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REVIEW

Health Benefits of High Voltage Electrostatic Field Processing of Fruits and Vegetables

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Abstract
High voltage electrostatic field processing (HVEF) is a food preservation procedure frequently used to produce healthy minimally processed fruits and vegetables (F&V) as it reduces the growth of microorganisms and activates or inhibits various enzymes, thus retarding their natural ripening while preserving and even enhancing native nutritional quality and sensory characteristics. HVEF is one of the various nonthermal processing technology (NTPT) regarded as abiotic stress that can activate the antioxidant system of F&V and can also inhibith spoilage enzymes as, polyphenol oxidase (PPO), lipoxygenase (LOX), pectin methylesterase (PME), polygalacturonase (PG), cellulase (Cel), β-xylosidase, xyloglucan and endotransglycosylase/hydrolase, bringing positive effect on hardness, firmness, colour attributes, electric conductivity, antioxidant compounds, microstructure and decreasing electrolyte leakage (EL), malondialdehyde (MDA) contents and browning degree. This technique can also increase the contents of fructose, glucose, and sucrose and decrease the production of CO_2 and H_2O_2. Additionally, it has been reported that HVEF could be used with other treatments, such as modified atmosphere packaging (MAP) and acidic electrolyzed water (AEW) treatment, to enhance its effects. Future works should deepen on elucidating the activation of the antioxidant systems by applying HVEF of critical enzymes related to the synthesis pathways of phenolic compounds (PC) and carotenoids (Car). Holistic approaches to the effects of HVEF on metabolism based on systems biology also need to be studied by considering the overall biochemical, physical, and process engineering related aspects of this technique.

Keywords High voltage electrostatic field · Abiotic stress · Phenolic compounds · Carotenoids · Antioxidant capacity · Food preservation

Introduction

NTPT is a suitable option to traditional thermal processes that aid in satisfying the growing demand for high-quality minimal processed F&V products; these technologies include high pressure processing (HPP), pulsed electric field (PEF), pulsed light (PL), plasma, ultrasound (US), and HVEF [1] among others. Also, they have the potential to assure microbial safety and inactivation of spoilage enzymes while guaranteeing considerable retention of phytochemicals [2]. Moreover, some of these technologies can induce postharvest abiotic stress by favouring the production of secondary metabolites [3], as HVEF, HPP, PEF, US, and ultraviolet irradiation. For example, US and PEF showed to have positive effects in significantly increasing nutraceutical compounds when applied to entire carrots, as they activate the biosynthesis of PC) [4] and Car [5], ascorbic acid (AsA), and glutathione as in pomegranates [6], mushrooms [7], carrot juice [8] and strawberries [9]. These compounds have antioxidant capacity and play a protective function in health conditions, such as cardiovascular diseases (CVD) and diabetes, since they are strongly related to the oxidative damage of cells [10]. One of the main advantages of using HVEF is that there are no reported increments in foods'

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temperature and, consequently, this process can successfully be applied to temperature-sensitive F&V; moreover, during HVEF, the consumption of electric power is kept to a minimum [11]. This review aimed to provide an updated report on the induced changes in health-promoting compounds and strategies to maintain or increase their contents by applying HVEF to fresh F&V to support the production of minimally processed products.

Antioxidant Compounds in Human Health

The amount of chemical radicals that an antioxidant molecule or composite material can eliminate or neutralize from the environment is known as the antioxidant capacity [12]. In the last decades, phytochemicals like Car and PC have gained attention in human nutrition due to their function as biological antioxidants, supporting the organisms' defence against reactive oxygen species (ROS), thus protecting against CVD [10] by disrupting cellular signalling pathways, interference of gene expression, and inhibition of specific enzymes [10]. Cellular ROS participate in signalling cascades as secondary messengers, essential for physiological processes, including cell development and differentiation, essential for physiological processes, including cell development and differentiation but in intracellular redox homeostasis, when cells present an imbalanced redox rate (ROS > antioxidants), they damage lipids, proteins, and DNA, a balanced redox (ROS = antioxidants) rate results in proper cell differentiation and growth and overall maintenance of homeostasis; additionally, imbalanced redox rate (ROS < antioxidants) reduces metabolic functions like cell proliferation and immune response [13].

