Review Article

Principles of application of electric fields and electro-technologies for food processing and extraction of bioactives from fruits and vegetables

Abstract

Enhancing food safety and optimum shelf life can be achieved without compromising appropriate nutritional and sensory attributes of food by application of low-temperature food processing technologies. Pulsed electric fields (PEF), high hydrostatic pressure, high-intensity light, pulsed X-ray technology and microwave heating are emerging electro-technologies that effectively inactivate deleterious food microbes at ambient processing temperatures and short processing time. In this review, the principles of pulsed electric fields food processing were evaluated along with requirements for scale-up operation. Other latest developments in the field of non-thermal processing methods were examined. In one study, PEF processing significantly improved the flavor and overall acceptability of tomato juice, grape juice, meat and processed seafood. The microbial stability of PEF processed food is quite comparable to thermally processed products. PEF and other emerging innovative electro-technologies are continuously improving the sensory characteristics and shelf life of processed foods.

Keywords: Pulsed electric fields (PEF), Extraction, Bioactives, Food Safety, Human health, Industrial application

1. Introduction

Preservation and reduction of detrimental changes in the sensory and physical properties of processed food products are becoming increasingly important as we strive toward satisfying consumers' demand for high-quality food products. Conventional food preservation technologies are centred on the prevention of microbial growth and/or microbial inactivation. This is often achieved by thermal treatment of processed foods. The target is to modify those specific factors that most effectively influence the growth and multiplication of microorganisms such as water activity or moisture content, temperature, pH, humidity and chemical additives[1]. This ensures that most microbial activities in the food product are effectively minimized throughout the shelf-life of such food products. However, microorganisms are not destroyed and will be metabolically active and viable under a favorable environment. The net effect is reduced shelf-life.

To this end, alternative food processing technologies that preserve food sensory attributes including flavour and overall acceptability become desirable. Pulsed electric fields (PEF) is a non-thermal food processing technology involving short electric pulses over microseconds duration for microbial inactivation whilst maintaining desirable sensory attributes of food. PEF food processing technology is in many ways superior to the conventional thermal food preservation methods as it aims to reduce detrimental changes in flavour, texture, taste and fresh-like appeal. PEF technology is easily adaptable to liquid and semi-solid food products. It has been effectively employed in the microbial inactivation of milk, egg products, tomato juice, carrot juice, apple juice, orange juice, pea soup and other liquid food products[2]–[5]. The pulsed electric field technology is considered today as the most promising non-thermal technique capable of microbial inactivation of food products over extended shelf-life [5].

In general, PEF food processing technology involves the generation of short (microseconds to milliseconds) high-voltage electric fields in the range of 5-80KV/cm between two electrodes [6] to cause microbial inactivation at temperatures below thermally processed food products. Such microbial inactivation by PEF is generally accepted to follow electropermeabilization of microbial membranes and thus, microbial inactivation[6]–[8]. Other nonthermal processing technologies such as high hydrostatic pressure, oscillating magnetic fields, photo-irradiation, ionizing radiation, gamma irradiation, ultra-sonication and application of chemical and biochemical additives and intense light pulses follow similar mechanisms and are intended to keep food processing below the temperature of thermal processing. The overall goal is to preserve the nutritional quality of food while consuming less energy than thermal processing methods.

During the thermal processing of food, several changes take place in the food product that alters its final quality [8]. This includes changes in appearance, colour, flavour, taste, texture, mineral content and vitamins. Consumers are now showing a preference for natural food products free of chemicals and additives[9]. The need to investigate and review an alternative food processing technology (PEF) capable of preserving the sensorial quality of processed food at minimal energy consumption becomes imperative. PEF and other aforementioned electro-technologies for food processing are not only cost-effective when compared to the conventional thermal method, but environmentally friendly and above all, preserve food's natural characteristics. The high hydrostatic pressure (HHP) technique has also shown comparable promise in preserving the nutrient content of food products, especially in fruit and vegetable processing. The high-pressure processing condition demonstrated little detrimental effect on one important phytonutrient (anthocyanin) responsible for antioxidant activity[10]. Similarly, HHP applied at ambient temperature has been reported to preserve important food quality including flavour, colour and texture. This is because high-pressure applications preserve covalent bonds of processed food products [11]. In this review, the principles of PEF food processing technology will be examined in detail including experimental setup from laboratory to pilot scale, mechanism of microbial inactivation, impact on the shelf-life and sensory attributes of processed foods. Similar innovations in electro-technologies especially high hydrostatic pressure, oscillating magnetic fields, photo irradiation and ionizing irradiations will be examined.

1.1. Current Extraction Techniques for Fruits and Vegetables Bioactive Compounds

The consumption of fruit and vegetables has increased with growing consumer awareness for nutritious and balanced diets. The production and processing of fruit and vegetables has increased manifold and so have the losses in the form of waste and by-products. Food and Agriculture Organization (FAO) has estimated the fruit and vegetable losses and waste up to 60% of the total horticulture production. The by-products generated during the processing of the fruit and vegetable industry alone account for 25–30% of the horticulture product loss [20]. Fruits such as oranges, pineapple, apple, grapefruit, chokeberry and vegetables such as potatoes, carrots, onions and asparagus are processed to produce value-added products. The by-products of such fruit and vegetable processing comprises seed, skin, pomace, and rind which are not commonly consumed but possess valuable bioactive compounds particularly phytochemicals and secondary metabolites entrapped in tissue [21-22].

