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REVIEW ARTICLE

Effects of Pulsed Electric Fields Processing Strategies on Health-Related Compounds of Plant-Based Foods

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Abstract In the last decades, pulsed electric fields (PEF) have been proposed as alternative or complementary to traditional food processing technologies in order to improve the competitiveness of the food industry. PEF has been suggested as a technology of choice to obtain safe and high-quality plant-based foods with a shelf-life similar to the attained with mild heat pasteurization treatments. On the other hand, the application of PEF as a pretreatment for the permeabilization of vegetable tissues has been demonstrated to enhance the efficiency of mass transfer of water or of valuable compounds from biological matrices in drying, extraction, and diffusion processes. Moreover, PEF treatments are currently under study to prospect their potential to induce stress reactions in plant systems, so that bioproduction of certain compounds can be enhanced or stimulated. However, the impact of different PEF processing strategies on health-related compounds of plan-based foods has not been always considered. These review aims to present recent results regarding the effects of PEF on health-related properties of plant-based foods, including those preserved by PEF and those obtained from PEF-assisted and PEF-stressed processing.

Keywords Pulsed electric fields · Health-related compounds · Preservation · Assisted processing · Abiotic stress

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Introduction

Consumers are increasingly concerned about the nutritional and health-related characteristics of plant-based foods. Human nutritional research has demonstrated that plant-based food diets promote good health and may reduce the risk of major chronic diseases, not only due to their high nutritive value and vitamin content (A, C, E, B) but also because they are a rich source of non-nutritive bioactive compounds (phenolic compounds, carotenoids, sulphur-containing compounds) with antioxidant and free-radical scavenging properties [20].

Pulsed electric fields (PEF) involve the application of high-voltage energy (typically 0.5–80 kV/cm) in form of very short pulses (microseconds to milliseconds) to foods placed between two electrodes. PEF treatments are conducted at ambient, sub-ambient, or slightly above ambient temperature [54]. PEF have been extensively studied for preservation purposes in plant-based foods, so that they can constitute an alternative to traditional thermal processing to inactivate spoilage and pathogenic microorganisms as well as quality related enzymes, with the advantage of retaining or minimally modifying sensorial, nutritional and health-promoting attributes of liquid food products [9]. Furthermore, PEF may also be used as a pretreatment to improve food processes such as extraction by pressing or solvent diffusion, osmotic dehydration, drying, and freezing [17]. Finally, PEF treatments are currently under study to prospect their potential to induce stress reactions in plant systems or cell cultures, so that bioproduction of certain compounds can be enhanced or stimulated [67].

During the last decade, many efforts have been made to evaluate the health-related potential of plant-based products processed by PEF. The present review aims at summarizing the state of the art regarding the effects of PEF technology on health-related compounds in plant food systems.

Health-Related Compounds of Plant-Based Foods Preserved by PEF

PEF have been developed during the last decades as an alternative to thermal pasteurization for preserving foods. This section summarizes the main results achieved regarding the effects of PEF on the main compounds affecting health-related properties of plant-based foods, such as vitamins, isoprenoid compounds, fatty acids, phenolic compounds, and glucosinolates.

Vitamins

Several authors reported high vitamin C retention after PEF processing compare to the heat treatment in different food matrix such as orange [18], tomato [50], grape [39], carrot [58, 82], and strawberry juices [48] as well as blended beverages with orange juice [40, 88] and gazpacho soup [19] (Table 1). Process parameters have been shown to play a key role in vitamin C retention. Losses of vitamin C in juices were accelerated when increasing intensity of PEF treatment, thus the lower the pulse frequency or the pulse width, the higher the vitamin C retention in juices, although the effect of these variables is nonlinear. PEF treatments conducted in monopolar mode better maintained vitamin C content than in bipolar mode irrespective of the frequency and pulse width applied [55]. Higher vitamin C retentions in fruit juices treated by monopolar pulses could be related to the inactivation of enzymes involve in the vitamin C oxidation. The effect of PEF treatment variables such as frequency, pulse with, and polarity on vitamin C of tomato (R^2 = 0.83), watermelon (R^2 = 0.94), and strawberry (R^2 = 0.83) juices has been modelled using quadratic response models [47, 55] [52]. Vitamin C content significantly depended on PEF treatment time and electric field strength during PEF-processing of the juice, the lower the treatment time and the electric field strength, the greater the vitamin C retention [19, 63, 86]. [49, 51] suggested that a Weibull model ($R^2_{adj} \geq 0.84$) can be used to relate the kinetics of vitamin C changes in tomato juice and strawberry juices as affected by PEF electric field strength and time. Several authors reported that PEF-treated juices retained more vitamin C than those equivalently heat treated during the storage period [48, 50]. Contrarily, vitamin C degradation was faster in PEF-treated fruit juice-milk beverages [61, 88] than in those thermally treated, irrespective of the PEF-treatment applied. Thus, it can be suggested that complex matrices do not behave as simple products such as fruit juices when they are preserved by PEF. Most authors have suggested that the vitamin C degradation kinetics in PEF fruit juices during the storage followed first-kinetic model ($R^2 \geq 0.968$) with rate constants from 1.7×10^{-2} to 4.1×10^{-2} days^{-1} [50, 58, 72]. A few authors found that the degradation of vitamin C was better fitted by a zero-order model than by a first-order model for PEF-treated orange [80] juice and orange juice-milk beverages [88] during storage. Other authors [61] proposed the Weibull model to accurately describe the degradation kinetics of vitamin C during refrigerated storage with $R^2 \geq 0.955$ and A_f values ranging from 1.01 to 1.11.