It has been reported that there is a strong relationship between the consumption of Car and PC in the prevention or treatment of CVD, cancer, asthma, chronic obstructive pulmonary condition, arthritis, neurodegenerative diseases, age-related macular degeneration, cataracts, glaucoma and diabetes [14]. Also, an optimal supply of antioxidants increases dermal defences in the skin against UV irradiation and supports long-term protection, contributing to the maintenance of skin health and appearance [14].

Minimally Processed Foods and Nonthermal Processing Technologies

The FAO encourages the consumption of unprocessed or minimally processed F&V since, as mentioned above, they maintain most of their overall quality [15]. Minimal processing includes technologies that have the potential to solve food preservation issues by keeping undesirable changes to a minimum and, in some cases, increasing their nutritional attributes by the reduction of the thermal load during production [16]. Extending the shelf life of F&V is a difficult task, but it is possible to achieve this by using preservation techniques based on chemical, biological, and physical factors [17]. The use of chemicals refers to the addition of compounds that have antimicrobial and antioxidant activity that can maintain at minimum levels or destroy microorganisms and also inhibit enzymes [18]. Biological methods are used by living organisms that negatively affect undesirable agents by damaging them or making them less abundant [19].

The biological effects of NTPT mainly rely on physical processes such as HPP, which damage microbial cells and induce protein structure modification [20]; high-power ultrasound that produces cavitation that harms cell integrity [21]; cold plasma, which generates reactive oxygen and nitrogen species (RONS) and provokes cell leakage, protein denaturation, and DNA damage [22]; pulsed electric field that induces the formation of pores in membranes (electroporation) followed by cell death [23], and ultraviolet irradiation that disrupts the DNA of microorganisms, modifying their metabolism and reproduction [24]. The abiotic stress associated with minimal processing and NTPT has raised interest since these processes increase the content of health-promoting compounds such as Car and PC in the tissues and, at the same time, aid in maintaining the quality, freshness, and safety of the products [25]. In particular, HVEF has been reported to affect enzyme activity, cell morphology and the disruption of cell membranes [21, 22], having negative effects on adverse microorganisms [9], and spoilage enzymes [26], and increases compounds that promote health, like Car and PC [27, 28], that positively influences the antioxidant capacity [29].

High Voltage Electrostatic Field Processing

HVEF can preserve the fresh-like quality of the processed F&V while ensuring food safety. An HVEF equipment consists of a source of high voltage, a generator and a modulator of frequency (for alternate current), a control unit, and a treatment chamber fitted with electrodes (anode and cathode) of different shapes and designs [30]. The sample is always placed on the cathode. In general, plate-to-plate parallel electrodes (Fig. 1A) are often used [11] and, in recent years, other configurations as needle plate-to-plate [31] (Fig. 1B) and barbed plate-to-plate [9] electrodes (Fig. 1C) have been used. The specific effects of nutriments, enzymes, and microorganisms using any of these configurations is a pending agenda in HVEF research. Besides the nonthermal nature of this technology [11], HVEF treated goods can also reduce their microbial load [9], inhibit enzymes, delay

