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Pulsed electric field: A novel technique for sustainability in fruit and vegetable processing

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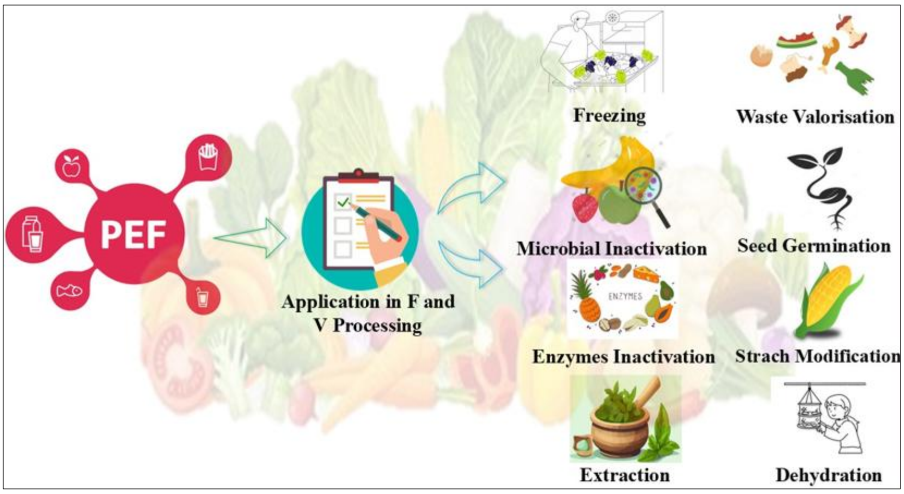
Abstract
Pulsed Electric Field (PEF) is a new method that can permeabilize cells found in fruit and vegetable tissues without significantly raising the product's temperature or causing the tissue to deteriorate too significantly. The basics of this innovative technology and its primary uses in the preparation of fruits and vegetables are outlined in this overview. Pulsed Electric Field has been suggested to improve or support several processing procedures, including dehydration, freezing, fruit and vegetable waste and by-product revalorization, and solid-liquid extraction. Pulsed Electric Field technology has several uses in fruit and vegetable processing, including improving fruit and vegetable safety by successfully inactivating dangerous microbes and increasing the nutritional content of fruit and vegetable by adding more health-promoting substances. This cutting-edge technology is at the forefront of fruit and vegetable processing solutions and promises to meet the rising demand from consumers for meals that are high-quality, safe, and nutrient-dense. The impact of this new technology on accomplishing the important industrial objectives of improved fruit and vegetable quality, lower water consumption, lower emissions, more energy efficiency, and the utilization of waste fruit and vegetable by-products is also covered. The necessity of comprehending the elements that can restrict the industrial adoption of this new technology is also emphasized by the current study.



Keywords: Pulsed electric field, sustainability, novel, processing

Introduction

A key idea in social, technological, and economic advancement, sustainability aims to create a circular economy and continue meeting societal demands. Consumers in developed nations are calling for a diet that is safe, nourishing, and has appealing sensory qualities. Concerns about the sustainability of the current fruit and vegetable systems include environmental issues (such as waste management, climate change, water and soil preservation), as well as a number of other issues like fruit and vegetable supply security, safety, quality, and accessibility.

By lowering manufacturing costs, bringing new goods to market, and enhancing product quality, the development of creative fruit and vegetable processing techniques can make the fruit and vegetable sector more competitive (Tiwari *et al*. 2009).

Innovative non-thermal processing technologies like Pulsed Electric Field (PEF), ultrasound (US), high hydrostatic pressure, and ultraviolet radiation are of interest to the fruit and vegetable industry because they can preserve fruit and vegetable quality, reduce nutrient loss during processing, and use less energy than traditional thermal processing methods (Manzoor *et al*., 2020) [3]. Among these, PEF is considered a cost-effective and environmentally friendly technique for microbial inactivation and enhancing mass transfer in fruit and vegetable products. The effectiveness of PEF depends on various parameters, including electric field intensity (kV/cm) and specific energy (J/kg), which influence different processes such as microorganism's/enzyme inactivation, recovery of bioactive or cell stimulation, structure modification, and freezing enhancement.