Little information is available about the impact of PEF on the in vitro bioaccessibility of vitamin C in fruit juices. Rodríguez-Roque et al. [59] reported that PEF processing (35 kV/cm for 1800 μs in bipolar 4-μs pulses at 200 Hz,) did not modify the bioaccessibility of vitamin C in comparison to untreated blended fruit juices, whereas significant losses in vitamin C bioaccessibility were observed in thermally-treated beverages.

The concentration of B vitamins after PEF processing and during storage in a beverage containing fruit juices (orange, kiwi, mango, and pineapple) and whole and skim milk was studied by Salvia-Trujillo et al. [61] (Table 1). In this study, niacin and thiamin contents in the fruit beverages were not affected by PEF treatment conducted at electric field strength of 35 kV/cm for 1800 μs, a pulse frequency of 200 Hz, and 4 μs bipolar pulses. However, PEF-treated beverages presented significantly higher riboflavin levels than those thermally treated immediately after processing and during the storage period (81 days at 4 °C).

Isoprenoid Compounds

Several studies have reported that carotenoid content is significantly enhanced after PEF processing compared to the untreated juice (Table 1). In this line, Carbonell-Capella et al. [13] reported an increase in total carotenoids (18.5%) of fruit juice-*stevia rebaudiana* blend after the application of PEF treatments at 35 kV/cm with an energy density of 256 kJ/kg. Regarding individual carotenoids, Odriozola-Serrano et al. [47] reported an enhancement of up to 46.2% in the lycopene relative concentration of tomato juices after applying different PEF treatments (35 kV/cm for 1000 μs). PEF-treated carrot juice (35 kV/cm for 1500 μs) exhibited higher β-carotene concentration (12.3%) than the untreated juice just after the treatment, which was related to greater vitamin A contents in the samples [58]. The concentration of cis-violaxanthin + neoxanthin (16%), anteraxanthin (10%), lutein (23%), and zeaxanthin (28%) increased after PEF treatment (35 kV/cm for 1800 μs) in fruit juice-whole milk beverages with respect to untreated beverages [60]. However, Odriozola-Serrano et al. [53] observed that β-carotene content in treated tomato juice significantly increased (31–38%), whereas γ-carotene depleted (3–6%) when PEF treatments (35 kV/cm for 1000 μs) were applied. Although the reason for these results is not well known, it was speculated that carotenoid conversions could be triggered by the PEF treatments. In addition, it has been reported that thermal treatment may imply an increase in some individual carotenoids, owing to a greater

Table 1 Effect of pulsed electric fields (PEF) on vitamins and isoprenoid compounds of plant-based foods

Health-related compounds	Product	Treatment conditions	Major finding	Reference
Vitamin C	Orange juice	35 kV cm^{-1}/1000 μs (bipolar 4-μs pulses at 200 Hz)	Decrease in vitamin C content (82.8% retention)	Elez-Martínez et al. [18]
	Tomato juice	35 kV cm^{-1}/1000 μs (bipolar between 1 to7-μs pulses at 50–250 Hz)	Decrease in vitamin C content (58.2–99% retention)	Odriozola-Serrano et al. [47]
	Strawberry juice	35 kV cm^{-1}/1700 μs (bipolar 4-μs pulses at 100 Hz)	Slight decrease in vitamin C content (98% retention)	Odriozola-Serrano et al. [48]
	Carrot juice	35 kV cm^{-1}/1500 μs (bipolar 6-μs pulses at 200 Hz)	Slight decrease in vitamin C content (95.1% retention)	Quitão-Teixeira et al. [58]
	Broccoli juice	35 kV cm^{-1}/2000 μs (bipolar between 4-μs pulses at 100 Hz)	Decrease in vitamin C content (74.6% retention)	Sánchez-Vega et al. [63]
Vitamins B	Fruit beverage	35 kV cm^{-1}/1800 μs (bipolar 4-μs pulses at 200 Hz)	Maintenance of niacin and thiamin contents	Salvia-Trujillo et al. [61]
Carotenoids	Tomato juice	35 kV cm^{-1}/1000 μs (bipolar 4-μs pulses at 100 Hz)	Increase in several individual carotenoids such as lycopene (10%), β-carotene (38%) and phytofluene (5%)	Odriozola-Serrano et al. [53]
	Carrot juice	35 kV cm^{-1}/1500 μs (bipolar 6-μs pulses at 200 Hz)	Substantial increase in β-carotene concentration (23%)	Quitão-Teixeira et al. [58]
	Watermelon juice	35 kV cm^{-1}/50 μs (bipolar 7-μs pulses at 200 Hz)	Slight increase in lycopene content (13%)	Oms-Oliu et al. [55]
	Fruit beverage	35 kV cm-1/1800 μs (bipolar 4-μs pulses at 200 Hz)	Increase in cis-violaxanthin + neoxanthin (16%), anteraxanthin (10%), lutein (23%) and zeaxanthin (28%)	Rodríguez-Roque et al. [60]

