Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 08, August - 2017

High Intensity Pulsed Electric Field Procesiing of Foods - A Review

SK. Gouse Masthan*, V. Ravi Chandra*, D. Naga Raju*, K. Yashwanth Kumar, K. Murali Naik**
** Assistant Professor,
A.M.Reddy Memorial College of Engineering & Technology (AMRCET),Narasaraopeta,
*4/4 B.Tech (Agril. Engg), Department of Agricultural Engineering (AMRCET), Narasaraopeta,

Abstract : **- Use of pulsed electric fields (PEFs) for inactivation of microorganisms is one of the more promising nonthermal processing methods. Inactivation of microorganisms exposed to high-voltage PEFs is related to the electromechanical instability of the cell membrane. Electric field strength and treatment time are the two most important factors involved in PEF processing. Encouraging results are reported at the laboratory level, but scaling up to the industrial level escalates the cost of the command charging power supply and of the high-speed electrical switch. In this paper, we critically review the results of earlier experimental studies on PEFs and we suggest the future work that is required in this field. Inactivation tests in viscous foods and in liquid food containing particulates must be conducted. A successful continuous PEF processing system for industrial applications has yet to be designed. The high initial cost of setting up the PEF processing system is the major obstacle confronting those who would encourage the system's industrial application. Innovative developments in high-voltage pulse technology will reduce the cost of pulse generation and will make PEF processing competitive with thermal-processing methods.**

Aim of the present paper is to summarize the numerical studies done so far on the PEF process.

APPLICATION OF PULSED ELECTRIC FIELD PROCESSING IN FOOD INDUSTRY INDUSTRIAL RELEVANCE:

The application of pulsed electric field (PEF) technology as a non-thermal alternative to traditional pasteurization of liquid foods has received considerable attention during the last years. Effective inactivation for most of the spoilage and pathogenic microorganisms has been shown in fruit and vegetable juices and milk with little or no impact on nutritional and sensorial properties of the food. However, very little is known about the growth abilities of the surviving population. Ensuring food safety requires a better understanding of the behavior of the surviving populations of microorganisms which may be recovering from sub lethal injury, such as PEF-induced stress**.**

In last 25 years, pulsed electric fields (PEF) technology research has been conducted by world-wide leading research groups as an alternative to the traditional thermal pasteurization of liquid foods. Many studies have demonstrated the feasibility of PEF technology to produce safe, fresher and more nutritious foods covering a wide range of liquid matrices such as milk and dairy products, liquid whole egg and derivatives, fruit juices and fruit juice-based beverages and vegetable soups among others (Ortega-Rivas, 2011).During this period, different bench-scale PEF units were developed with new designs in the treatment chamber geometry, such as the co-field design (applying the electric field in the same direction as the fluid flow) (Sampedro et al., 2013) making it possible to apply an uniform electric field and to scale-up to higher throughput for pilot-plant studies (400–2000 L/h) (Min et al., 2003b).

The application of pulsed electric fields at high field strength has been proposed as an alternative to conventional food preservation techniques. Several studies have demonstrated the ability of high intensity pulsed electric fields to produce shelf-stable liquid foods with high nutritional value by inactivating microorganisms and enzymes (Soliva-Fortuny et al., 2009). Other applications of pulsed electric fields, at moderate field strength, are currently under development. Moderate-intensity pulsed electric fields (MIPEF) permeabilise tissue structures, thus improving intracellular metabolite extraction (Soliva-Fortuny et al., 2009) and enhancing drying efficiency (De Vito et al., 2008). Metabolic responses of plant cells (Cai et al., 2011) and tissues (Galindo et al., 2009) upon the application of MIPEF have been studied. The analysis of potato demonstrated that, 24 h after the application of MIPEF, tissue metabolism showed MIPEF-specific stress responses, characterised by changes in the hexose pool that may involve starch and ascorbic acid degradation (Galindo et al., 2009). MIPEF-induced stresses could include a burst of ROS, which are endogenous signal components required for synthesis of secondary metabolites, such as polyphenols or carotenoids, which are known to be part of the defence response of plants to stress (Shohael et al., 2006).

The pulsed electric field (PEF) technology can be utilized for many operations in food and bioengineering. Applications include, for example, the inactivation of microbial cells, the improvement of mass transfer in plant or animal cells or sludge disintegration (Toepfl et al., 2006). In case of food preservation, the destruction of microorganisms such as molds, yeast and bacteria, which can act as spoilage organisms or pathogens, is of major concern. The inactivation by PEF as a non-thermal method was investigated extensively in the past (Manas and Pagan, 2005). Electric field pulses of short duration (1–100 µs) and high intensity (10–50 kV/cm) are applied to a food placed between electrodes. Microbial cells exposed to such fields can respond by an electrical breakdown of the cell membrane, which leads to membrane perforation (electroporation) and, in the irreversible case, to the inactivation or death of the microorganism. An electrical breakdown of the cell can be expected when a critical transmembrane potential larger than approximately 1 V is provided (Gerlach et al.2008).As a consequence, the required minimal electric field strength necessary for a proper inactivation depends on the cell size and geometry (Heinz, et al., 2002). Although the treatment of the food by an electric field leads to an increase in temperature due to ohmic heating, the process temperature is typically held low enough (sublethal temperatures) to exploit the advantages of a non-thermal technology. In contrast to a thermal treatment as a widely used procedure for the microbial inactivation, emerging non-thermal methods such as PEF better preserve the sensory, nutritional and functional properties of foods (Manas and Pagan, 2005), which is compatible with the increasing consumer demand for ‘fresh-like’ food. Numerous experimental studies have proven that a sufficient reduction of microorganisms can be achieved by the application of PEF (Toepfl et al., 2006). Most successfully was the treatment of liquid foods in a continuous process (Heinz, et al., 2003). However, the PEF technology has not reached yet a stage of commercial usability, which shows the demand for further intensive research to complete the understanding and to minimize the drawbacks.