1.2. An Overview of Pulsed Electric Field and Electro-Technologies

The basic components of PEF consist of a sample inlet, treatment chamber, high voltage pulse generator, control system and outlet for treated food products. Processing may be carried out in a static treatment chamber or a continuous treatment chamber through a pump. The choice is dependent on the scale of production. The static chamber is often sufficient for most laboratory studies whilst the continuous chamber system is desirable for a commercial-scale production.

Generation of pulsed electric fields requires a fast discharging of electrical energy through an electrical circuit system consisting of one or more power supplies with charging ability, switches, capacitors and resistors. The total power of the system is limited to the number of cycling times of the capacitors, that is, the charging and discharging in a given unit of time.

1.2.1. Pulsed Electric Field in Food Processing Technology

The PEF processing system can be illustrated by the schematic flow chart in **Fig. 1** for the OSU-6 commercial scale PEF system [5].

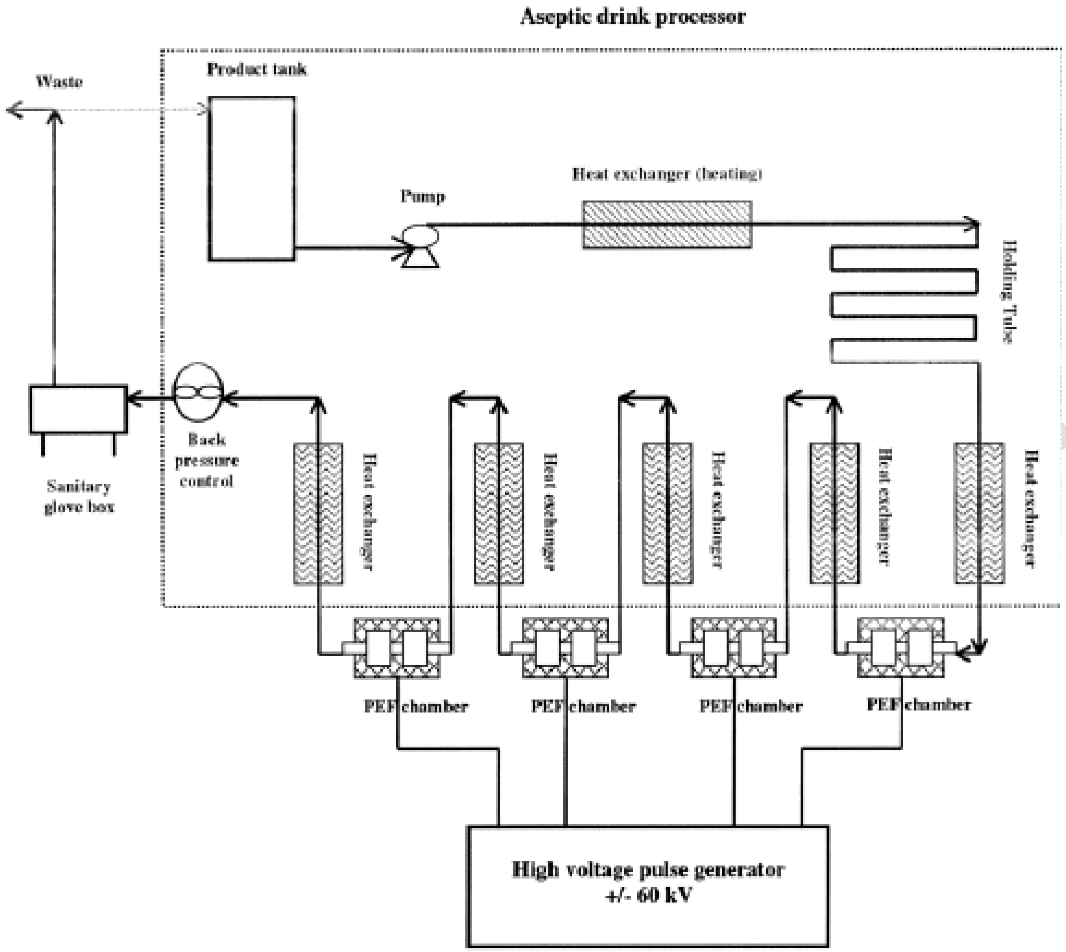

Figure 1: Flowchart of pulsed electric fields (PEF) processing system [5].

It consists of an aseptic drink processor, a high-voltage pulse generator and four tubular pulsed electric field chambers. Production parameters are controlled and monitored in the aseptic drink processor. The temperature, pressure and production rate are regulated in the aseptic processor. Electric pulses can be applied in the form of constant square waves, increasing square waves, exponentially decaying waves, and bipolar or oscillatory pulses which are generated in the high-voltage pulse generator. Each of tubular PEF chambers consists of two boron carbide tubular electrodes and a tubular insulator made of ceramic. The tubular diameter is typically in the range of 1.0 cm and the distance between electrodes is maintained at 1.270 cm. Electrochemical parameters are preset depending on the type of food product. Typical parameters[12] . For tomato juice PEF processing are peak current through each PEF chamber in the range of 50A to 75A; electric field strength set at 40KV/cm for a pulse duration of 2µs, and a total PEF treatment time of 57μs. A tubular PEF chamber is shown in **Figure2.** Recommendation for a liquid food product is centred mainly on three treatment chamber designs which include parallel plate electrodes, and coaxial or collinear configurations of cylindrical electrodes as shown in **Figure 3**. This is a good example of a treatment chamber with a diameter of 60 mm and a maximum treatment capacity of 5t/h shown in **Figure 2**.