stability caused by enzymatic degradation and unaccounted modifications at the food matrix level. The effects of PEF treatments over carotenoid composition mainly depended on processing conditions [14]. Process parameters such as electric field strength, treatment time, pulse frequency, pulse width and polarity should be controlled in PEF treatments for obtaining safe and stable juices with high nutritional properties. Higher frequency, electric field strength, treatment time and pulse width resulted in a greater carotenoid content in tomato juices compared to untreated samples, whereas the use of bipolar pulses led to a greater rise in the carotenoids content of tomato juices [47, 51]. Consistently, carotenoid contents were the highest in PEF-treated orange [14] and grape juices [1] when the most intense electric field treatments (25 or 40 kV/cm) were conducted. Some models have been proposed to predict the combined effect of PEF variables on carotenoids concentration of different juices. In this way, second-order response functions ($R^2_{adj} \geq 0.712$) have been proposed to fit lycopene retention after the application of electric field treatments set between 15 and 35 kV/cm for treatment times from 500 to 2000 μs using squared wave pulses, frequencies from 50 to 250 Hz, and a pulse width from 1 to 7 μs, in monopolar or bipolar mode in broccoli [63], watermelon [55], and tomato [47] juices. The combined effect of treatment time and electric field strength on lycopene concentration of tomato juice was successfully predicted ($R^2_{adj} \geq 0.754$) by a model proposed by Peleg [51]. The constants defined by the model (K_1 and K_2) revealed that treatment intensity, namely electric field strength, did not influence the rates of change for lycopene concentrations at initial treatment time, but was positively correlated with the steady value reached after a prolonged treatment. Several authors have studied the changes of some carotenoids in PEF-treated juices during storage, reporting higher stability of these health-related compounds in comparison to thermally pasteurized tomato juice [47, 78, 79], orange juice [15], carrot juice [58], and a fruit juice-milk beverage [41, 87]. Mild processing temperatures used during PEF treatments might explain the higher retention of carotenoids in fruit juice samples. However, changes in the relative amounts of carotenoids through the storage are not consistent for similar compounds. Trans-lycopene decreased much more considerably than other carotenoids through the storage period as a result of isomerization phenomena, since trans-lycopene can be converted to 13-cis-lycopene, which can be transformed into other cis-isomer [78, 79]. Odriozola-Serrano et al. [53] suggested that some carotenes of PEF-treated tomato juices such as neurosporene, γ-carotene, ξ-carotene, and β-carotene decrease in lesser extent than lycopene through the storage period at 4 °C. Zulueta et al. [87] mentioned that lutein and zeaxanthin of PEF-treated orange juice-milk beverages are highly susceptible to degradation during thermal treatments due to the presence of oxygen in their chemical structures. In this line, Plaza et al. [56] suggested that lutein concentration was considerably reduced in PEF-treated orange juices after 40 days of storage at 4 °C, since this xanthophyll is more susceptible to isomerization or oxidation processes than other carotenoids. First-order kinetic models ($R^2 \geq 0.866$) have been proposed to fit carotenoids changes as a function of storage time in PEF-treated tomato [50], carrot [58], and orange [80] juices as well as in an orange juice-milk beverage [87] with rate constants from 1.4×10^{-2} to 2.3×10^{-2} days^{-1}.

Regarding the bioaccessibility of carotenoids in PEF treated juices, Rodríguez-Roque et al. [60] reported a decrease in the bioaccessibility of carotenoids in PEF-treated fruit juice-based beverages in the range of 7.6 to 48.2%, whereas the bioaccessibility of carotenoids diminished up to 63% in thermally treated beverages compared to the untreated beverages.

To our best knowledge, information regarding the effect of PEF treatment on other terpenoid compounds such as phytosterols is not yet available.

Fatty Acids

Neither PEF nor thermal treatment affected free fatty acids concentration in whole milk since the concentration of short-chain fatty acids was maintained after treatments [46, 84]. On the other hand, the initial total fatty acid content of PEF-processed orange juice-milk [89] and fruit juice-soymilk [42] beverages, as well as grape juice [23] was slightly lower than in untreated samples. The depletion in beverages can be related to the decrease of the polyunsaturated fatty acids such as eicosanoipentanoic, docohexanoic, and linolenic acids concentration after PEF processing [42], whereas the reduction of lauric acid concentration by the action of PEF seemed to negatively affect the total content of fat in grape juices.

Up to now, only Zulueta et al. [89] have studied the effect of PEF variables on the fat concentration of PEF-treated beverages. These authors proposed a secondary model ($R^2 = 0.831$) to accurately predict the effect of electric field strength (35–40 kV/cm) and treatment time (40–130 μs) on the fat content of orange juice-milk beverages.

Some authors have reported the changes of free fatty acids through the storage. In this way, Odriozola-Serrano et al. [46] reported an absolute increase in the total free fatty acids content of fresh and PEF-treated (35.5 kv/cm with 7 μs bipolar pulses at 111 Hz for 300 μs or 1000 μs) whole milk during 12 days of storage at 4 °C. The authors attributed these changes to the presence of the spoilage of milk by microorganism that would contribute to an increase in fat degradation. In addition, Morales-de la Peña et al. [42] suggested that the enhancement of free fatty acids of PEF (35 kv/cm with 4 μs bipolar pulses at 200 Hz for 800 or 1400 μs) and heat-treated (90 °C for 60 s) fruit juice-soymilk beverage over storage time (56 days at 4 °C) might be possible related to biochemical changes of volatile compounds throughout the time. Contrarily, Zeng et al. [83] reported that the content and profile of saturated and unsaturated fatty acids in PEF-treated peanut oils decreased in a lesser extent than in untreated oil during the storage at 40 °C for 100 days due to oxidation processes.

Phenolic Compounds

Due to their ubiquitous role as secondary metabolites in plant tissues, with more than 8000 currently known structures, phenolic compounds constitute a wide and diverse group of biologically active compounds in most plant-based foods [16]. Literature provides extensive information regarding the effect of PEF on the overall amount of phenolic compounds in fruit juices and vegetable purées (Table 2). PEF treatments have not been reported to produce major changes in the phenolic content of several plant based products, including orange juice [6, 62], apple juice (Aguilar-Rosas et al. 2007; [45]), tomato juice [50], strawberry juice [52] carrot juice [58], blueberry juice [8], and fruit juice-milk beverages [59, 88].