Elisa Luengo et al. (2013) investigated the influence of pulsed electric field (PEF) treatment on the extraction by pressing of total poly phenols and flavonoids (naringin and hesperin) from orange peel. A treatment time of 60 µs (20 pulses of 3 µs) achieved the highest cell disintegration index (Zp) at the different electric field strengths tested. After 30 min of pressurization at 5 bars, the total poly phenol extraction yield (TPEY) increased 20%, 129%, 153% and 159% for orange peel PEF treated at 1, 3, 5 and 7 kV/cm, respectively. A PEF treatment of 5kV/cm to the orange peels increased the quantity of naringin and hesperidin in the extract of 100 g of orange peels from 1 to 3.1 mg/100 g of fresh weigh (fw) orange peel and from 1.3 to 4.6 mg100 g fresh weigh (fw) orange peel respectively. Compared to the untreated sample, PEF treatments of 1, 3, 5 and 7kV/cm increased the antioxidant activity of the extract 51%, 94%, 148% and 192%, respectively. The results of this investigation demonstrate the potential of PEF as a gentle technology to improve the extraction by pressing of poly phenols from fresh orange peel. This procedure enhances the antioxidant capacity of the extracts, reduces extraction times and does not require using organic solvents. Processing of orange fruits to obtain fresh juice or citrus-based drinks generates very large amounts of byproduct wastes, such as peels that are a rich source of poly phenols mainly flavonoids. Extraction of these compounds from orange peels is a crucial step for use of these compounds in the food and pharmaceutical industries as antioxidants. PEF-assisted extraction by pressing of poly phenols from fresh orange peels stands as an economical and environmentally friendly alternative to conventional extraction methods which require the product to be dried, use large amounts of organic solvents and need long extraction times. Pulsed electric field (PEF) assisted extraction has shown promise as a technology for obtaining valuable compounds from soft vegetal materials (Donsi et al., 2010).These treatments induce a permeabilization of the cytoplasmatic membranes, facilitating the release of intracellular compounds from the cells. PEF increases the extraction rates and yields of different compounds in which thefood industry is interested (Puertolas et al., 2012). Key advantages of PEF-assisted extraction are that it is a non-thermal treatment that does not affect the quality of the extracted products and the treatments might be able to be applied in continuous flow both at pilot plant and on an industrial scale (Toepfl and Heinz, 2011). It has also been demonstrated that the combination of PEF-assisted extraction and pressing is an effective technique to obtain different products from solid plant matrices. Several studies have shown the positive effect of this combined treatment on the yield and quality of the juice extracted from apples and carrots (Jaeger et al., 2012) and in the extraction yield of betanines from red beet (Lopez et al., 2009).

Xiufang Bi et al.(2013) investigated the effects of electric field strength (0–35 kV/cm) and pulse rise time (PRT) of 2 µs and 0.2 µs during pulsed electric fields (PEF) on enzymatic activity, vitamin C, total phenols, antioxidant capacities, color and rheological characteristics of fresh apple juice.With increasing the electric field strength and PRT, the residual activity (RA) of polyphenoloxidase (PPO) and peroxidase (POD) decreased, almost complete inactivation of both enzymes was achieved at 35 kV/cm and 2 µs-PRT. The content of vitamin C in apple juice decreased significantly (pb0.05) during PEF treatment, the largest loss was 36.6% at 30 kV/cm and 2 µs-PRT. The content of total phenols was not affected by PEF with 2 µs-PRT but decreased significantly (pb0.05) by PEF with 0.2 µs-PRT. The antioxidant capacity of apple juice was evaluated by DPPH radical scavenging activity, ferric reducing antioxidant power (FRAP) and oxygen radical absorbance capacity (ORAC).The DPPH value was not affected by PEF, whereas FRAP and ORAC values increased with increasing the electric field strength and decreasing the PRT. PEF-treated apple juice had a significantly higher (pb0.05) lightness (L) and yellowness (b) than the controlled sample. The apparent viscosity and consistency index (K) of apple juice decreased while the flow behavior index (n) increased with increasing the electric field strength, and apple juice treated at 2 µs-PRT had significantly higher apparent viscosity than treated at 0.2 µs-PRT. Apple juice is one of the most popular fruit juices, and it required strict treatment conditions to protect its quality, especially to prevent enzymatic discoloration. PEF is one promising novel non-thermal technique without compromising the flavor, taste and nutrition aspect of food. XiufangBi et al.(2013) analyzed the effectiveness of PEF as a method of preserving qualities of apple juice, including inactivating enzymes which are crucial to quality control. Available data provided in their investigation will benefit the fruit juice industry.

FUNDAMENTALS OF PEF PROCESSING

PEF processing involves the application of a high intensity electric field (20–80 kV/cm) in the form of short pulses (ms or μs) to a food placed between two electrodes. PEF technology provides fresh-like and safe foods while reducing quality losses that can be triggered after thermal processing (Morris et al., 2007). Application of continuous PEF processing is not suitable for solid food products that do not allow pumping and is restricted to low-conductive food products without air bubbles (Elez-Martinez et al., 2005). In contrast, controversial results regarding polarity have been obtained depending on the enzyme and the food under study. Pectin methyl esterase (PME) inactivation in orange juice subjected to bipolar treatments was greater than when monopolar pulses were applied (Elez-Martinez et al., 2005). However, PME activity in tomato and strawberry juice was not affected when a PEF treatment was applied in mono- or bipolar mode (Giner et al., 2000).