Pulsed Electric Field is typically regarded as a moderate or delicate technique in comparison to traditional physical methods because of its minimal impact on fruit and vegetable attributes. Due to its numerous application areas and the introduction of the first Pulsed Electric Field processed products to the market, Pulsed Electric Field is currently receiving more and more attention from the fruit and vegetable industry. Using Pulsed Electric Field in conjunction with other physical techniques, such as UV radiation (Gachovska *et al*. 2008) [18], high intensity light pulses (HILP) (Caminiti *et al*. 2011) [12], ultrasound (Aadil *et al*. 2018) [1], high pressure carbon dioxide (Pataro *et al*. 2010), and nanothermosonication (Palgan *et al*. 2012) [12], can increase its lethal effect on a variety of vegetative bacteria, mold, and yeast.

According to Baba, Parniakov, *et al*. (2015) [7], depending on the targeted fruit and vegetable and the application, electroporation occurs during Pulsed Electric Field therapy when the biological cells are exposed to the applied voltage with the corresponding electric field over the necessary critical transmembrane potential. Plant, animal, microbial, and algal cell membranes undergo hole creation following the application of the necessary critical transmembrane potential. Because they are larger than microbial cells (10–14 kV/cm), animal and plant cells only need a lower critical electric field intensity (0.5–2 kV/cm) for electroporation (Bhat *et al*., 2019) [10].

Electroporation is the process of creating either permanent (irreversible) or transient (reversible) pores. Pulsed Electric Field can be used extensively in the fruit and vegetable processing industries due to these features, which primarily include non-thermal microbial inactivation, the recovery of important chemicals from plant matrices, and as a pretreatment technique to improve freezing and drying operations (Arshad *et al*., 22020) [6].

Over the past ten years, a growing number of studies have examined the use of Pulsed Electric Field as a permeabilization pretreatment of fruits and vegetables to improve or support various processes, including solid-liquid extraction (e.g., ingredient extraction, winemaking, sucrose extraction from sugar beet, recovery of useful compounds from fruit and vegetable waste and by-product), mechanical extraction (e.g., juice expression, mechanical oil extraction), cutting/slicing (e.g., production of vegetable snacks or French fries), fruit and vegetable dehydration (e.g., hot air drying, osmotic dehydration, freeze-drying), and other intriguing operations (e.g., freezing, peeling). The foundations of Pulsed Electric Field technology for plant tissue permeabilization are the main emphasis of this chapter, which also highlights the technology's primary uses in the processing of fruits and vegetables.

This study demonstrates Pulsed Electric Field 's potential as a sustainable fruit and vegetable processing technique for use in industry, research, and education. Scientists and fruit and vegetable producers may find it useful to observe the commercial use of Pulsed Electric Field technology. The advantages of Pulsed Electric Field technology and treatment have also been investigated in order to assess the need for further advancements in order to make a more significant contribution to sustainable fruit and vegetable processing.

Principles of Electroporation

Pulsed Electric Field treatments entail applying high voltage, direct current pulses (<50 kV) with a very brief width (from a few microseconds to several milliseconds) intermittently (<300 Hz) to a target meal through at least one electrode, followed by its discharge through at least one grounding. Depending on the voltage, the distance between the electrodes, and the overall design of the treatment reactor, this produces a potential difference between the electrodes that subsequently leads to the application of pulsed electric fields to the fruit and vegetable, which can range from 0.1 to 50 kV/cm or even more (Puértolas *et al*. 2016).

A typical Pulsed Electric Field system is essentially made up:

1. A high voltage (HV) electric pulse generator
2. A treatment chamber (where fruit and vegetable is placed)
3. A suitable product handling system
4. A set of monitoring and controlling devices.

Treatment chambers are classified into two categories: dynamic or continuous flow chambers, which are made to satisfy industry needs, and batch or static chambers, which are mostly used for laboratory and foundational investigations (Toepfl *et al*. 2005).

Electric field intensities of 1 kV/cm are considered high-intensity electric fields, despite the lack of a precise definition. Depending on the fruit and vegetable, the application, and the Pulsed Electric Field system, low, moderate, or high electric fields are used to enhance disintegration/permeabilization processes.