Figure 2.: A continuous flow PEF treatment chamber with a diameter of 60 mm[12].

Several research groups around the world are working on PEF applications for food treatment and pilot scale equipment is available at Ohio State University, USA, Stork Food Systems, The Netherlands, Berlin University of Technology, Germany and the German Institute of Food Technology, Germany. As stated earlier, pulse generation is achieved by charging a capacitor bank and discharging the stored energy across a high-voltage switch into the treatment chamber.

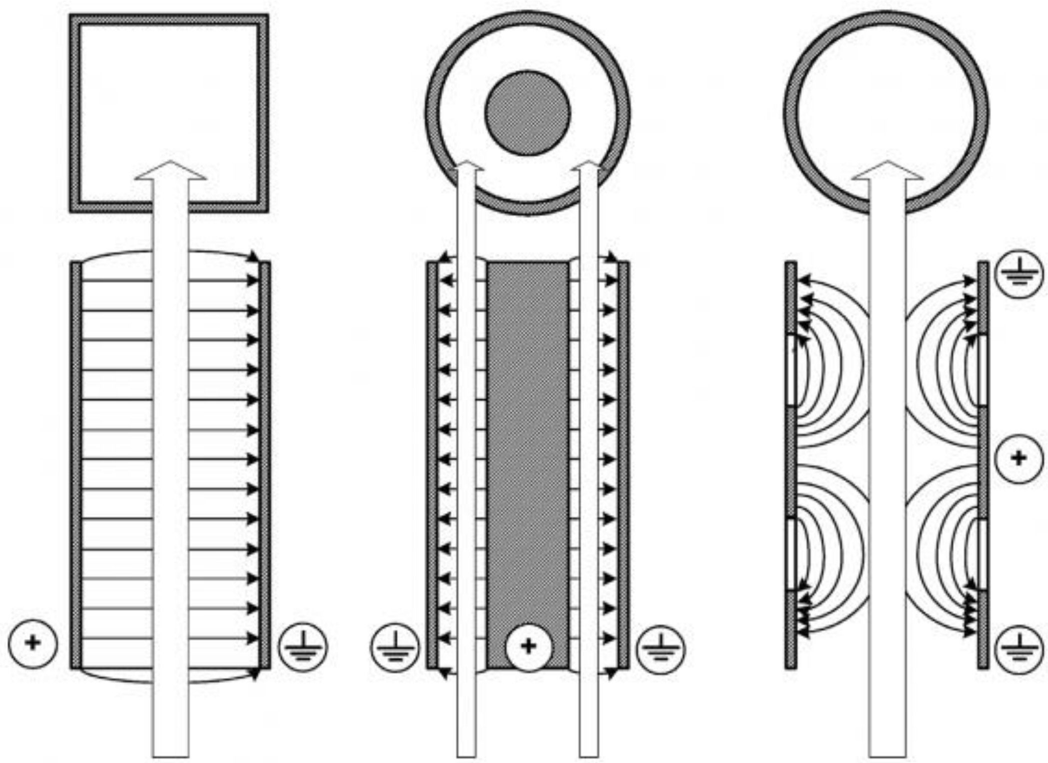

Figure 3: Different design configurations of internal PEF treatment chamber, (a) parallel plate configuration, (b) coaxial configuration and (c) collinear system[12].

The heat exchangers maintain inlet temperature at 45^{o}C at the upstream of each PEF chamber. The food product in the PEF chamber then experiences a force per unit charge (electric field) which is responsible for the microbial cell membrane breakdown. The PEF processed food is cooled to 25^{o}C through the chamber cooling system before packaging inside the sanitary glovebox. The food product is aseptically processed packaged and stored under refrigeration at a preset temperature. High current and high voltage probes are used to measure the voltage and current delivered to the tubular PEF chambers.

The PEF processing system can be summarized in a more simplified scheme as shown which represents the basic components of a PEF system.

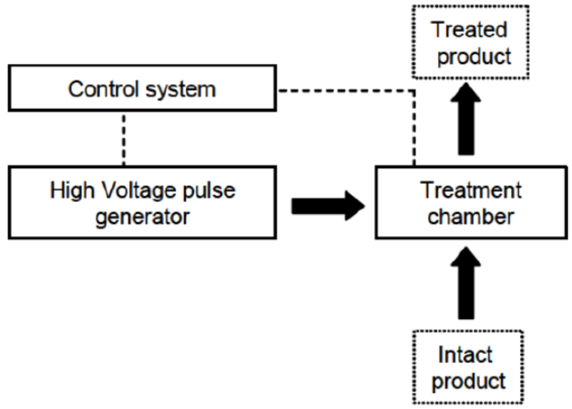

Figure 4: The basic components of the PEF system

The basic components consist of a product inlet, treatment chamber, high voltage pulse generator, control system and outlet for treated food. Food products may be processed in a static treatment chamber or a continuous treatment chamber through a pump. The choice is dependent on the scale of production. The static chamber is often sufficient for most laboratory scale studies whilst the continuous chamber system is desirable for commercial scale production.