Nowadays, the pulsed electric fields (PEF) become more and more popular in different applications for processing of bio-tissues, food or agricultural products (Vorobiev and Lebovka, 2010). PEF application at moderate electric field strengths E of 0.5 to 1 kV/cm and treatment times between 10 − 4 and 10 − 2 s allows effective disintegration (electroporation) of cell membranes (Vorobiev and Lebovka2012) with preservation of the fresh quality of products, e.g., bioactive compound purity, colour, texture, aroma, flavour, and nutrients (Odriozola-Serrano et al., 2009). The different examples of acceleration of the mass transfer processes (Donsi et al., 2010; Porras-Parral et al., 2012), pressing (Lebovka et al., 2004), drying (Ade-Omowaye, 2001), freezing (Jalte et al., 2009), extraction (Loginova et al., 2011a, 2011b) and osmotic dehydration (Amami et al., 2008) were already reported. PEF-treatment requires rather low power consumption, typically lying within 1–15 kJ/kg (Vorobiev and Lebovka, 2010) and it defines the unique industrial attractiveness of this approach. The practical implementations of PEF-assisted technologies were realised in different ways by application of PEF to the whole samples of agricultural species (Grimi et al., 2010) or mechanically fragmentized material, e.g. sugar beet slices, apple mash (Grimi et al., 2007). The mechanisms of electroporation were better studied for constant operation conditions and simple systems, e.g., biological membranes, suspensions of cells and single pieces of agricultural tissues (Lebovka and Vorobiev, 2010). However, more practical situations of PEF application with non-constant operation conditions or with complex samples (e.g., geometrically irregular shape, porous packing of slices, etc.) are still unclear and demand more thorough investigations in future.

Elez-Martinez et al.(2004)studied the effect of high-intensity pulsed electric field (HIPEF) treatment on the survival of S. cerevisiae suspended in orange juice. Saccharomyces cerevisiae is often associated with the spoilage of fruit juices. Commercial heat-sterilized orange juice was inoculated with S. cerevisiae (CECT 1319) (10(8) CFU/ml) and then treated by HIPEFs. The effects of HIPEF parameters (electric field strength, treatment time, pulse polarity, frequency, and pulse width) were evaluated and compared to those of heat pasteurization (90 degrees C/min). In all of the HIPEF experiments, the temperature was kept below 39 degrees C. S. cerevisiae cell damage induced by HIPEF treatment was observed by electron microscopy. HIPEF treatment was effective for the inactivation of S. cerevisiae in orange juice at pasteurization levels. A maximum inactivation of a 5.1-log (CFU per milliliter) reduction was achieved after exposure of S. cerevisiae to HIPEFs for 1,000 micros (4-micros pulse width) at 35 kV/cm and 200 Hz in bipolar mode. Inactivation increased as both the field strength and treatment time increased. For the same electric field strength and treatment time, inactivation decreased when the frequency and pulse width were increased. Electric pulses applied in the bipolar mode were more effective than those in the monopolar mode for destroying S. cerevisiae. HIPEF processing inactivated S. cerevisiae in orange juice, and the extent of inactivation was similar to that obtained during thermal pasteurization. HIPEF treatments caused membrane damage and had a profound effect on the intracellular organization of S. cerevisiae.

Seratlic et al. (2013) reported that the surviving population of the bacteria subjected to the PEF treatment could grow again, showing higher growth rates as the intensity of the PEF treatment increased. Also, the new bacterial population showed higher resistance to further PEF treatment. Therefore, for industrial application of the PEF technology, an in-depth characterization of surviving microorganisms in the treated product is required. Moreover, the evidence of bacterial persistence indicates that the PEF technology, as a non-thermal alternative to traditional pasteurization, could not completely replace thermal treatment, but can be applied as a supplement treatment.Ultrahigh pressure (UHP) and pulsed electric field (PEF) are emerging processing technologies developed to enhance the safety while maintaining the fresh-like quality of food. For each food and process combination, a pathogen of concern (i.e., target pathogen) must be determined, and a low-risk microorganism that serves as the pathogen surrogate for process validation must be identified.

Waite-Cusic et al. (2011)The objective of this study was to identify a surrogate for Listeria monocytogenes for UHP and PEFprocess validation. Potential surrogates tested include four *Lactobacillus spp*., *a Pediococcus sp*., and a *Listeria innocua* strain. These were compared with nine L. monocytogenes strains, with regard to sensitivity to UHP and PEF processing. For UHP treatment, the strains were suspended in citrate-phosphate buffer (pH 7.0 or 4.5), sweet whey, or acidified whey and pressure processed at 500 MPa for 1 min. For PEF treatment, the strains were suspended in NaCl solution, acid whey, or sweet whey and processed at 25 kV/cm. The lethality of UHP or PEF treatment varied considerably, depending on medium types and pH and the treated strain.Treating the tested microorganisms with UHP inactivated 0.3 to 6.9 log CFU/ml for L. monocytogenes strains and 0.0 to 4.7 log CFU/ml for the potential surrogates. When PEF was employed, populations of tested microorganisms decreased < 1.0 to 5.3 log CFU/ml. L. monocytogenes V7 and OSY-8578 were among the most resistant strains to UHP andPEF treatments, and thus are candidate target strains. Lactobacillus plantarum ATCC 8014 demonstrated similar or greater resistance compared with the target organisms; therefore, the bacterium is proposed as a surrogate of L. monocy togenes for both processes under the conditions specified in the food matrices tested in this study**.**

Few studies exist on flavored milk processed by pulsed electric fields (PEF). The main concern is product stability. Daniela Bermudez-Aguirre et al. (2010) analyzed the degradation of coloring agent Allura Red in strawberry milk under PEF. Four systems were tested containing Allura Red: two commercial milks and two model systems. PEF conditions were 40 kV/cm, 48 pulses (2.5 µs), and 55 °C; coloring agent was quantified via RP-HPLC. After processing, only minor changes were observed in color, Allura Red concentration, and pH. During storage (32 days) at refrigerated conditions (4°C) commercial samples maintained pH above 6. Model systems dropped below pH 6 after 10 days of storage. Color of samples showed important decrease in a; hue angle and chroma changed during storage. HPLC analysis reported a bi-phasic effect in Allura Red concentrations versus time. Concentration changed, reaching a maximum value during the middle of storage, possibly attributed to microbial growth, pH reduction, or interaction of proteins. However, PEF affected the stability of Allura Red in milk when additional ingredients were not added to the product.