The necessary electric field is rarely more than 10 kV/cm. Reversible electroporation is the process by which the membrane regains its structure and integrity once the Pulsed Electric Field treatment is complete, depending on the intensity of the treatment. The process is known as irreversible electroporation if the membrane is unable to regain its functioning. For biotechnological and medical applications like putting molecules into cells (classical electroporation), reversible electroporation is necessary. Irreversible electroporation is typically required to improve Pulsed Electric Field 's disintegration and permeabilization processes in the fruit and vegetable business.

Mechanism of Pulsed Electric Field

The mechanism of Pulsed Electric Field action is still unclear, but when applied to plant, animal, or microbial cells, it can temporarily or permanently disrupt the integrity of the cell membrane, increasing its permeability. Although a number of theoretical models have been proposed thus far, there is currently no proof of Pulsed Electric Field 's cellular action regimen (Soliva-Fortuny *et al*. 2009) [20]. According to experimental data, long, strong electrical pulses cause the water and lipids that make up the membrane to rearrange, resulting in the formation of aqueous hydrophilic holes (Weaver 2003). Using traditional techniques, such as electron microscopy, it is not feasible to directly examine pores of diameters in nanometres. However, the impact of an electric field on a cell membrane may now be modelled using computer techniques (molecular dynamics simulations) (Leach 2001) [29].

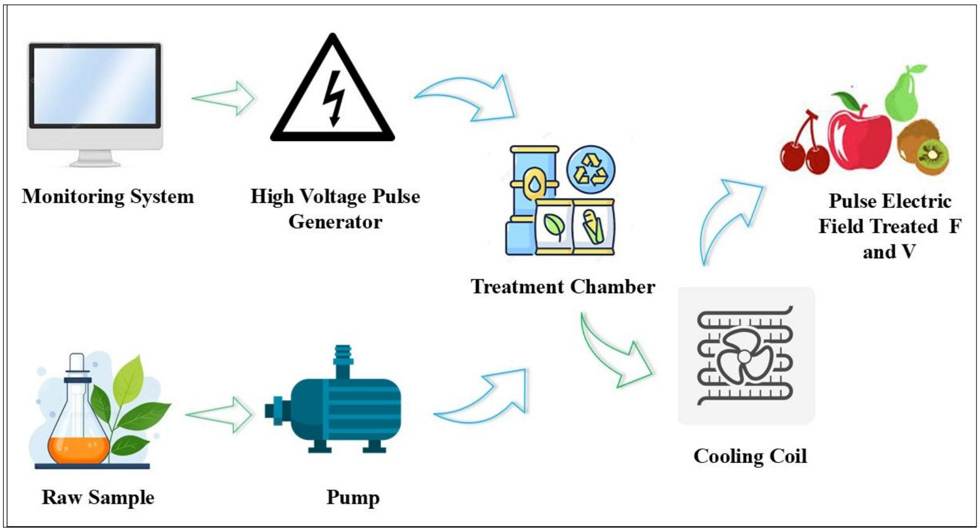


Fig 1: Mechanism of Pulsed Electric Field

According to Kotnik *et al*. (2010) [28], induced transmembrane voltage occurs when a biological cell is subjected to an external electric field while functioning as an electrolyte encased in an electrically insulted shell (the cytoplasm encircled by the plasma membrane). Because of the actions of potassium leak channels and sodium potassium pumps, there is an ionic gradient across the membrane under physiological conditions. Cell type determines its value, which normally falls between -80 and -40 mV (Kotnik and Miklavcic 2006) [27].

The local process of cell membrane permeabilization occurs when the electric field-induced transmembrane potential difference reaches 250 mV. For tiny charged molecules like DNA or metal ions, this area of the cell surface becomes extremely permeable (Teissie and Tsong 1981) [19]. Diffusion occurs for seconds and minutes and is primarily seen following the pulse (Gabriel and Teissie 1997) [18]. Field intensity, pulse characteristics (amplitude, duration, number, and repetition rate), membrane composition, ambient media, temperature, cell size and shape, and orientation to the electric field lines all affect permeabilization (Valic *et al*. 2003).

Membrane permeabilization is demonstrated by the cells' absorption of the indicator. The cells keep the added molecules or ions when the electric field stops working because the membrane flaws are sealed. The duration of exposure and the electric field's strength determine this. Depending on the temperature, resealing can take anything from a few seconds to several hours. For instance, the membrane flaws close in a few seconds at 37 °C, in a few minutes at 4 °C, and it takes several hours to keep cells on ice. The process is irreversible and may result in cell death if the field strength greatly beyond the critical value (Golzio *et al*. 2002) [19].