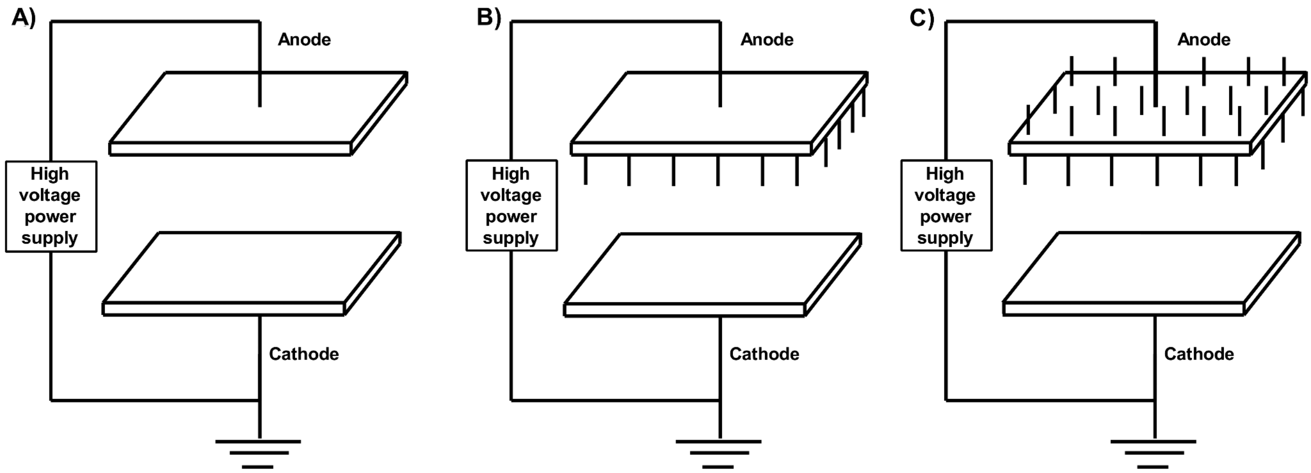

Fig. 1 Electrodes used in HVEF. (A) Plate-to-plate, (B) Needle plate-to-plate, and (C) Barbed plate-to-plate

tissue softening, and modulate cell metabolism [32]. Consequently, any temperature-sensitive food as F&V may be subjected to this methodology [11]. It has been reported that this process can decrease the respiration rate as observed in emblic fruit [33], persimmons [32], and strawberries [26], and at the same time, increasing their shelf life.

HVEF also inhibits various spoilage enzymes as PPO [7], LOX [28], PME, PG, Cel, β-xylosidase, β-galactosidase (β-gal), β-glucosidase (β-Glu) and xyloglucan endotransglycosylase/hydrolase [26], bringing a positive effect on the appearance, texture, and cell integrity of F&V, favouring their hardness, firmness, colour attributes, microstructure, and inhibition of browning, electric conductivity, MDA and EL [7, 26]. Inhibition effects of *Mycosphaerella tassiana*, *Monilinia laxa*, yeast and mould, among others, have also been reported [9]. This technique also increases the contents of fructose glucose, sucrose, total soluble solids (TSS) and reduces the production of CO_2, H_2O_2, and ethylene [8, 34, 35]. Due to the increment in simple carbohydrates after HVEF, consumers could perceive a sweeter taste in processed goods. Table 1 summarises the reported maximum effects (except the antioxidant features depicted in Table 2) of HVEF on F&V.

Increasing Antioxidant Compounds by HVEF on F&V

The abiotic stress response by the application of HVEF occurs by the production of stress-signalling molecules as RONS [40] that activates the expression of primary and secondary metabolism genes, inducing the production of enzyme mediated synthesis of secondary metabolites [41]. Also, hormones like ethylene and jasmonic acid trigger the activation of defence genes in plants subjected to HVEF mediated abiotic stress, modulating primary and secondary metabolism [42]. In the biosynthesis of PC, critical enzymes involved are coumarate 4-hydrolase (C4H), Phenylalanine ammonia-lyase (PAL) and 4-coumarate-CoA ligase (4CL), and for Car synthesis, main suggested enzymes are geranylgeranyl diphosphatase synthase (GGPPS), phytoene desaturase (PDS), carotene desaturase (ZDS), and phytoene synthase (PSY) [25]. Zhang et al. [9] applied HVEF to strawberries and found a higher activity in PAL and 4CL enzymes and PC content.

Figure 2 illustrates the primary mechanism of HVEF on F&V. Firstly, a generation of a high voltage electrostatic field produces a plasma discharge by ionizing the air surrounding the anode [43, 44], which leads to the production of ions, radicals [45], RONS, and ozone [46] as well as UV photons [47], which also form part of the induced abiotic stress. The generation of RONS can also affect the increment of antioxidant compounds, as reported in a work on fresh-cut green pepper for which the application of ozone and MAP treatments could enhance the activity of antioxidant enzymes such as SOD, PAL, and peroxidase (POD) [48]. Also, in a work on organic table grapes, authors found that treatments with ozone and MAP gave place to an increase in antioxidant capacity, anthocyanin accumulation, and total PC during cold storage [49] and, a research on sweet cherry fruit subject to UV irradiation, showed that fruits maintained native amounts of total PC, anthocyanins, and preserved their antioxidant capacity [50].