Generation of pulsed electric fields requires a fast discharging of electrical energy through an electrical circuit system consisting of one or more power supplies with charging ability, switches, capacitors and resistors. The total power of the system is limited to the number of cycling times of the capacitors. That is, the charging and discharging in a given unit of time. This is often expressed as the capacitance C_0 of the energy storage device (capacitor) as given in the following expression:

$$C_0 = \tau/R = \tau\boldsymbol{\sigma}A/d$$

Where τ (S) is the duration of the excitation pulse, R is the resistance (Ω), $\boldsymbol{\sigma}$ is the conductivity (S/m), d is the treatment gap (m) between electrodes and A is the electrode surface area (mm^2).

The total energy stored in the capacitor is given by,

$$Q = 0.5C_0V^2$$

Where Q is the stored charge (energy) and V is the charge voltage. Storage capacitors are the main components of high-power sources. The capacitors which can assume the form of conventional capacitor, supercapacitor or pseudocapacitor generates electromagnetic fields whilst discharging stored energy. The electric fields accelerate charged particles of food during processing leading to thermal, chemical, mechanical and electromagnetic waves. The overall effect is a modification of food products at the molecular level through mass and charge transport phenomena. Commonly applied excitation signals (wave shapes) of PEF including square wave and exponentially decaying wave are shown in Fig. 5.

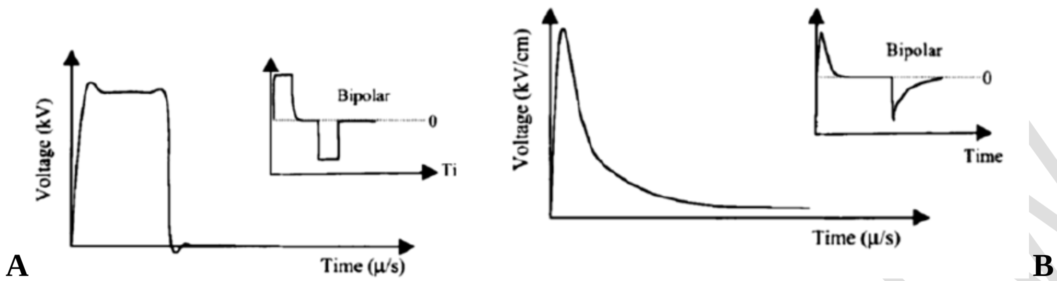

Figure 5: Excitation signals of PEF processing technology: A) square wave excitation signal and B) exponentially decaying wave excitation signal [12].

Desired electrical pulses are generated from high-voltage pulse generators following preset parameters such as step pulse potential (ΔE), waveform, pulse duration and interval between pulses.

1.2.2. Other Electro-technologies for Food Processing

Based on keeping food processing below temperatures normally employed in thermal processing, several innovations have emerged over the years. The ultimate goal is geared towards optimizing the nutritional quality of food including vitamins, minerals and essential flavours. HHP subjects liquid or solid food products to pressures between 40,000 to 80,000 pounds per square inch (PSI) for five minutes or less [10]. The high pressure is applied evenly to the food product to inactivate microorganisms on the surface and interior of a food product. This is accomplished by the alteration of the molecular structure of chemical compounds necessary for the metabolic activity of microorganisms in food products. The HHP is highly effective against bacteria, moulds, parasites and viruses. The technique requires a minimum amount of energy to compress solid or liquid seafood compared to 100^{o}C processing temperature for the thermal method. This technology offers several advantages over thermal processing including reduced processing time, retention of flavour, texture and freshness, minimal physical and chemical changes and reduced functionality operations[10]. High hydrostatic pressure units are in place in a number of juice and vegetable processors, oyster processing facilities and meat processing. Consumers of raw fish are particularly happy with this innovation that effectively reduced the risk associated with raw fish consumption.

The main components of the HHP system are:

1) A pressure vessel generation system
2) A pressure vessel and its enclosure
3) A temperature control device and
4) Material handling system.

These components are depicted in Fig.6 below.

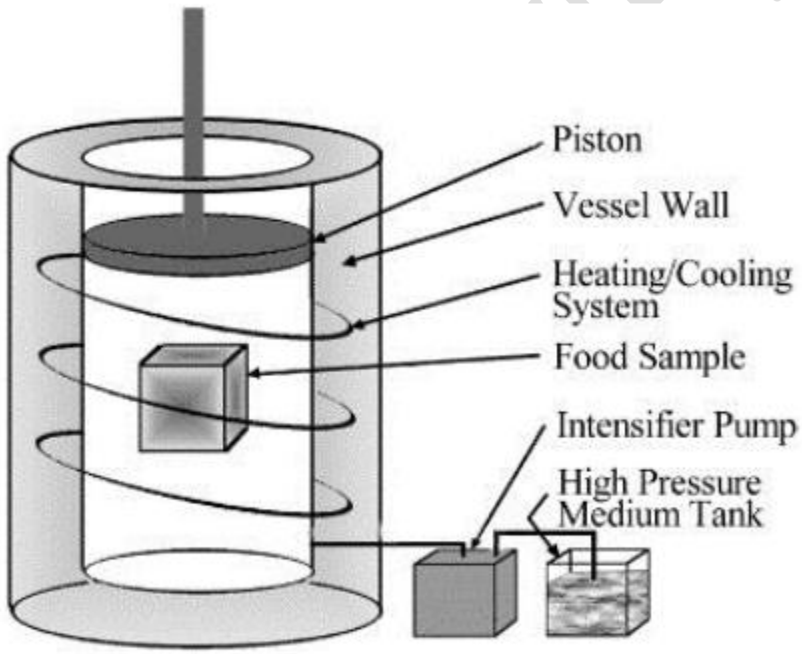

Figure 6: A high hydrostatic pressure system consisting of a pressure vessel, pressure generator, temperature control and food handling system[10].