PEROXIDASE INACTIVATION IN CARROT JUICE TREATED WITH PULSED ELECTRIC FIELDS:

Heat processing has traditionally been the most applied method for preventing the adverse effects caused by enzymes and microorganisms in fruit and vegetable juices (Rivas et al., 2006). Nevertheless, high processing temperatures trigger undesirable reactions that account for nutrients loss, color alterations, and off-flavor development (Elez-Martınez and Martın-Belloso, 2007). High-intensity pulsed electric fields (PEF) represent a non thermal alternative to conventional thermal processing of fruit and vegetable juices. Temperatures reached during PEF processing are low enough to keep heat-labile compounds such as volatiles and anti-oxidant compounds (Luciano Jose Quintao-Teixeira et al., 2013).

Luciano Jose Quintao-Teixeira et al., (2013) reported that Peroxidase activity accounts for quality losses in many plant-based foods. Observed the inactivation kinetics of peroxidase (POD) in carrot juice treated with pulsed electric fields (PEF). Juice samples were subjected to electric field intensities of 20 to 35 kV/cm for 300 to 2000µs. Up to 93% of the initial activity was inactivated after treating at 35 kV/cm for 1500 µs. POD activity inactivation correlated well with the increase in energy density input. A first-order fractional conversion model best fitted the experimental results. Other kinetic approaches such as the Fermi’s model can be used to estimate residual POD activity values in treated juices as a function of electric field strength.

Practical Application: Pulsed electric fields (PEF) are a processing technology that can be used for the pasteurization of liquid food products. Peroxidase activity inhibition is required in carrot juices to prevent undesirable quality losses, such as discoloration, flavor changes, and loss of nutrients. The most significant processing parameters ruling POD inactivation in PEF-treated carrot juice are identified and mathematical modeling of experimental data is conducted. Carrot juice POD activity can be reduced by applying PEF treatments. POD activity decreases as the electric field strength, treatment time, and energy density input increases. In general all models were able to describe the reduction of POD activity as a function of PEF processing parameters. Literature works describing the effects of PEF treatments on peroxidase are sometimes contradictory because its biological activity seems to be dependent on many factors such as processing conditions, the food matrix and intrinsic factors (Aguilo-Aguayo et al., 2010).Carrot juice POD activity can be reduced by applying PEF treatments. POD activity decreases as the electric field strength, treatment time, and energy density input increases. In general all models were able to describe the reduction of POD activity as a function of PEF processing parameters. Each one provides different information related to carrot juice POD inactivation by PEF. Among the kinetic models used to describe the depletion of POD activity as a function of the treatment time, a first-order fractional conversion model exhibited a better performance than plain first-order and Weibull’s models. The effect of POD inhibition as affected by field strength can be well fitted with the Fermi’s model for treatment times higher than 600µs. Thus, first-order fractional conversion and Fermi’s models were those that most accurately described the carrot juice POD inactivation as a function of electric field strength and treatment time. On the other hand, a plain first-order model is proposed to relate carrot POD inactivation to the amount of supplied energy.

Vallverdu-Queralt et al. (2013a) studied the effect of pulsed electric fields on tomato juices produced from tomatoes subjected to moderate-intensity pulsed electric fields (MIPEF) and from untreated tomatoes were preserved by high-intensity pulsed electric fields (HIPEF) or by thermal treatment (TH) having, in both cases, the fresh juice as a reference. The chemical and sensory changes of tomato juices stored at 4°C for increasing period of time were analyzed. A quantitative descriptive analysis was developed to characterize the sensory quality of samples. Tomatoes subjected to MIPEF treatments led to tomato juices with a higher content of volatile compounds and better sensory properties than those prepared with untreated tomatoes. An enhancement was observed in hexanal and (E)-2-hexenal just after processing in juices prepared with MIPEF-treated tomatoes. A slight decrease in volatile compounds and a loss of sensory quality was observed over time in TH and HIPEF juices, but HIPEF-processed samples just after processing and through storage maintained higher overall quality.

Moderate-intensity pulsed electric fields (MIPEF) have been studied as possible treatments to enhance the generation of secondary plant metabolites by inducing stress reactions. It has been described that MIPEF-induced stress affects metabolism with the consequent generation of reactive oxygen species (ROS) (Galindo et al., 2009). ROS are endogenous signal components required for synthesis of carotenoids, which take part in the defense response of plants to stress (Vallverdu-Queralt et al., 2012b). Increases in lycopene content as well as in the antioxidant capacity of MIPEF-treated tomato fruit were observed 24 h after treatments, depending on the electric field strength (0.4–2 kV/cm) and number of pulses (5–30) applied (Vallverdu-Queralt et al., 2012a). On the other hand, the application of high-intensity pulsed electric fields (HIPEF) in food processing has been gaining interest as a non-thermal preservation technology to inactivate microorganisms and enzymes by maintaining the nutritional quality, antioxidant content and freshness of liquid foods(Odriozola-Serrano et al., 2009).

MIPEF PROCESSING OF TOMATOES

MIPEF treatments were conducted in batch mode using anequipment manufactured by Physics International (San Leandro, CA, USA), which can deliver pulses from a capacitor of 0.1 lF with an exponential decaying waveform. A stainless steel parallel plate treatment chamber was used. A batch of tomato fruit was placed in the treatment chamber filled with tap water. Tomato fruit were treated at 1 kV/cm using 16 monopolar pulses of 4 µs at a frequency of 0.1 Hz according to a previous study (Vallverdu-Queralt et al., 2012b). MIPEF-treated tomatoes were collected and immediately refrigerated at 4 _C during 24 h. Untreated tomatoes were stored separately at 4˚C during 24 h. Two replicates of each treatment were carried out.