Pulsed Electric Field Fruit and Vegetable Processing towards sustainability

Pulsed Electric Field treatment is thought to be more environmentally friendly than conventional thermal fruit and vegetable processing. Because of its immediate benefits, such reduced energy and water use, Pulsed Electric Field technology has thus been proposed as a sustainable choice (Ostermeier *et al*., 2020). Furthermore, in many commercial fruit and vegetable production systems, fruit and vegetable losses, underutilization of by-products or processing residues, and quality losses are serious shortcomings (Picart-Palmade *et al*., 2019).

Sustainable technology for fruit and vegetable products can be achieved through two different technological techniques. First, it depends on the technological shift the replacement of outdated technology with new, more effective ones. The second tactic has to do with researching and applying current fruit and vegetable treatment technology. Pulsed Electric Field often supports an economic advantage for the fruit and vegetable industry while supporting sustainable fruit and vegetable processing without sacrificing product safety or quality (Clairand *et al*., 2020; Picart-Palmade *et al*., 2019) [13]. The sustainability of Pulsed Electric Field technology in each fruit and vegetable sector is technically assessed by life cycle evaluations, or LCAs. The table shows how Pulsed Electric Field contributes to sustainability in many fruit and vegetable applications, including fruit and vegetable safety, fruit and vegetable security, economic sustainability, and environmental sustainability.

Table 1: Pulsed Electric Field Contributions in sustainable fruit and vegetable processing.

Sustainability F &V Processing	Pulsed Electric Field Application	Pulsed Electric Field contributions toward sustainability	References
Fruit and vegetable safety	Nutrition security	Pulsed Electric Field preserves the nutritional values of the products	Pallares *et al*. (2020)
	Fruit and vegetable preservation	Pulsed Electric Field treatment is more effective for liquid fruit and vegetable pasteurization and solid fruit and vegetable dehydration/ freezing.	(Timmermans *et al*., 2019)
	Reducing fruit and vegetable contaminants	Pulsed Electric Field is an important technique to decrease fruit and vegetable processing toxins and contaminants.	Gulzar and Benjakul (2020) [21]
Environmental sustainability	Reduction of fruit and vegetable wastes	Pulsed Electric Field contributes to reducing fruit and vegetable wastes from an eco-friendly perspective.	Ahmad *et al*. (2020) [2]
	Minimizing the impact of pesticides on fruit and vegetable	Pulsed Electric Field reduces fruit and vegetable pesticides.	Misra (2015)
Economic sustainability	Reduced energy consumption	Pulsed Electric Field reduces the energy expenses of fruit and vegetable -processing by targeting the cell membranes.	Ferreira *et al*. (2019) [16]
	Solid fruit and vegetable pretreatment	Pulsed Electric Field treatment reduces the turgor pressure and softens plant tissue.	Vorobiev and Lebovka (2020)
Fruit and vegetable security	Improve the fruit and vegetable yield	Pulsed Electric Field treatment of seeds improves the yield.	Ahmed *et al*. (2020) [3]

Technical limitations of Pulsed Electric Field processing

Some issues still prevent Pulsed Electric Field technology from being commercialized into fruit and vegetable industry operations, despite the fact that it is progressing toward wider industrial use. There are still certain technological issues, financial disadvantages, market acceptance, legal ramifications, and toxicity hazards that must be addressed, particularly for applications from the fruit and vegetable sector that require rigorous Pulsed Electric Field treatment. The primary barriers to this technology's adaptation are as follows:

1. The main obstacle to Pulsed Electric Field 's commercial clearance is acknowledged to be the lack of more dependable and useful electrical systems. Therefore, process design can be greatly enhanced by energy efficiency.
2. The product may be disturbed throughout the treatment process due to the fouling and corrosion of these electrodes, migration of electrode material components, chemical changes, and electrolysis of water caused by the treatment chamber (Arshad, Abdul-Malek, Munir *et al*., 2020) [6].
3. Inadequately defined protocols also restrict the ability to compare data between laboratory and commercial scales; improperly chosen Pulsed Electric Field treatment parameters may lead to an ineffective course of treatment. reduction in the bioactive compound's concentration **(**Timmermans *et al*., 2019).
4. It is still unknown what the specific internal energy (J/kg) efficiency is for various fruit and vegetable applications.
5. Using renewable energy is a major problem for all processors because higher electricity usage results in more equivalent CO_2 emissions.
6. During processing, some of the electrical energy input is transformed into moderate heat, which could have an impact on the final product's quality (Aadil *et al*., 2018) [1].
7. Pulsed Electric Field was extensively studied, and certain commercial Pulsed Electric Field systems are currently in use in various nations; nonetheless, the conclusions obtained still pertain to laboratory-scale trials.

Table 1: Potential applications of Pulsed Electric Field in the Fruit and Vegetable Processing

Application	Sample	Treatment	Effect	References
Drying	Basil (*Ocimum basilicum* L.) leaves	65 pulses of 650 V/cm, 150 ls pulse width, 760 ls between pulses	Drying times reduced 57% for air drying, 33% for vacuum drying and 25% for freeze drying	Telfser and Gomez Galindo (2019)
	Carrot	Pulse number 10, 50 and 100; 1,85 and 5 kV/cm; 5,63, 8 and 80 kJ/kg	Drying time reduced up to 8.2%. Decrease of sample lightness up to 25.3%	Wiktor *et al*. (2015) [17]
	Potato, carrot, apple, mango, kiwifruit, pepper, and strawberry	0.3–4 kV/cm 1–20 kJ/kg	Drying times reduced	(Liu *et al*. 2020)
Freezing	Potato, carrot, spinach, green bean, apple	0.4–2 kV/cm 1–20 kJ/kg	Improving freezing through acceleration of cooling processes	(Parniakov *et al*., 2016a) [7]
	Apple tissue	800 V/cm, pulse duration 1000 ls, time interval 100 ms, 10 pulses	Acceleration of cooling processes; good preservation of the macro-shape, inhibition of shrinking, development of large pores in the electroporated tissue	Parniakov *et al*. (2016a) [7]
Extraction	Apple, carrot, chicory, beetroot, sugar beet, grapes, potato, tomato, and olive	0.6–10 kV/cm, 1–100 kJ/kg	Increasing the extraction of bioactive compounds; selective recovery of bioactive compounds	(Barba *et al*., 2016; Buchmann *et al*., 2019) [9]
	Citrus fruits and peel	3 kV/cm—fruits	Increased yield of juice by 25% for oranges,	El Kantar *et al*.

	(orange, pomelo and lemon)	10 kV/cm—peel	37% for pomelos and 59% for lemon, improved extraction of polyphenols to 50%	(2018) [15]
Preservation	Fresh berries	2 kV/cm, pulse width 1 ls and 100 pulses per second for 2, 4 and 6 min ? disinfectant solution (60 ppm peracetic acid [PAA])	The softening of the berry structure Conc. of anthocyanins and phenolic compounds increased by 10 and 25%, respectively	Jin *et al*. (2017) [26]

Applications of Pulsed Electric Field in Fruit and Vegetable processing

In the twentieth century, the Pulsed Electric Field approach was already gaining popularity. A low-frequency alternating electric field was employed in the development of a milk pasteurization technique in the start of the 1990s. Doevenspeck, a German engineer, invented a technique in 1960 that broke down the structure of fruit and vegetable material cells using high voltage electric waves (Toepfl et al. 2006). The effectiveness of Pulsed Electric Field technology in fruit and vegetable processing is largely dependent on processing variables such electric field intensity, pulse width, shape, and frequency, treatment duration, temperature, and whether the system is batch or continuous flow.

Drying

The mass and heat transfer rates between the cells and their surroundings rise when the sample is pre-treated with Pulsed Electric Field to break down the cell structure, which also decreases the sample's resistance to diffusion (Barba *et al*. 2015) [8]. Alam *et al*. (2018) [4] conducted research on the effects of initial Pulsed Electric Field treatment on drying kinetics and color and texture changes in sliced carrot and parsnip. In comparison to the untreated samples, the drying time was shortened to 28% at 70 °C and to 21% at 60 °C.
According to Wiktor *et al*. (2015) [17], the Pulsed Electric Field -treated carrot samples showed a reduction in drying time of up to 8.2%, an increase in the effective water diffusion coefficient of up to 16.7%, and a greater degree of lightness and redness upon drying than the undamaged tissue. Ostermeier *et al*. (2018) looked into how a Pulsed Electric Field pre-treatment affected the drying of onions. According to the study, increasing the electric field intensity up to 1.07 kV/cm increased cell disintegration, which made it easier for moisture to escape to the product's surface. For Pulsed Electric Field -treated onion samples dried at 45°C, the increased diffusion resulted in a 30% reduction in drying time.

