solution (0.152 g/L)	Reduced drying time by up to 28% at 70 °C and up to 21% at 60 °C, and increased redness values (a∗) in dried parsnips	Alam et al. (2018)

Table 3 (continued)

Product	Drying method	PEF treatment	Observation	Reference
Spinach	Hot air drying	2.8 kV/cm, 1 μs, 30 Hz, 0.218 μF, 27.1 kJ/kg	Inhibited shrinkage during drying, reduced degradation of L-ascorbic acid and surface color. Prevented elution of water-soluble components, producing high-quality dried spinach	Yamakage et al. (2021)
Plum	Convective drying	1–3 kV/cm	Increased cell disintegration index (0.147 to 0.572) with increased PEF intensity, leading to higher drying rate and shorter drying time. Enhanced water diffusion coefficient (0.27 to 16.47 × 10^ − 9 m^2/s). Improved lightness and chroma, microscopic analysis revealed tissue shrinkage	Rahaman et al. (2019)
Cranberry	Microwave-vacuum drying	5.5 kV/cm,7 μs pulse duration, 0.25 μF, 0.5 Hz + US (3.6 W/g, 30 min)	Increased color preservation, reduced sugar content especially sucrose, increased quality assessment	Nowacka et al., (2019a, 2019b)
Mango	Hot air/vaccum drying	1–3 kJ/kg	Decreased rehydration by up to 21%, and antioxidant capacity, increased phenolic compound retention by up to 70%, maximum carotenoid retention	Lammerskitten et al. (2020)
Pineapple	Freeze drying	1.07 kV/cm, 1 and 4 kJ/kg	Highest cell disintegration at 4 kJ/kg for both red beet and pineapple, reduced moisture content for both specific energies, better preservation of shape, darker color, crunchier texture, higher rehydration capacity for PEF-treated samples	Ammelt et al. (2021)

Economic and Environmental Impact

Sustainability is crucial for social, technical, and economic development. It sets up a regenerative model of the economy and ensures that social needs are constantly supplied. Compared with all the traditionally used methods of thermal food processing approaches, PEF technology is much more environmentally benign. Therefore, PEF treatment is regarded as a sustainable replacement. The advantages of such a system include lower consumption of energy (Arshad et al., 2021a, 2021b; Shams et al., 2024). Other pressing concerns for most commercial systems of food production include food losses, under-utilization of by-products or processing residues, and degradation in quality, which affect the large scale and are complex in nature (Guo et al., 2024a, 2024b; Taha et al., 2022). The researchers focused on the technical transition approach relative to sustainable technology in food production for efficiency, which pointed out the efficiency of replacing outdated technologies with new ones (Giteru et al., 2018; Golberg et al., 2016; Zhang et al., 2021), while others focus on studying and utilizing existing technologies in food treatment (Hassoun et al., 2024).

Life cycle assessments analyze the viability of PEF from both environmental and economic perspectives. From an environmental standpoint, PEF application reduces the wastage of F&V by environmentally friendly means. From the literature, it has been indicated that PEF is essential in the recovery of compounds within the pomace, skin, and flesh of varied fruits and vegetables, which are otherwise irrecoverable from all other techniques (Chatzimitakos et al., 2023; Naliyadhara et al., 2022; Xi et al., 2021). Furthermore, PEF is a non-chemical method of treating wastewater that works fairly dependably for the safe disposal of sludge with substantial cost savings, perhaps up to 30–50% of the overall operating process cost and low environmental impact (Capodaglio, 2021; Martínez et al., 2023; Bocker & Silva, 2024). Moreover, many researchers have determined that PEF technology can efficiently reduce toxicants and contaminants in food processing systems (Gavahian et al., 2020; Pallarés et al., 2020; Tang et al., 2023; TK et al., 2022; Zhang et al., 2022a, 2022b). It has been concluded that the degradation pathway of pesticides during the PEF process may vary according to their chemical nature. However, the exact chemical pathways involved were not revealed in those studies; hence, no firm conclusion can be drawn at this point.