Effect of HVEF on Antioxidant Enzymes

Abiotic stress also influences plants' growth, productivity, and development. The homeostasis and ion distribution in plant cells are often perturbed by this factor, causing osmotic stress and increased accumulation of ROS [51]. The first plant defence against oxidative stress is via the endogenous mechanism pathways involving enzymes such as ascorbate

Table 1 Effects of HVEF on general features of F&V by its combined or single application*

Product	Inhibition of spoilage enzymes and microorganisms (%)	Changes in physical properties (%)	Preservation of cell integrity (%)	Effect on the content (%) of other molecules	Changes in sensory profile (%)	References
Fresh cut broccoli	PME (14.3)	Hardness (+264.2), a* (–23.5), b* (+11.3)	EL (–509.2),	TSS (+15.2)	–	[36]
Mushroom	PPO (68.1),	Maintain of whiteness index (+14.2), L* (+13.7), a* (–24.7), b* (–29.1), hardness (+42.4)	MDA (–23.2)	–	–	[7]
Fresh carrot juice	–	–	–	Sucrose (+7.9), fructose (+10.2), glucose (+8.9)	–	[8]
Fresh-cut cabbage and baby corn	Fresh-cut cabbage: PME (65.3)	Fresh-cut cabbage: a* (–34.2), colour change (+503.1), hardness (+112.6) Baby corn: b* (+62.1), colour change (–80.8),	–	Fresh-cut cabbage: CO2 (–88.9), TSS (+99.9) Baby corn: CO2 (–79.1), TSS (+33.3)	Fresh-cut cabbage: smell (–48.3), colour (–15.6), texture (+18.2), overall acceptability (+50) Baby corn: smell (+75), colour (+68.4), texture (+93.8), overall acceptability (+44.4)	[37]
Whole pomegranate fruit	PPO (5.1)	Weight loss (+49.2)	EL (+23.4)	H2O2 content (–37.5)	–	[6]
Pakchoi	PPO (65.1), aerobic plate count (28)	Hardness (+38.9), springiness (+11.4), gumminess (+57), chewiness (+58.4)	Respiration rate (–42.5), electrical conductivity (–65.2)	TSS (+9.6)	Sensory score (+58.4)	[31]
Strawberry	PG (26.9), PME (23.8), Cel (43.2), β-xylosidase (14.2), Xyloglucan endotransglycosylase/hydrolase (7.2)	Weight loss (–29.9), firmness (+17.3),	MDA (–22.4), protopectin (+25.4), water soluble pectin (–14), electrical conductivity (–36.8)	H2O2 (–54.1), O2 (–37.9)	Decay index (–45.8)	[26]
Cherry tomatoes	Aerobic plate count (12.6)	Weight loss (–23.1), hardness (+14.2), L* (+16.8)	–	TSS (+6.8), pH (–1.7)	–	[29]
Huping jujube	–	Weight loss (–27.2)	Respiration rate (–40)	TSS (+13.6), total soluble sugar (+17.8), reducing sugar (+18.9), titratable acidity (+30.3)	Decay index (–88.3), reddening index (–39.5), L* (+29.2), a* (–82–4), b* (–29.2),	[35]
Jujube fruit	PG (18.7), β-Gal (20.5), Cel (24), β-Glu (12.3), LOX (9.3),	Firmness (+20%),	EL (–23.1), MDA (–16.2)	H2O2 (–16.2)	–	[38]
Tomato	PME (49.2), PG (63.7), Cel (56.8), PPO (56.3)	L* (+16.2), a* (+55.1), b* (+9.4), browning degree (–31), weight loss (–33.9), hardness change (–39.3)	Electrical conductivity (–69.7%)	TSS (–53.7), organic acid content (+46), CO2 (–65.1), ethylene (–33.3)	–	[34]

Table 1 (continued)

Product	Inhibition of spoilage enzymes and microorganisms (%)	Changes in physical properties (%)	Preservation of cell integrity (%)	Effect on the content (%) of other molecules	Changes in sensory profile (%)	References
Strawberries	*M. tassiana* (42.1) and lesion diameter (88.3), *M. laxa* (28.6) and lesion diameter (82.9), total bacteria count (62.7), yeast and mould count (55.1)	L* (+14.8),	–	–	Decay index (–74.8)	[9]
Plum fruit	PPO (25.2)	Firmness (+23.9), weight loss (–25.5)	MDA (–20.1), electrical conductivity (–16.5)	TSS (+32), titratable acidity (+23.1)	–	[39]