Freezing

One significant drawback of freezing fruit and vegetable is that ice crystals can develop and damage tissue, causing products (such soft fruits and leafy vegetables) to become soggy and lose their shape when thawed. Customers do not accept them in this form. It has been shown that infant spinach leaves can be made more resistant to freezing by applying pulsed electric fields. In the presence of cryoprotectants such trehalose, sucrose, glucose, and fructose, Pulsed Electric Field was applied by vacuum impregnation. After the freezing and thawing cycle, the leaves maintained their turgor and their leaf cells remained viable due to the combination of these techniques (Demir *et al*. 2018) [14].
According to Shayanfar *et al*. (2014), carrot discs treated with Pulsed Electric Field after being soaked in various cryoprotectants and texturizing agents were more solid after thawing than the control sample. Studies on potato strips were conducted similarly. According to the findings, Pulsed Electric Field treatment alone without the use of texturizing or antifreeze agents was an inappropriate pretreatment technique; but, when combined with trehalose and $CaCl_2$, potato strips retained their color, firmness, and structural integrity after thawing (Shayanfar *et al*. 2013). It's interesting to note that using Pulsed Electric Field in conjunction with vacuum infusion and cryoprotectants did not improve the texture of frozen and thawed strawberries. However, according to Velickova *et al*. (2018), this treatment improved the thawed fruits' color retention.
The freezing time and rate are impacted when Pulsed Electric Field technology is used in conjunction with freezing or freeze-drying. For instance, Jalte *et al*. (2009) [25] shown that Pulsed Electric Field pre-treatment can shorten freezing times, speed up the freeze-drying process, and enhance the quality of the freeze-dried potato. Similar findings were made by Wiktor *et al*. (2015) [17], who investigated the impact of Pulsed Electric Field on the freezing and thawing of apple tissue. They found that the overall freezing and thawing times were decreased by 3.5–17.2% and 71.5%, respectively.

Fruit and vegetable preservation

The growth of microbes and the activity of endogenous enzymes are two examples of the processes that might lead to fruit and vegetable deterioration. In contrast to the conventional pasteurization process, the Pulsed Electric Field technology reduces the loss of fruit and vegetable 's inherent flavor, color, texture, nutrients, and other thermolabile components while also partially inactivating harmful microbes and enzymes (Syed *et al*. 2017).

Microbial inactivation

Jin *et al*. (2017) [26] investigated the effects of Pulsed Electric Field on the population of E. coli Listeria innocua and the natural microbiota on blueberries that have been artificially grafted. E. coli and Listeria innocua were reduced by the combination of Pulsed Electric Field and PAA (60 ppm peracetic acid), but the blueberries' color and appearance remained unchanged. The process's weakening of the berry structure was its lone drawback. Phenolic compounds and anthocyanins both rose by 25% and 10%, respectively.

Spore inactivation

A certain degree of spore inactivation is described in some articles as being possible provided the required severe conditions are applied, although Pulsed Electric Field processing appears to have no effect on endospores. The small size, limited permeability, dehydration, and mineralization of spores make them more resistant to Pulsed Electric Field than vegetative cells.
According to Siemer *et al*. (2014), B. subtilis spores were inactivated for three log cycles when the following process parameters were met: an electric field strength of 9 kV/cm, an inlet temperature of 80 °C, and the addition of 10% sugar to the medium. In a similar vein, Reineke *et al*. (2015) used

the following process parameters to inactivate B. subtilis spores in saline water: 70ºC, 5 l/h flow rate, 150 Hz frequency, and 226.5 226.5 kJ/kg energy input.