From the viewpoint of economic sustainability, technology enables food processing to be conducted at a cheaper cost in terms of energy. Continuous application of PEF has been indicated to be more energy-efficient than most thermal treatments by a large body of literature (Arshad et al., 2021a, 2021b; Guo et al., 2024a, 2024b; Zhang et al., 2023a, 2023b). Moreover, PEF pretreatment is considered particularly promising for the industrial sector because of less energy consumption and the production of quality products compared to conventional drying techniques (Punthi et al., 2022). The reduction in the energy requirement was reported to be 30–65% for drying different F&V through various reviewed papers. This manifests the effectiveness of PEF pretreatments through this decrease in thermal energy needs for consequent processing steps (Liu et al., 2020a, 2020b; Ostermeier et al., 2018; Punthi et al., 2022). In addition, treated plant cells led to easier peeling and consequently lowered resistance during cutting. Consequently, the final product is cut more accurately yet with less energy. Koch et al. (2022) and Giancaterino and Jaeger (2023) have evaluated the potential of PEF regarding the peeling process of a variety of F&V and ascertained that peeling treatment significantly increases peeling efficiency by a factor of 3–5 times and enhances product yield up to 41.53% when compared to untreated samples. Therefore, the application of novel strategies, for example, PEF processing in postharvest industries, minimizes product loss, increases final quality, and reduces environmental impact and energy consumption that is associated with conventional peeling methods.

Challenges and Future Work

PEF has limitations in the postharvest process of F&V due to its potential for the high energy costs associated with the technology. The pulse generators must be designed to realize the short, high-intensity pulses needed for efficient treatment, hence making them very specialized and expensive to manufacture (Arshad et al., 2020). The electrodes in PEF systems also need to be constructed from materials that can withstand high voltage and are resistant to corrosion (Ghoshal, 2023; Gómez et al., 2019). In addition, high voltage creates the need for proper insulation and safety measures for both the operators and the system. Since high-voltage systems have been invested in, the insulation and the safety mechanism that is practiced lead to significant expenses (Arshad et al., 2020; Wang et al., 2018). High initial investment costs hinder the adoption of the PEF technology, especially among the small food industries. Future work on the PEF technology needs to focus on energy efficiency and the cost reduction of pulse generators for better accessibility. Research in the areas of advanced electrode materials with resistivity to corrosion and innovation in insulation design is necessary to reduce manufacturing and operating costs. The other important aspect for improving operator protection and reducing complexity is safety mechanisms for high-voltage systems. Eventually, modular and scalable PEF systems can be developed that may allow easier adoption by minor agricultural and horticultural industries with a lower cost.

Some questions remain regarding the extension of shelf life for fruits and vegetables (F&V) treated by pulsed electric fields (PEF). PEF cannot guarantee the inactivation of all microorganisms, particularly spores and certain resilient bacterial strains that cause microbial regrowth during storage. The susceptibility to PEF varies among individual microorganisms, largely influenced by their structural differences. Generally, Gram-positive bacteria are more resistant to PEF treatment due to their thick peptidoglycan layer, which offers greater protection against the electric fields. In contrast, Gram-negative bacteria, with their thinner peptidoglycan layer and outer membrane, tend to be more susceptible. Additionally, yeasts are generally more sensitive to electric fields than bacteria, which can lead to more effective inactivation during PEF treatment (Demir et al., 2023; Li et al., 2023a, 2023b, 2023c). While PEF be used to inactivate some enzymes, such an approach cannot be generally applied. Not every enzymatic process can be successfully mitigated and, more importantly, inactivated to prevent spoilage and the loss of quality over time (Arshad et al., 2021a, 2021b). Furthermore, minimal residual enzymatic activity under mild conditions may lead to spoilage or modify the sensory attributes of food products during storage (Morales-De la Peña et al., 2021; Zhang et al., 2023a, 2023b). PEF processing still incurs degradation of labile vitamins and minerals over time and ultimately results in a lower quality from a nutritional point of view. Further studies should be directed toward the application of this technology in combination with other preservation methods to guarantee inactivation of resistant microorganisms and further improve enzyme control so as to prevent spoilage. Besides, further optimization of process parameters of PEF is needed in the interest of reducing losses of vitamins and minerals to sustain for a longer period, the nutritional quality of fruits and vegetables after treatment.