The effect of PEF treatments on the stability of phenolic compounds found in food matrices is not so noticeable and not so easy to anticipate, on the one hand, because treatment intensities used in food processes are far from those required for producing that kind of deleterious reactions and, on the other hand, because of the inherent complexity of most food matrices. However, from a qualitative point of view, some effects may be expected, depending on the phenolic composition of the treated product. Polyphenols greatly differ in molecular size and structure as a consequence of a complex biosynthetic metabolism that involves hydroxylation, methoxylation, and glycosylation patterns, among others [16]. Therefore, molecular structure is one of the main relevant factors regarding the effect of PEF treatments on phenolic compounds. The degradation of simple phenolic compounds in aqueous solutions as affected by intense pulsed electrical discharges has been extensively reported in literature works as a consequence of the triggering of oxidative processes [27, 68]. Evidences of minimal changes in the phenolic content of fruit juices can be found in literature, especially in what pertains to low molecular weight phenolics, namely phenolic acids. In this line, PEF-treated tomato juice was reported to exhibit higher concentrations of chlorogenic acid that heat-pasteurized juices, whereas slight changes in ferulic, p-coumaric, and caffeic acids [53] could be observed over storage probably as a consequence of the action of residual enzymes. Similarly, slight changes in ellagic acid and p-coumaric acid have been reported throughout storage of PEF-treated strawberry juices [48], although concentrations are always above those found in thermally treated products. In contrast, Agcam et al. [6] did not find any change in the content of phenolic acids in PEF-treated orange juice as a consequence of the treatments, although the initial concentrations in the juice were better preserved in comparison to a heat-pasteurized juice.

Table 2 Effect of pulsed electric fields (PEF) on phenolic compounds and glucosinolates of plant-based foods

Health-related compounds	Product	Treatment conditions	Major finding	Reference
Phenolic compounds	Strawberry juice	35 kV cm^{-1}/1700 µs (bipolar 4-µs pulses at 100 Hz)	Better preservation of total phenolics in PEF-treated samples compared to heat-treated juices throughout storage	Odriozola-Serrano et al. [48]
	Tomato juice	35 kV cm^{-1}/1000 µs (bipolar 4-µs pulses at 100 Hz)	Higher total phenolic content reported throughout storage in the HIPEF-treated juice compared to that treated at 90 °C for 60 s	Odriozola-Serrano et al. [53]
	Mixed beverage (fruit juice-soy milk)	35 kV cm^{-1}/1400 µs (bipolar 4-µs pulses at 200 Hz)	Total phenolic content enhanced in PEF-treated beverages; it was especially attributed to the dramatic rise in hesperidin.	Morales-de la Peña et al. [41]
	Orange juice	Up to 25.26 kV cm^{-1}/ up to 1206.2 µs (bipolar square-wave pulses).	Overall preservation of phenolic compounds through storage; enhancement in flavonoid levels after the application of PEF	Agcam et al. [6]
	Mixed beverage (fruit juice-milk)	35 kV cm^{-1}/1800 µs (bipolar 4-µs pulses at 200 Hz)	Better preservation of total phenolics compared to thermally treated beverages	Morales-de la Peña et al. [43, 44]
Glucosinolates	Broccoli juice	15–35 kV cm^{-1}/ up to 2000 µs (monopolar or bipolar 4-µs pulses at 200 Hz)	3-fold increase in glucobrassicin levels reported after applying 35 kV·cm^{-1} treatments, regardless the rest of studied parameters	Frandsen et al. [21]

Regarding the effect of PEF treatments on the flavonoid content of plant-based foods, literature works do not reveal a major effect. Special attention should be focussed on anthocyanins, which are responsible for the colours of many fruits and vegetables such as apples, berries, beets and onions. Although an increase in the degradation of cyanidin-3-glucoside, the main anthocyanin in red raspberries, was reported by Zhang et al. [85] in an aqueous-methanolic medium when increasing field strength and treatment time, substantial changes have not been reported in food systems. Odriozola-Serrano et al. [49] reported anthocyanins retention in PEF-treated strawberry juice within the 96.1–100.5% range, even for very intense treatment conditions (35 kV cm^{-1} for up to 2000 µs). Similar results have been reported for other flavonoid compounds. Sánchez-Moreno et al. [62] did not find changes in the flavanone content in a PEF-treated orange juice, neither in the hesperetin and naringenin aglycones nor in their glycosidic forms, after a treatment at 35 kV/cm for 750 µs with 4-µs bipolar pulses at 800 Hz. Results by Agcam et al. [6] generally support these findings, although slight differences in the flavonone and flavonol profile of a PEF-treated orange juice were highlighted. In any case, flavonoid concentrations were enhanced compared to heat-treated juices. In line with these results, Morales-de la Peña et al. [40] did not report changes in the total isoflavone concentrations in a fruit juice-soymilk beverage after a PEF treatment at 35 kV/cm for up to 1400 µs using 4-µs bipolar pulses at 200 Hz. In this study, authors could demonstrate that PEF processing substantially contributed to the preservation of the glycosidic isoflavone forms present in the untreated beverage, whereas a mild thermal treatment (90 °C, 60 s) promoted the cleavage of malonyl compounds.

The kinetics of the changes in phenolic compounds as affected by PEF have been studied in several research works. Odriozola-Serrano et al. [49] proposed a Weibull kinetic model to describe anthocyanin changes in strawberry juices as affected by PEF processing conditions. The model best predicted the slight decrease of anthocyanins in the juice (up to 3.9%) just after the treatments within the range of 20–35 kV/cm for up to 2000 µs. In a subsequent work (2009a), the same authors reported a significant influence of pulse frequency, pulse width, and polarity on the loss of anthocyanins in the treated juices. A treatment of 35 kV/cm for 1000 µs applying bipolar pulses of 1 µs at a rate of 250 Hz led to the highest retention of anthocyanins. On the other hand, Agcam et al. [6] suggested a second-order kinetic model for describing the changes in total phenolic compounds in PEF-treated orange juice samples throughout storage. An increase in treatment intensity led to a rise in rate constants and half-life time of the samples, as defined by the model.