Enzyme inactivation

Enzymes require more strong Pulsed Electric Field treatments to be inactivated since they are less sensitive to its effect than bacteria (Ho *et al*. 1997). However, the mechanism underlying this phenomenon is still unclear. The structural and conformational changes in enzymes that result in their deactivation are most likely caused by both the electrochemical and thermal effects linked to Pulsed Electric Field (Terefe *et al*. 2013).

Pulsed Electric Field decreased the activity of polyphenyl oxidase and peroxidase but had no discernible effect on the physicochemical and sensory properties of grape juice, which is sensitive to the action of numerous enzymes. The relative activity of specific enzymes was significantly impacted by the length, intensity, and frequency of Pulsed Electric Field action; this effect was eliminated when the aforementioned parameters increased (Marselles *et al*. 2007).

Extraction of bioactive compounds

Extraction, which typically entails treating a sample chemically and/or thermally, is one of the most widely utilized procedures in the industry to extract valuable molecules. According to a number of studies, using a Pulsed Electric Field during the extraction process can increase extraction efficiency, shorten extraction times, and prevent damage to the nutrients being extracted. Improved intracellular chemical extraction from fruits and vegetables has been achieved with the use of Pulsed Electric Field.

According to Luengo *et al*. (2013), Pulsed Electric Field treatment boosted the amount of polyphenols extracted from grapes and tomatoes. By using this method, borage (*Borago officinalis* L.) leaves yielded more polyphenols and had higher antioxidant activity.

Soliva-Fortuny *et al*. (2017) [20] investigated how Pulsed Electric Field affected the antioxidant capacity and phenol, flavonoid, and flavan-3-ol content of apples that were kept at varying temperatures (4 and 22 ºC) for 48 hours. The apple treated with the mildest electric field conditions showed the greatest rise in flavone-3-ol (92%) and total phenol content (13%) of all fruit. In comparison to the untreated samples, apples that were exposed to Pulsed Electric Field also had a higher antioxidant activity (by 43%).

Liu *et al*. (2018a, b) looked into how Pulsed Electric Field affected the extraction of water-soluble phenolic components from onions and the extracts' antioxidant capacity. According to the results, Pulsed Electric Field treatment after water extraction considerably raised the yield of water-soluble phenolic and flavonoid chemicals isolated from onions by 2.2 and 2.7 times, respectively, compared to control. The authors observed that as treatment duration and electric field intensity increased, so did the extracts' antioxidant activity.

El Kantar *et al*. (2018) [15] looked into how Pulsed Electric Field affected citrus fruits, such as lemon, orange, and pomelo. A Pulsed Electric Field was applied to the peel and fruits at a field voltage of 10 kV/cm and 3 kV/cm, respectively. Pulsed Electric Field processing boosted the extraction of polyphenols to 50% and raised the output of juice by 25% for oranges, 37% for pomelos, and 59% for lemons.

Solid–Liquid Extraction of Valuable Compounds

A common industrial process for obtaining intriguing substances from the tissues of fruits and vegetables is solid-liquid extraction. It primarily deals with the migration of molecules under the effect of a concentration gradient from a solid phase (such as fruit or vegetable tissue) to a liquid phase. Typically, solvents (such as ethanol, water, and hexane) are used as liquid phases, involving subsequent processes for extract purification and solvent removal.

Natural ingredients with technological uses (like pigments, preservatives, and emulsifiers), nutritional value (like sugar, proteins, and fiber), or beneficial effects on human or animal health (like bioactive compounds, antioxidants) are recovered using this process in the fruit and vegetable and pharmaceutical industries. Solid-liquid extraction has been specifically suggested as a way to repurpose fruit and vegetable wastes and by-products, enhancing both the fruit and vegetable industry's economic performance and environmental sustainability.

According to Luengo *et al*. (2014), a Pulsed Electric Field pretreatment (5 kV/cm; 90 μs) increased the amounts of carotenoids recovered from tomato peel by-product by 39% when compared to the control. The extraction medium from red grape and red beetroot that were prepared with Pulsed Electric Field are shown as a visual illustration, along with the extract from control samples. The quantity of betalains and anthocyanins derived from red grape and red beetroot, respectively, is closely correlated with the color intensity. It is evident that the use of Pulsed Electric Field raises the color intensity and, thus, the concentration of these substances.