An HHP system of 400 MPa at 20°C is reported to have significant inhibition on microorganisms: 3 log reduction in the case of bacteria species and 6 log reduction in the case of Penicillium mould.

1.2.2.1. Pulsed X-ray

Pulsed X-ray is another emerging electro-technology that utilizes a solid-state opening switch to generate high-intensity electron beam X-ray pulses. Whilst electrons have limited surface penetration of ca. 5 cm, X-rays have significantly higher penetration up to 400cm from the surface depending on the energy source. Pulsed X-ray has been used in the inactivation of E.coli in meat product and eliminate salmonella from food.[13].

1.2.2.2. Microwave Heating

Microwave heating is another effective electro-technology that utilizes electromagnetic waves of certain frequencies to generate heat in food products. Applicable microwave frequencies are in the range of 2450MHz to 915MHz for pasteurization, sterilization or to simply improve food's digestibility[14]. It is based on the principle of orientation of polar molecules with dipole moments, such as water molecules, according to the alternating electromagnetic field upon absorption of microwave energy. The rotation of water molecules in food generates heat for food processing. In addition to water molecules, other ionic species in food products are accelerated by the magnetic fields to generate heat through collisions. A magnetron embedded in a microwave system is a vacuum tube in which electrical energy from the power supply is converted to an oscillating magnetic field. The technique is widely applicable to meat, fish, vegetable and other food products.

1.2.2.3. High-Intensity Light Pulse

High-intensity light pulse is a surface sterilization technology using the broad spectrum of electromagnetic radiation from UV region (180nm) up to short intense pulses of near-infrared (NIR) wavelength around 1100nm. Pulses of light across the spectrum are emitted from one to twenty flashes per second[13]. This technique is highly effective in microbial reduction in meat and fish processing, reduction of Escherichia coli in juice processing and reduction of aerobic microbes in vegetables such as spinach, cabbage, lettuce and green bell pepper.

The key component of High-Intensity light pulses is a flash lamp filled with an inert gas, such as Xenon, which emits broadband radiation from UV up to NIR. Application of high-current electrical pulses to the inert gas in the lamp causes collision between electrons and gas particles leading to excitation of gas molecules which on subsequent relaxation emit light of high intensity and short pulses (1 µs to 0.1 s). The antimicrobial effect of UV light has been attributed to the cause of structural changes in DNA.

1.3. Shelf-life of Thermal and PEF Processed Food Products

The shelf–life of processed food products is a measure of several factors causing the degradation of food products. The onset of such biological or physicochemical alteration in processed food is detrimental to the ultimate shelf-life of food products. Thus, a measure of microbial stability, lipoxygenase activity, lycopene activity, viscosity and pH of processed food are important measures of shelf-life of food products [15]. These parameters were evaluated for thermally processed, PEF processed, and control juice products stored at various temperatures ranging from 4^0 C to 95^0 C. The shelf-life study was conducted for 112 days.

Microbial Stability. Juice without incubation was thermally processed or PEF processed for the shelf-life study. The initial total aerobic plate count and yeast and mould count of juice before thermal or PEF processing was established. The microbial stability was determined by using the same method for the microbial inactivation study.

Lipoxygenase Activity. Lipoxygenase activity can be measured according to standard methods[13].

Lycopene Analysis. Analysis of hexane extract obtained using standard method[15].

Ascorbic Acid Analysis. The concentration of ascorbic acid in juices can be measured following the procedure described[15], [16] using an HPLC system.

Particle Size Distributions. Analysis of the particle size of juices can be carried out by Particle size Mastersizer (Malvern Instruments, Inc.). A computer equipped with Mastersizer (Micropulus 2.15 Malvern Instruments, Inc.) recorded distributions of the particle size of juice products.

pH. The pH of tomato juice was measured using a pH meter at room temperature.

Viscosity. The viscosity of juice products can be measured by using a Brookfield viscometer. Viscosity is determined at room temperature and 4 rpm.

1. The effect of storage on these biological and physicochemical markers are expressed on **Table 1** for a control sample, thermally treated and PEF processed juice product.

Parameter	Days	Control	Thermally processed	PEF processed
Microbial stability (log cfu/ml)	112	5	2	3
Lipoxygenase activity	112	100% @ 30 d	Below detection	20%

			limit	
Licopene Analysis mg/100g	112	ND	4.08%	5.73%
Ascorbic acid	60	40% @ 30 d ND	20%	10%
Particle Size (µm)	112	277.08	281.11	273.32
pH	112	4.33	4.27	4.30
Viscosity (mPa)	112	42	42	42

Table 1: Comparison of microbial activity, lycopene, lipoxygenase, ascorbic acid, pH and viscosity at 4^{o}C storage for 112 d for thermally processed, PEF processed and controlled samples [15].