HIPEF PROCESSING OF TOMATO JUICES:

Vallverdu-Queralt et al. (2012b)HIPEF-treatments were carried out using a continuous flow bench scale system (OSU-4F, Ohio State University, Columbus, OH, USA). The flow rate of the process was adjusted to 60 mL/ min and controlled by a variable speed pump (model 752210-25, Cole Palmer Instrument Company, Vermon Hills, IL, USA). Juices were passed through a cooling coil connected between each pair of chambers and submerged in an ice-water shaking bath. Thermocouples were attached to the surface of the stainless-steel coils, 2.5 cm away from the HIPEF zones along the flow direction. The thermocouples were connected to temperature readers and isolated from the atmosphere with an insulation tape. The temperatures of the inlet and outlet of each pair of chambers were recorded every 0.1 s during HIPEF treatment and the samples never exceeded 40 _C. HIPEF treatment was set up at 35 kV/cm for 1500 µs using bipolar squared-wave pulses of 4 µs and a frequency of 100 Hz, as described in the literature (Odriozola-Serranon et al., 2009). Two replicates of each treatment were carried out.

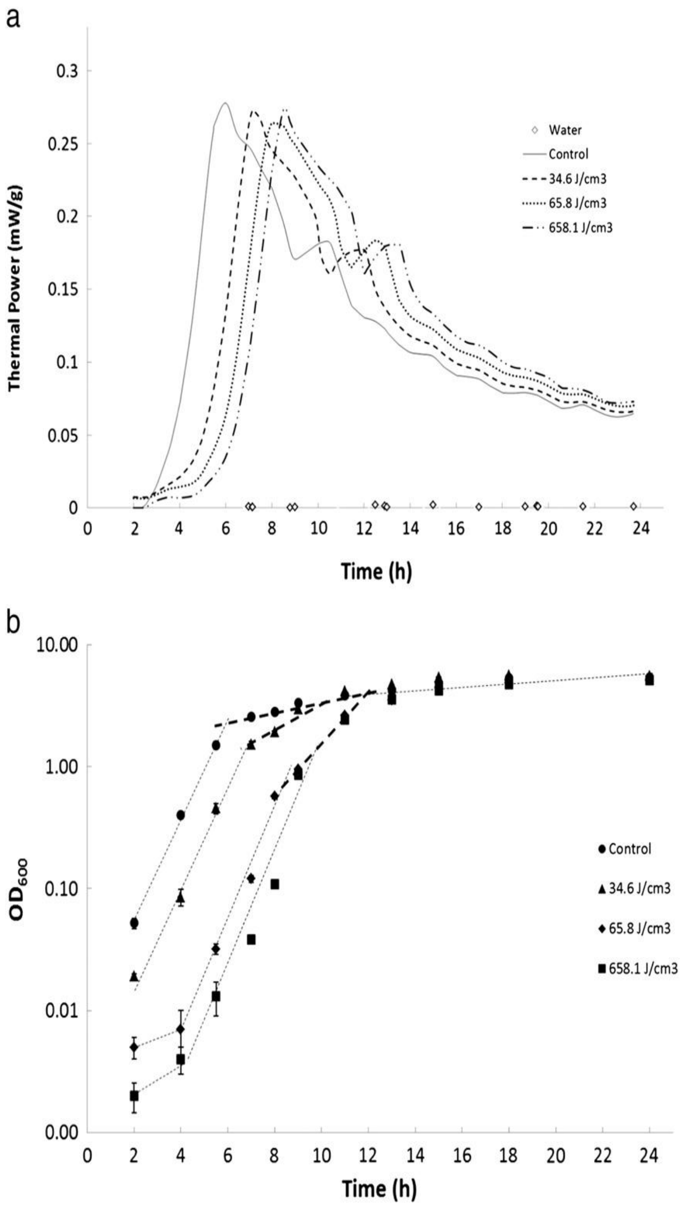
Anna Vallverdu-Queralt et al., (2013b) used a metabolite profiling approach to study the effect of moderate-intensity pulsed electric field (MIPEF) treatments on the individual polyphenol and carotenoid contents of tomato fruit after refrigeration at 4˚C for 24 h. The MIPEF processing variables studied were electric field strength (from 0.4to2.0 kV/cm) and number of pulses (from 5 to 30). Twenty four hours after MIPEF treatments, an increase was observed in hydroxycinnamic acids andflavanones, whereas flavonols, coumaric and ferulic acid-O-glucoside were not affected. Major changes were also observed for carotenoids, except for the 5-cis-lycopene isomer, which remain unchanged after 24 h of MIPEF treatments. MIPEF treatments, conducted at 1.2 kV/cm and 30 pulses, led to the greatest increases in chlorogenic (152%), caffeic acid-O-glucoside (170%) and caffeic (140%) acids. On the other hand, treatments at 1.2 kV/cm and 5 pulses led to maximum increases of a-carotene, 9- and 13-cis-lycopene, which increased by 93%, 94% and 140%, respectively. Therefore, MIPEF could stimulate synthesis of secondary metabolites and contribute to production of tomatoes with high individual polyphenol and carotenoid contents.

The effect of pulsed electric fields on the polyphenol profile of tomato juices was studied. First, tomatoes were subjected to moderate-intensity pulsed electric fields (MIPEFs) and then were immediately refrigerated at 4 °C for 24h. Treated and untreated juices were then subjected to high-intensity pulsed electric fields (HIPEFs) or thermal treatment (90 °C for 60 s). In comparison to references, tomatoes subjected to MIPEF treatments led to juices with a higher content of polyphenol compounds. A slight decrease in polyphenol compounds was observed over time in thermal- and HIPEF-treated juices, with the exception of caffeic acid. However, HIPEF-processed tomato juices had a higher content of polyphenol compounds (ferulic acid, caffeic-O-glucoside acid, p-coumaricacid,chlorogenic acid, rutin, and naringenin) just after processing and through storage than those thermally treated. Therefore, the combination of MIPEFs and HIPEFs could be proposed as a strategy for producing tomato juices with a higher content of phenolic compounds (Vallverdu-Queralt et al.,2012).