Starch modification

The Pulsed Electric Field can be utilized to modify potato and corn starches (Han *et al*. 2009; Hong *et al*. 2018) [24]. Along with an increase in field strength (1.25–5 kV/cm and 30–50 kV/cm), the researchers also saw a decrease in gelatinization characteristics, viscosity, and crystallinity, as well as the reorganization and destruction of starch molecules. In potatoes, wheat, and peas, the application of Pulsed Electric Field increased the amount of quickly digested starch (Pulsed Electric Field intensity of 2.86, 4.29, 5.71, 7.14, and 8.57 kV/cm, 600 Hz of pulse frequency, and 6 ls of pulse width) (Li *et al*. 2019).

According to Hong *et al*. (2018) [24], Pulsed Electric Field treatment can greatly improve starch modification techniques like acetylation (Pulsed Electric Field parameters: pulse frequency of 1000 Hz; field intensity of 1.25, 2.50, 3.75, and 5.00 kV/cm; pulse duration time of 40 ls). Pulsed Electric Field can improve process efficiency, decrease reaction time, and conserve reagents when used in conjunction with starch modification techniques.

Waste valorisation in the fruit and vegetable industry

Large amounts of trash and by products are produced by the fruit and vegetable business, which is troublesome since disposing of them can have negative effects on the environment and human health. However, particularly in the fruit and vegetable business, they can still be abundant sources of naturally occurring bioactive chemicals. The recovery of these molecules using new technologies, such as Pulsed Electric Field, has received a lot of interest lately.

Pulsed Electric Field was used in tomato processing by Andreou *et al*. (2020) [5] to improve the value of tomato waste. They observed that the carotenoid extraction yield had increased to 56.4%. For a Pulsed Electric Field treatment at 1.0 kV/cm for 7.5 ms, lycopene extraction also increased (from 9.84 mg lycopene/100 g to 14.31 mg/100 g tomato residue). When 700 pulses and 2 kV/cm were applied to tomato waste, the concentration of extracted total phenolic compounds quadrupled.

Seed germination

Significant and long-lasting modifications in the seedlings' metabolism are brought about by Pulsed Electric Field therapy. It was discovered that pretreating seeds with Pulsed Electric Field before to planting changed and enhanced some biological and biochemical effects in the seeds.

According to Gonzalez-Casado *et al*. (2018) [20], Pulsed Electric Field treatment raised lycopene and total carotenoid concentrations to over 50%. They observed notable and long-lasting alterations in the resulting wheatgrass seedlings' metabolism. The growth performance of wheatgrass seedlings from untreated and treated with Pulsed Electric Field (1.4 kV cm−1) seeds was also observed by Leong *et al*. (2016) [30]; the seedlings from treated seeds were marginally bigger than those from untreated seeds.

According to Ahmed *et al*. (2020) [3], Pulsed Electric Field stimulated and enhanced the harvested shoot's bio-protective capacity, which in turn elevated the activities of antioxidant enzymes in the resulting seedlings. Therefore, Pulsed Electric Field treatment under mild conditions is a suitable method to promote the output of agro-products and aid in fruit and vegetable security.

Conclusion and future aspects

The current review covered a few current and possible uses of pulsed electric fields in the fruit and vegetable industry. The need for environmentally friendly fruit and vegetable production methods and consumers' increasing desire for fresh-looking, high-nutrient products are two factors driving the development of new technologies in fruit and vegetable processing. Pulsed Electric Field's general benefits include: (1) increasing process velocity, (2) improving process yield, (3) improving fruit and vegetable quality (e.g., reducing fat uptake, reducing impact on sensory properties, increasing health-related compounds), (4) lowering the intensity of other processing variables (e.g., temperature, grinding degree), and (5) increasing the operation's cost efficiency (e.g., reducing energy consumption).

Research on the use of pulsed electric fields in fruit and vegetable processing aims to inactivate microorganisms, extract active ingredients, and alter biomacromolecules, which improves chemical reactions and speeds up the aging of fermented fruit and vegetable products. In response to "consumers'" desires for better sensory and quality features, including flavour, longer shelf life, and more nutrient-dense, healthful, and environmentally friendly processing, Pulsed Electric Field was founded. Compared to traditional methods, fruit and vegetable processing based on pulsed electric fields produces less industrial waste.

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