* All figures presented are with respect to control sample

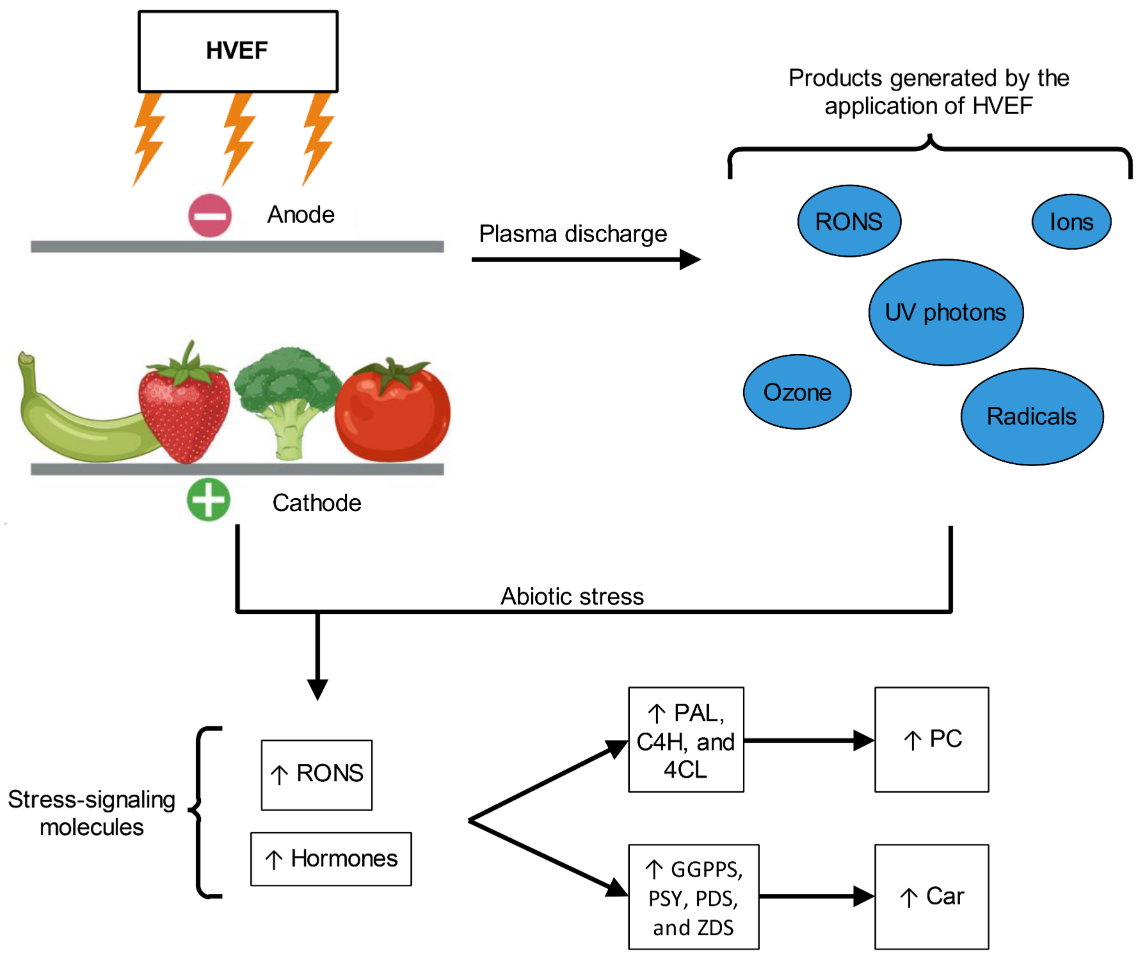

Fig. 2 Pathway related to the biosynthesis of antioxidant compounds in F&V by abiotic stress due to HVEF

peroxidase (APX), superoxide dismutase (SOD), catalase (CAT), guaiacol peroxidase (GOPX), glutathione reductase (GR) and, glutathione peroxidase (GPX), among others [52]. Also, this pathway includes non-enzymatic defences as those mediated by AsA, Car and PC, among other antioxidant compounds [52]. Several publications on this subject have been directed to develop fresh-like products containing health-promoting agents by controlled stress [19, 23, 24, 41], carried out by a series of immediate, early, and late responses that activate antioxidant systems and accumulation of health-promoting compounds [53].