The effects of high intensity pulsed electric fields (HIPEF) (35kV/cm with 4µs bipolar pulses at 200Hz for 800 or 1400µs) or thermal (90°C, 60s) treatments over phenolic and carotenoid compounds of a fruit juice-soymilk (FJ-SM) beverage stored at 4°C were evaluated and compared, having the untreated beverage as a reference. Coumaric acid, narirutin and hesperidin were the most abundant phenolic compounds in the FJ-SM beverage, while the main carotenoids were lutein, zeaxanthin and β-carotene. Immediately after HIPEF or heat processing, hesperidin content of the beverage showed a huge rise, resulting in a significant increase on the total phenolic concentration. Regarding carotenoidconcentration, HIPEF or thermal treatment lead to a significant decrease; lutein, zeaxanthin and β-cryptoxanthin being the most affected compounds. In contrast, the content of some individual phenolics and carotenoids increased with time, while others tended to decrease or remained with no significant changes with regards to their initial values. Total phenolic concentration seemed to be highly stable during storage; while, total carotenoid content gradually diminished, irrespectively of the treatment applied. Overall, the changes observed in HIPEF treated FJ-SM beverage were less than those in the heat processed one. Hence, HIPEF is a feasible technology to obtain FJ-SM beverages with extended shelf-life and a similar profile of antioxidant compounds to freshly made beverages (Morales-de la Pena et al.,2011).

Pulsed Electric Field (PEF) processing, a novel, non-thermal food preservation method, has been shown to inactivate both spoilage and pathogenic microorganisms, while minimizing changes in the physical and organoleptic qualities of the food, such as those observed under conventional thermal processing. An understanding of the inactivation mechanisms and kinetics of microorganisms exposed to lethal or sub-lethal PEF treatments would allow industry and consumers to better understand and evaluate the potential of PEF technology as an alternative or complement to traditional methods of food preservation. This study consisted of three sets of experiments which sought to determine: (i) the electrical conductivity (EC) of various liquid food products (apple, orange and pineapple juices, egg white, whole egg and egg yolk) at different temperatures (5-55°C); (ii) the capacity of PEF (15 kV cm-1, 0°C) to inactivate Escherichia coli O157:H7 in dialyzed liquid egg products; and (iii) the effect of PEF (20 or 30 kV cm-1) in combination with temperature (10-40°C) on the inactivation of E. coli and Salmonella Enteritidis in liquid egg yolk (EY), whole egg (WE), or egg white (EW). The treatment chamber design was based in part on regression equations of EC vs. temperature developed in the first set of experiments. After only 0.1 sec of PEF (15 kV cm-1) treatment, 1, 3 and 3.5 log reductions of E. coli were noted in dialyzed egg white, egg yolk and whole egg, respectively. Kinetic models of bacterial inactivation were proposed. A 210 µs exposure to PEF (30 kV cm-1) resulted in log reductions of 5.0 and 5.0 in egg yolk, 3.9 and 3.6 in whole egg and, 2.8 and 3.6 in egg white, for E. coli and S. Enteritidis, respectively. A maximum energy of 914 J was required to inactivate S. Enteritidis in WE. In egg white, cells injured by PEF represented 0.9 and 0.4 log for S. Enteritidis and E. coli, respectively. An exponential decay model and an Arrhenius equation were used to describe the inactivation kinetics of the bacteria in liquid egg products. The kinetic constant (k T) showed E. coli to be more resistant to PEF treatment than S. Enteritidis.

Pulsed electric fields (PEF) have been proven to inactivate microorganisms during nonthermal conditions and have the potential to replace thermal processing as a method for food preservation. However, there is a need to understand the recovery and growth of survivors and potentially injured microorganisms following PEF processing. The purpose of this investigation was to study the growth ofEscherichia coli at 10 degrees C following exposure to electrical field strengths (15, 22.5 and 30 kV/cm) in relation to inactivation and the amount of potentially sublethally injured cells. One medium was used as both a treatment medium and an incubation medium, to study the influence of environmental factors on the inactivation and the growth of the surviving population. The pH (5.0, 6.0 and 7.0) and water activity (1.00, 0.985 and 0.97) of the medium was varied by adding HCl andglycerol, respectively. Growth was followed continuously by measuring the optical density. The time-to-detection (td) and the maximum specific growth rate (micromax) were calculated from these data. Results showed that the PEF process did not cause any obvious sublethal injury to the E. coli cells. The number of survivors was a consequence of the combination of electrical field strength and environmental factors, with pH being the most prominent. Interestingly, the micromax of subsequent growth was influenced by the applied electrical field strength during the process, with an increased micromax at more intense electrical field strengths. In addition, the micromax was also influenced by the pH and water activity. The td, which could theoretically be considered as an increase in shelf life, was found to depend on a complex correlation between electrical field strength, pH and water activity. That could be explained by the fact that the td is a combination of the number of survivors, the recovery of sublethal injured cells and the growth rate of the survivors.