The initial total aerobic plate count of the control hot break juice at 0 days was 10 CFU/mL (0 day). Both PEF and thermally processed juices had <10 CFU/mL (0 days). The number of total aerobic microorganisms in thermally processed juice was <100 CFU/mL during the storage at 4^{o}C. The number of total aerobic microorganisms of PEF processed juice was <1.0 × 10^{4} CFU/mL during storage at 4^{o}C for 112 d, whereas that of control juice reached 1.0 ×10^{5} CFU/mL at 4oC after 49 d [15]. Control juice was not sampled after 49 d due to the gas formation by multiplied microorganisms. The higher rate of microbial growth in PEF-processed juice than in thermally processed juice during storage may be due to the relatively lower inactivation of the spores by PEF and the germination of the surviving spores during storage. Spores of *Bacillus,* moulds and yeasts were detected from the PEF-processed juice by a microscopic examination. Most studies reported that PEF does not efficiently inactivate bacterial spores [17], [18]. Little or no effect of PEF on the inactivation of mould. A higher number of spores of *Bacillus* and ascospores of moulds and yeasts probably survived in PEF processed juice than in thermally processed juice so there was more growth of microorganisms in PEF processed juice than in thermally processed juice. PEF processing can be effective for microbial inactivation, extending the shelf life of foods, but not for the complete disintegration of microorganisms including spores [18]. PEF technology does not inactivate enzymes to the extent of thermal processing.

The lipoxygenase activity is irreversibly inactivated during thermal and PEF processing. The most important flavour in juice products are impacted by lipoxygenase activity. This includes such compounds as hexanal, cis-hexenal, trans-2-hexenal, hexanol and tran-2-hexenol.

Pulsed electric field processed juice possesses a better flavour than thermally processed juice due to the activity of residual lipoxygenase compounds.

Ascorbic acid decreased significantly after thermal processing compared to pulsed electric field processing. Thermal processing causes considerable loss of ascorbic acid due to the higher processing temperature which accelerates chemical reactions in food leading to loss of ascorbic acid. The higher retention of ascorbic acid in thermally processed juice is attributed to the low temperature of processing in PEF technology. Minimization of Oxygen in the headspace of the package and oxygen permeation through the package is essential for minimal oxidative degradation of ascorbic acid thus, food flavour and colour characteristics [15]. Higher concentrations of ascorbic acid can be achieved over a prolonged storage period through proper selection of packaging material and flushing the processed food product with an inert gas such as nitrogen just before packaging since the loss of ascorbic acid increases with increasing storage period irrespective of processing method [15].

1.4. Sensory Properties of Thermally and PEF processed Food products

The sensory attributes of food products consist of flavour, colour, appearance, texture and overall acceptance by consumers. These properties are often evaluated by some panelists from 20 up to 60-member panels. The pane may be trained or untrained in food testing and may simply consist of students or faculty members. The sensory evaluation may be carried out on freshly prepared food products (thermally and non-thermally processed) or stored for a specified period to confirm the absence of some microorganisms. The panellists were asked to rate their preference of appearance, colour, texture, flavour and overall acceptability by marking on a horizontal line corresponding to the amount of the perceived stimulus. A hedonic scale [15] of 1-9 may be used for each attribute, where a higher number represents a higher preference of the attribute.

It is usual to test the statistical significance in the differences of data between thermally processed and PEF-processed food products. There were reported significant differences in flavor and overall acceptability[15] between thermally processed and PEF-processed tomato juices ($p < 0.05$). The panel scored 6.2 for flavour (PEF processed) and 4.7 for thermally processed tomato juice. Also, overall acceptability was 4.8 for thermally processed juice and 6.2 for PEF-processed juice. The higher number indicates a higher preference for PEF-processed juice. The higher flavour intensity of PEF processed juice compared with thermally processed juice was related to the higher activity of lipoxygenase of PEF processed tomato juice [15], [16], [18].

1.5. Applications of Pulsed Electric Field Food Processing Technology

Potential applications of PEF cuts across all facets of food processing industries. Several food processors are taking advantage of this PEF technique to enhance the extraction of intracellular compounds from fruits and vegetables; to improve drying rates of carbohydrates such as yam, cassava, potatoes and meat products; and gentle decontamination of liquid foods including orange juice, grape juice, tomato juice and dairy products[19]. An overview of potential applications of PEF processing technology in food and bioprocessing industries is shown in **Figure 5**.