Table 2 depicts works on HVEF and its effects on the antioxidant system of F&V as from 2018. Notably, HVEF can enhance the production and liberation of Car, PC, and

Table 2 Effects on antioxidant characteristics of F&V by the combined and single application of HVEF*

Product	Technology	Treatment conditions	Maximum increase of antioxidant characteristics (%)			References
			Antioxidant compounds content	Antioxidant capacity	Antioxidant enzymes activity	
Fresh cut broccoli	HVEF	0.5–4 kV cm^{-1} 5–40 min	–	–	SOD (30.1)	[36]
Mushroom	HVEF	During storage: 0.097 kV cm^{-1} 50 Hz For 12 days	PC (27.9)	–	SOD (23.9) and CAT (48.6)	[7]
Fresh carrot juice	HVEF cold plasma	20 kV cm^{-1} 4 min	Car (25.5), lycopene (107.8), lutein (14.2), and chlorogenic acid (25)	–	–	[8]
Fresh-cut cabbage and baby corn	HVEF assisted MAP	During storage: 1 kV cm^{-1} for 60 days for cabbage and 0.94 kV cm^{-1} for 48 days for baby corn	For fresh-cut cabbage: total PC (50.5) For baby corn: total PC (7.8)	–	For fresh-cut cabbage: SOD (69.5) For baby corn: SOD (12)	[37]
Whole pomegranate fruit	HVEF	1.5 and 3 kV cm^{-1} Treatment was replicated from the second week and continued every week under the same conditions for 2 h	PC (22.3) and AsA (15.4)	–	SOD (25.3), APX (12.2) and CAT (36.8)	[6]
Pakchoi	HVEF assisted MAP	1, 2, 4, and 8 kV cm^{-1} Once every 5 days for 2 h	AsA (255.2) and Chl (152.78)	–	SOD (30)	[31]
Strawberry	Low voltage electrostatic field	0.45 kV cm^{-1} during storage	AsA (3.1) and glutathione (23.3)	–	SOD (47.3), CAT (20.5), and APX (29.5)	[26]
Cherry tomatoes	HVEF	1.5 kV cm^{-1} 50 Hz 30,60, 90 and 120 min	PC (120) and AsA (15.9)	DPPH radicals-scavenging (23.2)	–	[29]
Huping Jujube	AEW and HVEF	2 kV cm^{-1} for 3 h	Flavonoids (6.2) and Chl (27.4)	ABTS radicals-scavenging (14.5)	GR (80.9)	[35]
Jujube fruit	AEW and HVEF	2 kV cm^{-1} for 3 h	AsA (12.2) and total PC (17.8), glutathione (12.1), and total flavonoids (36.5)	–	SOD (46.6) and CAT (83.6), APX (40.8), and POD (64.9)	[38]
Tomato	Direct and alternating current electric field	2.5 kV cm^{-1}, 50 Hz for 30, 60, 90, and 120 min	AsA (284.9)	–	SOD (114.2), and CAT (52.8)	[34]
Strawberries	Intermittent HVEF and static magnetic field assisted to MAP	1.5, 3 and 4.5 kV cm^{-1} 2, 5 and 8 mT (respectively) for 120 min	PC (67)	–	PAL (109) and 4CL (152.4)	[9]
Plum fruit	HVEF	During storage: from 0.005 to 0.008 kV cm^{-1} and from 0.012 to 0.015 kV cm^{-1} For 49 days	PC (20.1)	–	POD (37.25)	[39]

* All figures are with respect to control sample

chlorophyll (Chl) with the concomitant increment of the antioxidant capacity. It can also be noted that HVEF conditions were within 0.005 kV cm^{-1} to 20 kV cm^{-1}, and it was pointed out that mild HVEF in the range of 0.005 to 1.0 kV cm^{-1} was applied during the storage of plum fruit [39], mushroom [7], baby corn, and cabbage [37]. For HVEF above 8 kV cm^{-1}, it was necessary to use a dielectric barrier to reach the required field strength of 20 kV cm^{-1}, as in fresh carrot juice [8].

Moreover, HVEF, in combination with other processes such as MAP and AEW treatment, increased antioxidant capacity and the presence of antioxidant compounds in fresh-cut cabbage and baby corn [37], pakchoi [31], jujube fruit [38], and strawberries [9]. Most MAP use O_2, N_2, and CO_2, which have antimicrobial effects [54]. When HVEF is applied in a rich O_2 and N_2 medium, RONS can be produced [55] and, as earlier mentioned and shown in Fig. 2, these molecules can induce abiotic stress in F&V. Additionally, it has been reported that the exposure to CO_2 can affect the secondary metabolism pathways [56] as well as those related to fermentation [57] and respiration [56]. Furthermore, the MAP with CO_2 can maintain some antioxidant compounds, including antioxidant enzymes, such as fresh-cut lotus root [58] and sweet cherry [59]. The mixture of O_2, N_2, and CO_2 also gave place to these effects, as reported for pakchoi [60], apricot fruit [61], and fresh-cut amaranth leaves [62].