Glucosinolates

Scarce information is available regarding the effect of PEF treatment conditions on glucosinolate transformations in food products (Table 2). Glucosinolates are sulphur-rich, anionic compounds found in *Brassicaceae* plants that, upon hydrolysis by endogenous hydrolytic enzymes called myrosinases (EC.3.2.1.147), produce several products (e.g. isothiocyanates, thiocyanates, and nitriles) that exhibit diverse biological activities in both plant and human tissues [32]. Epidemiological studies indicate that consumption of cruciferous vegetables such as broccoli may reduce the risk of some cancers [34], which can be related to the high reactivity of glucosinolates hydrolysis products. Because of their anionic nature, some changes during PEF processing on the structure of glucosinolates could be expected. Nevertheless, the main effect might be linked to the disruption of cell membranes caused by electroporation as, in intact cells, glucosinolates are separated from myrosinases by membranes that prevent their transformation to bioactive products [10].

In a recent study, Frandsen et al. [21] evaluated the effect of PEF treatment conditions on broccoli glucosinolates and associated myrosinase isoenzymes. The study could not find differences in glucosinolate contents related to the type of waveform and treatment time. However, the levels of glucobrassicin, one of the main glucosinolates in broccoli, in broccoli juices processed with an electric field of 35 kV/cm were reported to increase with respect to those found in broccoli juices subjected to less intense conditions (15 and 25 kV/cm). This suggests that high electric fields could be able to inactivate myrosinase enzymes, as has been extensively reported for other metallo enzymes.

Effects of PEF-Assisted Processing on Health-Related Compounds of Plant-Based Products

Currently, PEF-assisted processing has attracted a strong interest in food processing for enhancement of diffusion extraction, osmotic treatment, pressing extraction, drying, and freezing [9]. There is a lot of information regarding the effects of using PEF-assisted processing on the yield of products, processing efficiency, mass transfer, cell membrane permeabilization, and physical properties of products. However, the information related with the impact of integrating PEF pre-treatments on the health-related properties of the obtained foods is very limited. Table 3 shows the effects of PEF-assisted processing on health-related compounds of plant-based products.

Juice Expression

The positive effects of PEF as an intensification method for improving yield, nutritional value, and sensory attributes of fruit juices have been reported.

Ade-Omowaye et al. [3] observed higher values of β-carotene and vitamin C contents in juice obtained from PEF-treated (1.7 kV/cm, 5 pulses, 0.5 kJ/kg) paprika mash compared to enzyme treated or untreated samples.

A remarkable rise in antioxidant capacity of apple juice was observed when apple mash was treated at 3 kV/cm and the specific energy input was set at 10 kJ/kg, due to an enhancement in the release of phenolics from the mash into the juice [65]. Turk et al. [74] observed that the concentration of total native polyphenol of the juices increased due to PEF treatment of apple mash (0.65 kV/cm, 23.2 ms, 32 kJ/kg). The influence of apple mash treatment with different PEF intensities (1, 3, 5 kV/cm, n = 30 pulses) on polyphenolic content and antioxidant capacities of the resulting cloudy juices was investigated by Schilling et al. [64]. In contrast to the expectations, a rise in phenolic content and antioxidant capacities of the juices as a result of improved disintegration of the plant cells by PEF was not observed. Turk et al. [75] also reported a decrease in the content of total native polyphenols in the apple juice obtained from PEF-treated mash (1 kV/cm, 32 ms, 46 kJ/kg).

Other processing parameters, such as mash size and processing mode, are critical for the extraction of apple juice from PEF-treated apples. Turk et al. [73] explored the effects of PEF treatment (0.45 kV/cm, 10 ms, 3 kJ/kg) and apple mash size on polyphenolic compounds of the juice. Increasing mash size had a negative effect on the polyphenols content in the juices, especially for hydroxycinnamic acids and flavan-3-ol families. PEF had a negative influence on the polyphenol content of each family. However, the interaction between mash size and PEF for all polyphenolic families was positive. Grimi et al. [26] investigated the effects of PEF processing modes of apples (PEF treatment of whole samples before cutting and PEF treatment of apple slices after cutting) on the phenolic content and antioxidant capacity of apple juice. The PEF pre-treatment was accompanied by an increase of the content of polyphenols and the antioxidant capacity of the juice. These effects were more pronounced for the whole PEF-treated apples as compared to untreated sliced apples and treated apple slices.

PEF pre-treatment (0.4 kV/cm, 100 ms, 15 kJ/kg) of white grapes led to an increase in the polyphenols content (15%) of the subsequent juice [25]. In the same line, Leong et al. [36] evaluated the health-promoting properties of Pinot Noir grape juices obtained after PEF-treatment (15 or 70 kJ/kg) of grape mash. Compared to untreated grapes juice, PEF pre-treatment on grapes enhanced the release of the major anthocyanin

Table 3 Effect of pulsed electric fields (PEF)-assisted processing on health-related compounds of plant-based products