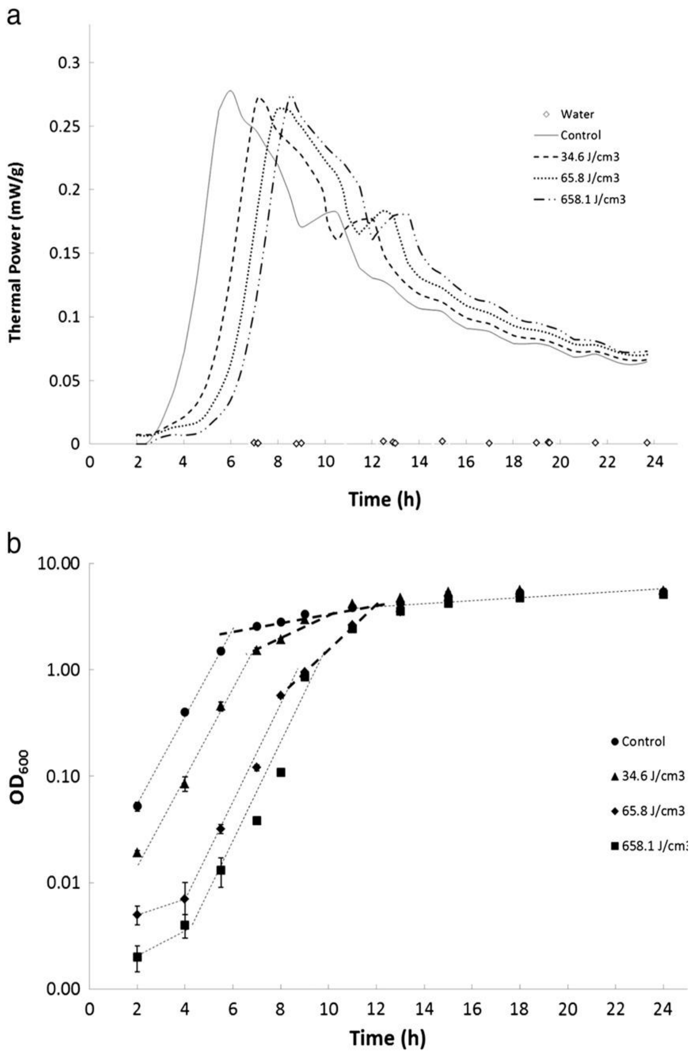


Fig. 1.Growth of Lactobacillus plantarum 564 after different PEF treatments. (a) Effect of PEF on thermal power production by the surviving population. Average curves of duplicates are reported. The initial disturbance of the calorimetry signal is omitted in the figure and thermal powers from the second hour of recording are reported. The small oscillation seen after 10h are disturbances from temperature variation in the laboratory. (b) Growth curves based on optical density measurements at 600 nm. Average results of four determinations are reported. Vertical bars represent the standard deviation.PEF offers the ability to inactivate microorganisms with minimal effects on the nutritional, flavor and functional characteristics of food products due to the absence of heat. PEF technology is based on the application of pulses of high voltage (typically 20– 80 kV/cm) delivered to the product placed between a set pair of electrodes that confine the treatment gap of the PEF chamber. The large field intensities are achieved through storing a large amount of energy in a capacitor bank (a series of capacitors) from a direct current power supply, which is then discharged in the form of high voltage pulses.

The pulse caused by the discharge of electrical energy from the capacitor is allowed to flow through the food material for an extremely short period of time (1–100 ls) and can be conducted at moderate temperatures for less than 1 s (Deeth et al.,2007). When food is subjected to the electrical high-intensity pulses several events, such as resistance heating, electrolysis (Hulsheger&Niemann, 1980) and disruption of cell membranes (Sitzmann, 1995), can occur contributing to the inactivation of microorganisms. In fact, several theories exist for the destruction of bacterial cells by PEF, but they commonly describe damage on the cell membrane (electroporation) which affects its functioning and may lead to cell death (Deeth et al., 2007). PEF technology is mainly intended for preservation of pumpable fluid or semi-fluid foods (Qin et al.,1995). In particular it could be used to improve the shelf-life of milk (Craven et al., 2008; Sampedro, Rodrigo, Martinez, Rodrigo, & Barbosa-Cánovas, 2005), green pea soups (Vega-Mercado et al.,1997), liquid whole eggs (Barbosa-Cánovas, 2001) and fruit juices (Heinz et al.,2002; Hodgins et al.,2002). In fact, the adoption of PEF for commercial non-thermal pasteurization of fruit juices has been first implemented by Genesis Juices, Oregon, USA (Clark, 2006). A combination of mild heat and PEF might also be helpful to achieve sufficient enzyme inactivation to avoid the necessity of refrigerated storage. When operating at high treatment temperatures and making use of synergetic heat effects, PEF energy input might be reduced close to the amount required for conventional thermal pasteurization, assuming 95% of heat recovery (Toepfl, Mathys, Heinz, & Knorr, 2006). Although the study of PEF technology has been focused on its ability to inactivate microorganisms in liquid food products at low temperatures, some other applications in the food industry have been explored as well, such as the enhancement of drying efficiency and decontamination of liquid waste (Barbosa-Cánovas& Sepulveda, 2005). The lack of understanding of the factors that can affect the efficacy of PEF-treatment, such as proper processing conditions and design of equipment, type of microorganism, suitability and properties of the treated food (Deeth et al., 2007), are currently limiting the validation of this technology for commercial application.

Pereira and Vicente, (2010) studied the preservation of liquid foods by high intensity pulsed electric fields (PEF). High intensity pulsed electric fields (PEF) is an interesting alternative to traditional techniques like thermal pasteurization. Based on the underlying mechanism of action, in this paper the crucial process parameters electrical field strength, total pulse energy input and treatment temperature were investigated experimentally. Inactivation studies were performed with three bacteria (*E. coli, Bacillusmegaterium, Listeriainnocua*) and one yeast (*Saccharomyces cerevisiae*). Stainless steel and carbon electrodes have been tested to investigate their applicability as electrode material. Simulating the influence of cell size and orientation as well as the presence of agglomerations or insulating particles indicated that the applied field strength has to be increased above the critical one to achieve product safety. It was found that temperatures higher than 40 ◦C can strongly increase the lethality of the PEF process. In this way also small cells like *Listeria* are easily affected by pulsed fields even at field strength as low as 16 kVcm−1. In addition, heating of the product prior to PEF has the advantage that most of the required process energy can be recovered using heat exchangers. Exemplary, such a process is analyzed by an enthalpy balance.