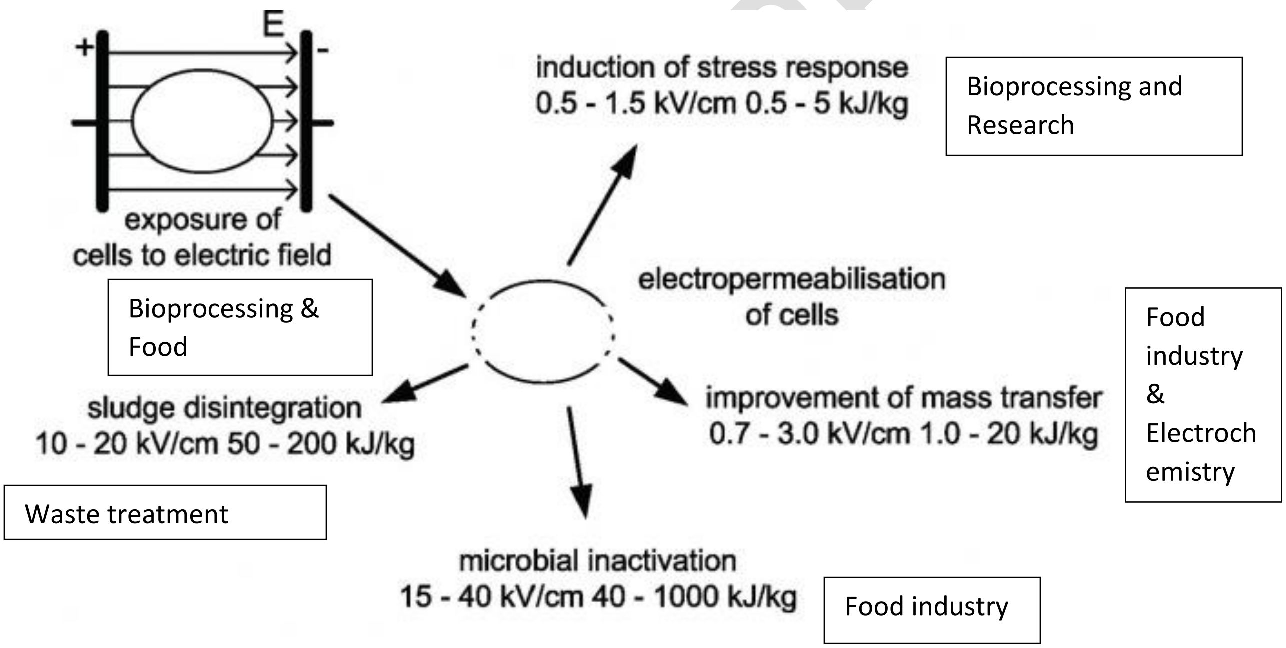

Figure 7: Applications of PEF in food, bioprocessing, waste treatment and research industries

Cell disintegration is often a crucial prerequisite before liquid-solid separation during the extraction of fruit and vegetable juices. Conventionally, an enzymatic maceration is applied, requiring residence times of 30 to 60 minutes and holding tanks[19]. With the application of PEF technology food processing residence time was extensively reduced to microseconds or some few seconds under continuous PEF treatment to induce cell disintegration in juice and vegetables. Dependent on apple variety and PEF treatment intensity, an increase in juice yield was found, similar to or higher than after enzymatic treatment. A specific energy input of 3kJ/kg was sufficient to achieve an increase in juice yield. An advantage of this PEF food processing technology over the thermal system is that PEF technology does not cause depolymerisation or de-esterification of hydrocolloids. The first industrial prototype for this application was installed in a German fruit juice-producing company in 2006.

The PEF technology has dramatically improved drying time in the drying of foodstuffs. Drying often significantly contributes to production costs and time requirements due to limited moisture diffusion from the product core to its surface. PEF can significantly improve water removal from the product surface under various drying conditions, but high removal will cause the formation of a dry crust inhibiting further moisture supply. Improvement in drying several fruit and vegetable products using a PEF food processing technology has been shown, allowing for a reduction of drying times of up to 30 per cent for potatoes [6], [9]. The PEF technique has also improved the production of dry-cured ham and sausages requiring the application of gentle drying conditions. Typical drying times are in a range of up to 30 days. The potential to enhance drying rates of dry-cured ham was investigated by subjecting samples of pork shoulder to a treatment at a field strength of 3 and 4kV/cm and a specific energy input of 5 and 20kJ/kg. Shortest drying times were achieved after a PEF treatment and brine injection, emphasizing the PEF technique's potential to improve moisture transport in meat tissues[19]. Significant energy savings can be expected due to faster moisture transport and increased production capacities of existing lines[10].

Induction of membrane pores by PEF can also be utilized in food preservation through inactivation of microorganisms. Loss of membrane barrier function and leakage of intracellular liquid cause cell death. This is often referred to as cell membrane permeabilization which can be visualized using fluorescent cell staining and flow cytometric analysis via the use of propidium iodide (PI) and carboxy-flourescine (cF) for cell staining and cytometric analysis respectively. Propidium iodide is a membrane-impermeant probe that will not penetrate cells with intact membranes. After a PEF treatment, PI diffuses into and stains the cells. The second probe, cF, is used primarily for the evaluation of cellular enzymatic activity. Depending on a number of pulses applied, membrane permeabilization increases, whereas cellular esterase activity is maintained in contrast to a thermal treatment at 95°C. Successful inactivation of 5 to 7 log cycles of microbial cells has been shown in tap water, fruit juices, milk and cream and beer as well as vitamin solutions or nutrient media [19]. It is noteworthy that a PEF treatment is only effective on vegetative organisms, whereas spores, viruses or enzymes are mostly unaffected by the pulse electric field treatment technology, as the primary target (cell membrane) is missing. Process variables to improve energy efficiency are electric field strength, specific energy input and treatment temperature. Combining the application of PEF and mild heat microbial inactivation can be achieved with a low consumption of electrical energy while operating at a lower maximum temperature and residence time in comparison to thermal processing[14]. Products are distributed while chilled to prevent degradation by residual enzyme activity. Retaining enzyme activity which is a potential disadvantage during juice processing by PEF technology might be an advantage in media where microbial decontamination is desired, but preservation of enzymes or prevention of protein denaturation is important such as the production of raw milk cheese and treatment of enzyme or protein preparations of egg yolk where a reduction of microbial load could be performed without heat application and related changes in protein structure. It was shown that the activity of lipid peroxidase, a component of the native antimicrobial system can be retained after microbial decontamination of milk [17]. A reduction of maximum temperatures during decontamination of liquids containing proteins could also help to minimize fouling at heat exchanger surfaces, and thus preservation of food flavour. To maintain their competitiveness, these facts have led to the wineries of traditional wine production zones in Europe to introduce new production technologies in an attempt to obtain high-quality wines. The use of pulsed electric field technology that can enhance polyphenol extraction during red winemaking may represent an important alternative to traditional techniques.