Raw Material	PEF treatment conditions	Product	Health-related compounds	Major effects	Reference
Apple mash	3 kV/cm, 10 kJ/kg, 56 Hz	Apple juice	Phenolics	Increase in total and individual phenolics content (79.8%)	Schilling et al. [65]
Apple	0.4 kV/cm, 0.1 s	Apple juice	Phenolics	Increase in total phenolic content (32%)	Grimi et al. [26]
White grape	0.4 kV/cm, 100 ms, 15 kJ/kg	Grape juice	Phenolics	Increase in total phenolic content (15%)	Grimi et al. [25]
Red grape mash	15–70 kJ/kg, 1.5 kV/cm, 50 Hz, 20-µs pulse width	Grape juice	Vitamin C, phenolics	Increase in vitamin C content (19%) and total phenolic content (61%)	Leong et al. [36]
Blueberry	1–5 kV/cm, 10 kJ/kg, 10 Hz, 20-µs pulse width	Blueberry juice	Phenolics	Increase in total phenolic content (43%) and total anthocyanin content (60%)	Bobinaite et al. [11]
Carrot mash	0.4–0.8 kV/cm, 73–392 µs, 2–12 kJ/kg, 16–85 Hz,	Carrot juice	Carotenoids	Increase in total carotenoid content (20–33%)	Jaeger et al. [33]
Maize germ	7.3 kV/cm, 120 pulses, 91.4 kJ/kg	Maize germ oil	Phytosterols	Increase in phytosterols content (14.7%)	Guderjan et al. [28]
Rapeseed	5–7 kV/cm, 60–120 pulses, 42–84 kJ/kg, 30-µs pulse width	Rapeseed oil	Phenolics, phytosterols, tocopherols	Increase in total phenolics (270%), phytosterols (3%) and tocopherols (20%) contents	Guderjan et al. [29]
Olive paste	1–2 kV/cm, 1.47–5.22 kJ/kg, 50 pulses, 3-µs pulse width, 125 Hz	Olive oil	Carotenoids, phenolics, tocopherol	Increase in tocopherols (1.7%) Decrease in carotenoid (9.6%) and total and individual phenolics content (24.7%)	Abenoza et al. [2]
Olive paste	2 kV/cm, 11.25 kJ/kg, 25 Hz	Olive oil	Phenolics, phytosterols, tocopherols	Increase in total phenolic (11.5%), total phytosterols (9.9%) and total tocopherols (15%) contents	Puértolas and Martínez de Marañón [57]
Apple slices	0.5–2.0 kV/cm, 2–50 pulses, 12–192 J/kg, 1 Hz, 400-µs pulse width	Osmotically dehydrated apple slices	Vitamin C	Increase of vitamin C content (6.3%) at low PEF intensities and decrease at high intensities (84.4%)	Taiwo et al. [70]
Red bell pepper discs	0.5–2.5 kV/cm, 38–730 J/kg, 20 pulses, 400-µs pulse width, 2 Hz	Osmotically dehydrated red bell pepper discs	Vitamin C, carotenoids	Decreases of vitamin C content (87–93%) and total carotenoids content (20–45%)	Ade-Omowaye et al. [4]
Red bell pepper discs	1–50 pulses, 2 kV/cm, 320 J/kg, 400-µs pulse width, 1 Hz	Air dehydrated red bell pepper discs	Vitamin C	Decrease of vitamin C content (35–44%)	Ade-Omowaye et al. [5]
Actinidia kolomikta fruit	5 kV/cm, 150 s, 20-µs pulse width, 20 Hz	Air dehydrated *Actinidia kolomikta* fruit	Vitamin C	No effect on vitamin C content	[35]

found in Pinot Noir, i.e. malvidin-3-O-glucoside (+224%). The increase in the content of total phenolic (+61%) and vitamin C (+19%) as well as the improvement in the antioxidant activity (+31%) were observed in grape juices following PEF pre-treatment of grapes. López-Alfaro et al. [38] studied the effect of different PEF treatments on the antioxidant potential (total phenolics, anthocyanins, stilbenes, antioxidant capacity) of three grape varieties (Graciano, Tempranillo, and Grenache). PEF pre-treatments of grapes improved the antioxidant potential of juices. The highest PEF energy treatment was the one yielding the best results for total phenolics, anthocyanins, and stilbenes. The variety most favoured by PEF application was Tempranillo, followed by Graciano and, finally, Grenache. However, the antioxidant capacity of the samples was increased with the application of the lowest PEF energy treatments.

The influence of PEF pre-treatments (1, 3, and 5 kV/cm, and 10 kJ/kg) of blueberry fruits on the antioxidant properties of juice obtained by pressing was investigated by Bobinaite et al. [11]. The juice obtained from PEF pre-treated berries also had a significantly higher total phenolic content (+43%), total anthocyanin content (+60%), and antioxidant activity (+31%). However, PEF treatment intensity higher than 1 kV/cm did not significantly improve the antioxidant characteristics of the juice. However, total phenolics and anthocyanin content as well as antioxidant activity in red raspberries juice did not change after PEF pretreatment of raspberries [37].

The adjustment of milling, mash electroporation, and pressing for the development of a PEF-assisted apple and carrot juice production in industrial scale were studied by Jaeger et al. [33]. For this purpose, different mash structures were subjected to PEF treatment at two different treatment intensity levels (3 and 12 kJ/kg), and solid–liquid separation was performed using four different systems (belt press, rack-and-cloth press, hydraulic filter press and decanter). A trend towards an increase in total phenolics in apple juice due to PEF pre-treatment of apple mash can be shown for all dejuicing systems and mash types except for fine mash processed with the belt press. A lower release of polyphenols was found for the coarse mash in comparison to the fine mash (for untreated samples). For PEF-treated samples, the increase in total phenolic values of the juice was higher for coarse mash in comparison to fine mash. An increase in the carotenoids content in carrot juice due to PEF treatment of the mash was observed for the belt press and rack-and-cloth press and for the filter press (mash type 2).

To sum up, the optimization of critical parameters such as PEF treatment intensity, mash size, mode of processing, process scale, and type and variety of fruits, is necessary in order to further improve the beneficial effects of PEF pre-treatments of fruits for the obtaining of juices with high health-related properties.