HVEF combined with a pretreatment using AEW gave place to a synergistic effect related to the decrement of antioxidant enzymes like APX, CAT, SOD and POD as well as with the increment of cell-wall degrading enzymes as PG, β-gal, Cel and βGlu [38]. During electrolysis for the production of AEW, the redox potential of the medium is increased by the presence of Cl^- and Na^+ and, consequently, pH is reduced to values <2.8 [63, 64] and an abiotic stress is induced [65] with the concomitant enhancement or reduction of the loss of antioxidant compounds, including enzymes, as observed in longan fruit [64] and jujube fruit [66].

PC directly impact the accepted quality attributes of F&V, such as bitterness, color, and flavor [67]. Also, Car are associated with the colours orange and red, and Chl is correlated with the green colour in F&V [68]; with the increment of these compounds after HVEF, quality attributes can be perceived as more intense than those of untreated samples. An example of the application of HVEF on the progression of spotting in bananas (*Musa paradisiaca* var. *sapientum*) was reported by Valdez-Miranda et al. [69]. Fruits presented spotting on day 4, while untreated samples showed it on day 2; also, the HVEF group showed less surface spotting than the untreated ones on days 4 and 6. In these fruits, the yellow colour of the peel is related to Car accumulation [70]. Vu et al. [71] showed that when fruits turned from green to yellow, the Chl content decreased while Car, total PC, proanthocyanidins and flavonoids increased. It was possible to observe that HVEF retarded the colour and spotting of the peels.

On the other hand, *in vitro* and *in vivo* studies have shown that PC and Car possess antioxidant [72, 73], anti-inflammatory [73, 74], anti-angiogenic [73, 75], and antitumor [73, 76] properties. Also, clinical trials have demonstrated the potential health benefits of these compounds in humans [73].

Since phytochemicals play an essential role in human health, it is convenient to maintain or increase their content during the product's shelf life. In this respect, HVEF represents a promising technology since it allows the preservation of sensorial characteristics and maintains or increases the content of phytochemicals.

For future works, it is suggested to study the kinetics of HVE effects on biochemical and physical changes of diverse F&V and to deepen studies on the induced impact of this technique when used in combination with other preservation methodologies. In particular, the possible activation of the antioxidant systems by key enzymes as PAL, C4H, and 4CL as well as GGPPS, PSY, PDS, and ZDS involved in the synthesis pathways of PC and Car respectively. Also, it would be important to deepen the holistic approaches to applications of this procedure as those based on systems biology [73] by considering the overall cellular and molecular biochemical, physical, and process engineering related aspects of this technique. It is recommended to study extracts from the different matrices mentioned in this work to assess if the increment of antioxidant compounds enhances the above mentioned in *vitro* and in *vivo* effects.

Conclusions

Several human health related effects of HVEF within 0.005 kV cm^{-1} to 20 kV cm^{-1} on F&V have been reported in this review, and most of them, as a consequence of the induced abiotic stress that stimulates the primary and secondary metabolism and, consequently increases the availability of simple carbohidrates as glucose, fructose and sucrose and antioxidant compounds as PC, Car, and various antioxidant enzymes, and diminishes production of CO_2 and H_2O_2. This treatment also causes inhibition of spoilage enzymes as, for example, PPO, PME, PG and Cel, bringing positive effect on hardness, firmness, colour attributes, microstructure and decreasing electric conductivity, EL and MDA. All of thse changes also brings modification of sensorial characteristics of the treated foodstuffs. It has been reported that HVEF may be used in combination with other treatments as MAP and AEW, to enhance its positive effects towards health. The impact of this methodology varies depending on the applied conditions and food matrix. Thus, it is necessary to direct future research to a broader range of F&V for which no published information exists. Also, the molecular mechanisms related to the antioxidant response and production of varied metabolites that promote human health against some conditions like CVD should be further studied including more in *vivo* and in *vitro* studies. For future works, it is also suggested to study the kinetics of HVEV effects on biochemical pathways and to deepen holistic approaches based on systems biology by considering the overall biochemical, physical and process engineering related aspects of this technique.

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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.

Conflict of interest The authors have no conflicts of interest to declare.

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