The potential of the PEF technique to achieve disintegration of plant, animal or microbial cells has been shown, and pre-treatment of tissue before extraction or drying and preservation of premium, chilled products or media containing proteins have been identified as promising applications. The technique can be scaled up to industrial size as demonstrated in many food industries in the US, Germany and around the world

1.6. Conclusion

Thermal processing strongly affects the sensory attribute and some physicochemical properties of food products including loss of freshness, flavour, texture, colour and appearance.

Pulsed electric field processing and other innovations in electro-technologies of food processing such as high hydrostatic pressure, high-intensity pulses, microwave and oscillating magnetic fields can inactivate microorganisms at ambient or sub-lethal temperatures. These non-thermal processes have gained tremendous preference for their inherent capability of preserving the nutritional values of food and fresh-like characteristics.

References

[1] M. Mohamed and A. Eissa, "Pulsed Electric Fields for Food Processing Technology," *Struct. Funct. Food Eng.*, p. 32, 2012.

[2] G. A. Evrendilek, T. Baysal, F. Icier, H. Yildiz, A. Demirdoven, and H. Bozkurt, "Processing of Fruits and Fruit Juices by Novel Electrotechnologies," *Food Eng. Rev.*, 2012.

[3] S. Min, G. A. Evrendilek, and H. Q. Zhang, "Pulsed electric fields: Processing system, microbial and enzyme inhibition, and shelf life extension of foods," *IEEE Transactions on Plasma Science*, vol. 35, no. 1. pp. 59–73, 2007.

[4] H. Vega-Mercado *et al.*, "Non-thermal food preservation: Pulsed electric fields," *Trends Food Sci. Technol.*, vol. 8, no. 5, pp. 151–157, 1997.

[5] U. Zimmermann, "Electric field-mediated fusion and related electrical phenomena," *BBA - Reviews on Biomembranes*, vol. 694, no. 3. pp. 227–277, 1982.

[6] S. Sastry, "Ohmic heating and moderate electric field processing," *Food Sci. Technol. Int.*, vol. 14, no. 5, pp. 419–422, 2008.

[7] S. Y. Ho, G. S. Mittal, and J. D. Cross, "Effects of high field electric pulses on the activity of selected enzymes," *J. Food Eng.*, vol. 31, pp. 69–84, 1997.

[8] Y. Q. Li, Q. Chen, X. H. Liu, and Z. X. Chen, "Inactivation of soybean lipoxygenase in soymilk by pulsed electric fields," *Food Chem.*, vol. 109, no. 2, pp. 408–414, 2008.

[9] D. Baines and R. Seal, *Natural Food Additives, Ingredients and Flavourings*. 2012.

[10] V. M. Balasubramaniam and D. Farkas, "High-pressure food processing," *Food Sci. Technol. Int.*, vol. 14, no. 5, pp. 413–418, 2008.

[11] B. R. Thakur and P. E. Nelson, "High-pressure processing and preservation of food," *Food Rev. Int.*, vol. 14, no. 4, pp. 427–447, 1998.

[12] M. E.A. and A. H. Amer Eiss, "Pulsed Electric Fields for Food Processing Technology," *Structure and Function of Food Engineering*. 2012.

[13] N. K. Rastogi, "Application of high-intensity pulsed electrical fields in food processing," *Food Rev. Int.*, vol. 19, no. 3, pp. 229–251, 2003.

[14] S. Chandrasekaran, S. Ramanathan, and T. Basak, "Microwave food processing-A review," *Food Research International*, vol. 52, no. 1. pp. 243–261, 2013.

[15] S. Min, Z. T. Jin, and Q. H. Zhang, "Commercial scale pulsed electric field processing of tomato juice.," *J Agric Food Chem*, vol. 51, no. 11, pp. 3338–3344, 2003.

[16] S. Toepfl, "Pulsed Electric Field food treatment - scale up from lab to industrial scale," *Procedia Food Sci.*, vol. 1, pp. 776–779, 2011.

[17] C. Siemer, S. Toepfl, and V. Heinz, "Inactivation of Bacillus subtilis spores by pulsed electric fields (PEF) in combination with thermal energy II. Modeling thermal inactivation of B. subtilis spores during PEF processing in combination with thermal energy," *Food Control*, vol. 39, no. 1, pp. 244–250, 2014.

[18] T. Tanino, T. Yoshida, K. Sakai, S. Bing, and T. Ohshima, "Inactivation of Escherichia coli phages by PEF treatment and analysis of inactivation mechanism," *J. Electrostat.*, vol. 73, pp. 151–155, 2015.

[19] F. Donsì, G. Ferrari, and G. Pataro, "Applications of pulsed electric field treatments for the enhancement of mass transfer from vegetable tissue," *Food Eng. Rev.*, vol. 2, no. 2, pp. 109–130, 2010.

[20] Sagar NA, Pareek S, Sharma S, Yahia EM, Lobo MG. Fruit and vegetable waste: Bioactive compounds, their extraction, and possible utilization. Comprehensive reviews in food science and food safety. 2018 May;17(3):512-31.

[21] Rudra SG, Nishad J, Jakhar N, Kaur C. Food industry waste: mine of nutraceuticals. Int. J. Sci. Environ. Technol. 2015;4(1):205-29.

[22] Kosseva MR. Functional food and nutraceuticals derived from food industry wastes. InFood Industry Wastes 2013 Jan 1 (pp. 103-120). Academic Press.