Oil Extraction

PEF treatment has also been proposed to enhance the extraction of oil from tissues, such as maize, olives, and rapeseed.

Maximum increase in phytosterol yield by 14.7% in maize germ oil was reached when maize germ was PEF-treated at 7.3 kV/cm and 120 pulses (91.4 kJ/kg) [28]. The application of PEF (5–7 kV/cm and 42–84 kJ/kg) on the recovery of oil and functional food ingredients as antioxidants, tocopherols, polyphenols, and phytosterols as well as oil quality parameters from hulled and non-hulled rapeseed were investigated by Guderjan et al. [29]. PEF treatment has a marked effect on oil yield and content of functional food ingredients. Higher concentrations of total antioxidants, tocopherols, polyphenols, and phytosterols were observed in oil by the application of PEF to rapeseeds.

The effect of the application of PEF treatments at different intensities (up to 2 kV/cm and 5.22 kJ/kg) on Arbequina olive paste in reference to olive oil extraction at different malaxation times (0, 15, and 30 min) and temperatures (15 and 26 °C) was studied by Abenoza et al. [2]. It was observed that the concentration of the main pigments in virgin olive oils (chlorophylls and carotenoids) was somewhat higher for the control. The concentration of phenolic compounds that are related to the oxidative stability of olive oils was higher for the control than for the PEF-treated olive. However, the α-tocopherol content of olive oil was slightly higher when olives were PEF-treated. Puértolas and Martínez de Marañón [57] investigated the impact of the use PEF technology (2 kV/cm, 11.25 kJ/kg) on Arroniz olive oil production in terms of extraction yield and chemical and sensory quality at pilot scale in an industrial oil mill. Olive oil obtained by PEF exhibited significantly higher total phenolic content, total phytosterols and total tocopherols contents than control (11.5, 9.9, and 15.0%, respectively).

PEF processing integration in the production of oils has been shown as an appropriate technology to improve the antioxidant potential and health-related properties of oils.

Dehydration Processes

The permeabilization of vegetable tissues caused by PEF treatment induces an increase in the mass and heat transfer rates between the cells and their surroundings, which can be also exploited in order to enhance the efficiency of the dehydration processes [17].

Taiwo et al. [69] studied the influence of PEF pre-treatment (1.4 kV/cm, 0.8 ms) on the mass transfer, physical properties, and vitamin C of osmotically dehydrated apple slices. They observed vitamin C contents in PEF-treated apples similar to those of untreated samples after osmotic dehydration. In another study, Taiwo et al. [70] investigated the effects of applying PEF at different field strengths (0.5, 1.0, 2.0 kV/cm corresponding to 12, 48, and 192 J/kg, per pulse, respectively) and pulse numbers (2 to 50) to apple slices as a pretreatment to study their influence on osmotic dehydration. Using higher field strength resulted in samples containing lower amounts of vitamin C, whereas the effect of higher pulse number was not distinct on vitamin C retention in the samples.

Ade-Omowaye et al. [4] determined the mass transfer rates during osmotic dehydration by pre-treating red bell peppers with PEF (0.5–2.5 kV/cm) and evaluated their effects on vitamin C and carotenoids. Combination of PEF (2.5 kV/cm) with subsequent osmotic dehydration led to bell peppers with a higher content in vitamin C and carotenoids than osmotically dehydrated paprika at 55 °C. The concentration of vitamin C in red bell peppers pre-treated with PEF varying number of pulses (1–50) at 2 kV/cm during osmotic or convective air dehydration was studied by Ade-Omowaye et al. [5]. Osmotic dehydration reduced vitamin C levels more significantly than air drying. Vitamin C retention consistently was significantly decreased in samples treated with up to 20 pulses, whereas a significant increase in the retention occurred when 50 pulses were applied. Furthermore, the vitamin C retention during air drying decreased significantly and consistently with the number of pulses.

After PEF treatment (5 kV/cm, 150 s) and subsequent hot air drying, the vitamin C content of *Actinidia kolomikta* fruit remained unchanged. Even when drying time was increased to up to 3 h, PEF treatment did not impact the vitamin C content of of *A. kolomikta* fruits [35].

Health-Related Compounds of Plant-Food Systems Stressed by PEF

Recent studies have suggested the possibility of using PEF to stress cells and thus stimulate the biosynthesis of secondary metabolites. The low intensity PEF technology has been proposed as a useful tool for stress induction and accumulation of bioactive compounds in plants, due to the permeabilization phenomenon. The external application of an electric field about 1 kV/cm induces a potential difference of about 200 mV to 1 V across the cytoplasmic membrane for a period long enough (microseconds to milliseconds) to induce pore formation in the cell membrane [81]. However, depending on the electric field parameters as intensity, frequency, pulse length and shape, and material properties, the character of electroporation can be reversible or irreversible. When low treatment intensity (0.1–1.5 kV/cm) is used, the voltage-induced openings of channels in the cell membrane cause reversible damage [71].