Although the PEF technology has established its great potential for the waste valorization of F&V, there are some critical limitations to be managed to maximize this potential. F&V waste is quite heterogeneous in composition, moisture content, and physical properties, which challenges one to develop a general PEF treatment protocol. These features of fibrous plant materials offer low amenability to the PEF treatment, often requiring intense further processing (Chatzimitakoset al., 2023; Faria and Silva, 2024). The conditions used in the PEF procedure might hinder the stability of the bioactive compounds or other valuable extracts from their quality by causing possible malfunction or degradation. The variation of raw waste material does not allow consistency in valorized product quality (Arshad et al., 2021a, 2021b). Such optimization and validation of PEF treatment parameters for the different waste types would probably be quite an investment in resources and time, representing a considerable amount of money expended on research and development. In prospects, PEF technology for the valorization of F&V waste should be focused on treatment protocol optimization, taking into account variations in the waste composition that would provide for maximum extraction of bioactive compounds without any quality degradation. Further improvements in the efficiency of the PEF treatment of fibrous materials and the elaboration of scalable systems will lead to a constant product quality with reduced processing costs.

While PEF can reduce drying time and energy consumption in the subsequent drying processes, the pretreatment consumes a significant amount of energy. Various F&V respond to PEF treatment differently, where the protocols have to be adjusted and therefore make it cumbersome (Punthi et al., 2022). Considerable modifications and infrastructure investment of already existing lines are needed to fit them into the integration of PEF technology in drying (Radojčin et al., 2021; Zhang et al., 2022a, 2022b). Many existing drying systems must be engineered and even have their processes adjusted to incorporate PEF in a manner that many processing plants simply do not find viable. Solving such issues is very important to help realize the full potential derived from PEF technology for postharvest processes involving F&V. Further research on PEF technology for the treatment of F&V should give more emphasis to two main aspects: enhancing the energy efficiency of the pretreatment and developing adaptable protocols for different F&V. The development will be required to translate into cost-effective methods that result in the integration of PEF into existing drying systems without significant infrastructure modification, making it industrially practical for application.

Conclusion

Advantages of PEF in postharvest processing of F&V are many-faceted, from food preservation while keeping the quality to energy efficiency, low environmental impact, and safety. Since PEF is non-thermal, it does not lead to any nutritive losses; all nutrients, such as vitamins, antioxidants, and other bioactive compounds, are heat-sensitive. PEF technology facilitates the efficiency of extraction of bioactive compounds and other valuable substances from F&V. The rapid application of electric pulses significantly reduces processing time and total energy consumption compared to traditional methods. Thus, PEF technology is more energy-saving than traditional thermal treatment methods. Although the numerous benefits associated with the PEF technology and applications are tangible, engineers and researchers still try to overcome some challenges coupled with developing the PEF systems.

They assess the factors of adaptability and scalability, as these enable a broad size range, from small-scale operations driven by supermarket demand to large agricultural and horticultural units. Furthermore, with future developments of PEF technology, it will be possible to better influence the texture and flavor properties of processed F&V, allowing for still more consumer-oriented end-products. PEF technology may also allow both categories of products to result in better extraction yields and longer shelf life, both at the processing level and among consumers. More investigations into these mechanisms and effects on different F&V will further deepen the understanding and optimization of the technology. The future of PEF technology is promising for producing high-quality F&V. Advanced development and application in the food industry using PEF would contribute to making healthier products and friendliness to the environment. Life cycle assessments analyze the viability of PEF from both environmental and economic perspectives. PEF application reduces the wastage of F&V by environmentally friendly means. PEF is essential in the recovery of compounds within the pomace, skin, and flesh of varied fruits and vegetables, which are otherwise irrecoverable from all other techniques. In addition, scalability of PEF secures its application in sizes varying from small-scale operations driven by supermarket demand up to large-scale food units.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

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