Some studies have shown that reversible membrane permeabilization induces generation of radical oxygen species (ROS) within plant cells and changes in cell metabolites accumulation [12, 24]. ROS have been suggested to be part of the endogenous signal components required for elicitor induced synthesis of secondary metabolites, which are widely believed to be part of the defence response of plants to stress [66]. To characterize stress response after reversible permeabilization of potato tissue, metabolite profiling was used, providing insight in tissue response to stress induced by external stimulation [22]. Changes in hexose pool and decrease in chlorogenic acid content of potato tissue were observed 24 h after induced electroporation with a single rectangular pulse (duration of 1 ms) at electric

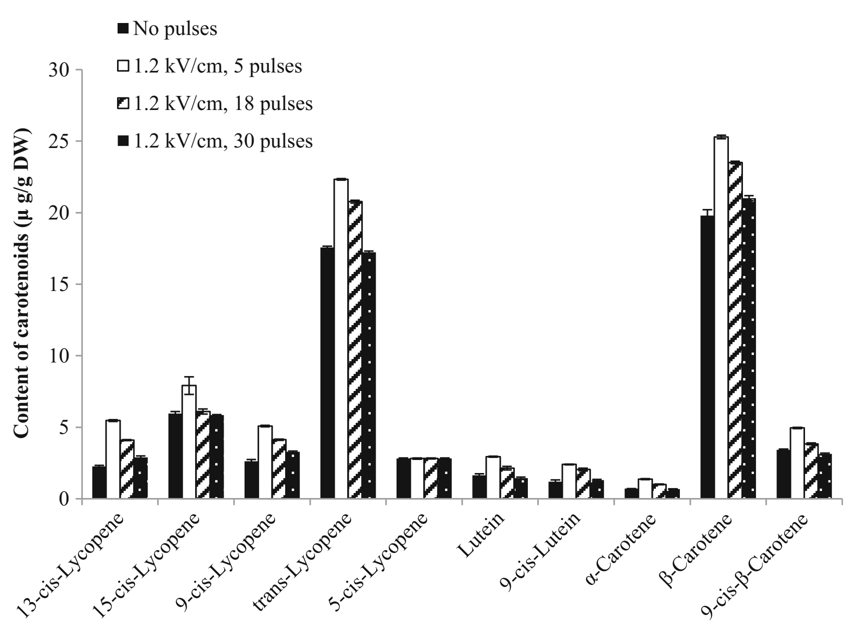

Fig. 1 Content of carotenoids (µg/g DW) of pulsed electric fields (PEF)-treated tomato fruit. Data shown are the mean ± SD of two PEF treatment repetitions

field strength in the range of 200–400 V/cm. Reversible pore formation and osmoregulation were suggested as relevant events caused by PEF stressor that contributed to observed changes. PEF treatments may also induce stress reactions in tomato fruits after 24 h of refrigeration by stimulating metabolic activity and accumulating secondary metabolites, depending on the electric field strength (0,4–2 kV/cm) and number of pulses (5–30). The maximum overall level of bioactive compounds and antioxidant capacity in the treated tomatoes was obtained under 16 pulses at 1 kV/cm. Maximum increases in total polyphenol (36.58%) and lycopene (20.10%) contents were obtained by combining 1 kV/cm and 16 pulses, contributing to an increase in the antioxidant capacity of tomato fruit by more than 20% [76]. High individual polyphenol and carotenoid contents were obtained in PEF treated tomato fruits after refrigeration at 4 °C for 24 h. Treatments at 1.2 kV/cm and 30 pulses, led to the greatest increases in chlorogenic (152%), caffeic acid-O-glucoside (170%) and caffeic (140%) acids. On the other hand, as it can be shown in Fig. 1. treatments at 1.2 kV/cm and 5 pulses led to maximum increases of a-carotene, 9- and 13-cis-lycopene, which increased by 93, 94, and 140%, respectively [78]. Moreover, the combination of moderate and high intensity PEF treatments could be used as a strategy for producing tomato juices with higher content of phenolic compounds and carotenoids. An enhancement of 63–65% in 15-cis-lycopene, 25% in chlorogenic acid, and 52% in naringenin-7-O-glucoside was observed in juices prepared with tomatoes subjected to treatments of moderate intensity [77, 79].

The ability of higher plants to synthesize secondary metabolites is transferred into cell cultures, which offers an alternative way for production of bioactive compounds [12]. PEF can be an external stimulus to enhance secondary metabolite biosynthesis from plant cell cultures. Guderjan and Knorr treated soy plant tissue culture with 20–50 pulses of 1.3 kV/cm PEF, and found out that daidzein and genistein contents increased by 20% and 21%, respectively compared to the control. Gueven and Knorr [30] also found that 1.6 kV/cm PEF treatment increased isoflavanoid production of 7 days old soy plant tissue culture. Application of PEF increased the phenolic acids accumulation in *Vitis vinifera* suspension culture medium, the total extracellular phenolic acids was 11% higher than that of the control [12]. It has been shown that PEF treatment can offer an alternative to other methods for increasing phenylalanine ammonia lyase (PAL) activity in plant cell cultures, the key enzyme for secondary metabolite synthesis from tomato cell culture. PEF treatment combined with the sub-culturing technique increased PAL activity due to the ability of the sub-culturing of enhancing the cell structure and improved the cell membrane permeability [31].

Conclusions and Future Trends

PEF processing strategies have been revealed as useful tools to preserve and enhance the contents of health-related compounds and functional characteristics of plant-based foods. In this way, PEF could increase the extraction of bioactive compounds from fruit and vegetables and increase their healthy potential. PEF have been shown to be an interesting technology to preserve plant-based foods without significant depletion of their fresh bioactive potential. The integration of PEF technology in the conventional processes for obtaining plant-based products entails the increase of the concentration of bioactive compounds in the resultant products. Moreover, the use of PEF as abiotic stressor could be a feasible strategy for increasing the bioproduction of secondary metabolites in raw fruits and vegetables, thus promoting their antioxidant potential. Therefore, PEF technology has good prospects for commercial implementation, provided that different PEF strategies could be used in order to offer the consumers novel healthy plant-derived products. However, more research and development activities are required to understand, optimize, and apply these complex PEF processes to its full potential.

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Compliance with Ethical Standards In this review, principles of ethical and professional conduct have been followed. This study does not involve research on human participants and/or animals.

Conflict of Interest The authors declare that they have no conflict of interest.

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