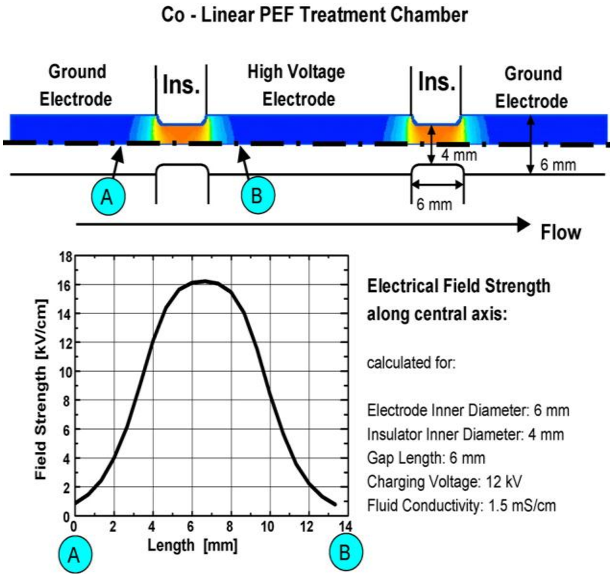


Fig. 2.Features of co-linear PEF treatment chambers. Top: sectional view of the electrode configuration and the resulting electrical field. The central high voltage electrode is separated from two grounded electrodes on either side by an electrical insulator. One example is given which shows the field strength along the central axis at the treatment zone A–B.

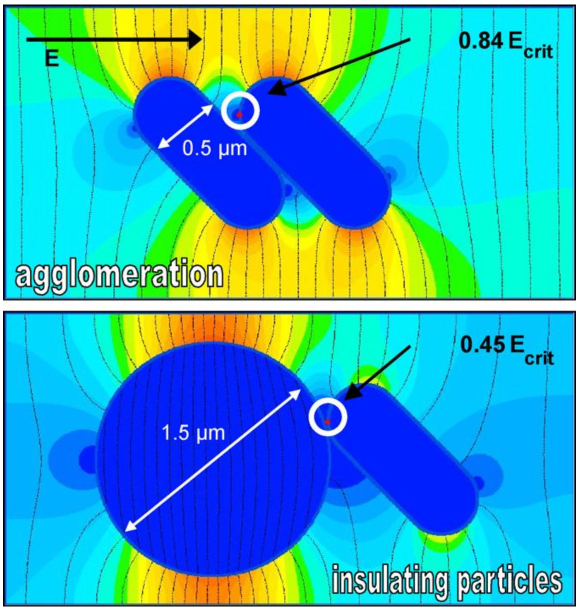


Fig. 3. Factors which may cause inhomogenities in the electrical field—top: agglomeration of two bacterial cells; bottom: bacterial cell attached to a fat globule. The external electrical field strength is 12.5 kV cm−1. The white ring shows the location on the membrane where the pore-formation is expected to happen when the field strength is high enough to produce 1V membrane potential difference (=2000 kV cm−1). However, due to the configurations shown, in both cases the required critical membrane potential *E*crit is not reached. Finite elements modeling have been performed by the Software Quick Field (Tera Analysis Ltd., Denmark).

In Fig. 3 the membrane potential of small bacterial cells (similar to *Listeria*) was simulated by application of the Quickfield® FEM code (Tera Analysis Ltd., Denmark). The exposure to an external electrical field of 12.5 kV cm−1 which can induce a critical electrical field strength *E*crit of 2000 kV cm−1 oriented along the electric field lines and without presence of agglomerations. The white rings show the location where the membrane field strength is maximized. The reduced peak values of 0.84 and 0.45 *E*crit show that agglomeration of cells as well as the presence of insulating particles can strongly reduce the lethality of the PEF process, as the required membrane potential for an electroporation is not achieved. Variations of cell orientation and in particular the presence of particles or fat globules as well as formation of clusters might result in an even lower factors as 0.45. Dependent on the properties of the food matrix and its contents a worst case scenario has to be developed to choose appropriate electric field strength to excess the critical trans membrane potential for all cells. Electrically insulating gas bubbles which may be produced at the electrode by electrolysis can cause a similar weakening effect (Gongora-Nieto et al., 2002).

A computational fluid dynamics (CFD) model describing the flow, electric field and temperature distribution of a laboratory-scale pulsed electric field (PEF) treatment chamber with co-field electrode configuration was developed. The predicted temperature increase was validated by means of integral temperature studies using thermocouples at the outlet of each flow cell for grape juice and salt solutions. Simulations of PEF treatments revealed intensity peaks of the electric field and laminar flow conditions in the treatment chamber causing local temperature hot spots near the chamber walls. Furthermore, thermal inactivation kinetics of lactoperoxidase (LPO) dissolved in simulated milk ultra filtrate were determined with a glass capillary method at temperatures ranging from 65 to 80_C. Temperature dependence of first order inactivation rate constants was accurately described by the Arrhenius equation yielding an activation energy of 597.1 kJ mol_1. The thermal impact of different PEF processes on LPO activity was estimated by coupling the derived Arrhenius model with the CFD model and the predicted enzyme inactivation was compared to experimental measurements. Results indicated that LPO inactivation during combined PEF/thermal treatments was largely due to thermal effects, but 5–12% enzyme inactivation may be related to other electro-chemical effects occurring during PEF treatments.

Sampedro et al. (2013) estimated the cost of pulsed electric field (PEF) pasteurization of orange juice.The cost analysis was based on processing conditions that met the US FDA (5 log reduction) requirement for fruit juice pasteurization and that achieved a sufficient microbial shelf-life. PEF-treated samples processed at 30 kV/cm and 60 °C had reductions in Escherichia coli, Salmonella Typhimurium and Lactobacillus spp. of greater than 5 log and had a microbial shelf-life of 2 months at 4 °C. Total pasteurization cost was estimated to be 3.7 ¢/L. Of this,capital costs accounted for 54% (2.0 ¢/L), labor costs accounted for 35% (1.3 ¢/L) and utility charges, mainly electricity, accounted for 11% (0.4 ¢/L). The total PEF cost was 147% (2.2 ¢/L) more than that of conventional thermal processing (1.5 ¢/L). A deeper knowledge of the processing costs of PEF technology will afford companies a better understanding of the benefits and limitations of nonthermal processing. Industrial relevance: Pasteurization of orange juice by pulsed electric fields (PEF) results in a higher quality product compared to traditional thermal pasteurization. However, industry has not embraced this new technology and the main reason for this may be the lack of a comprehensive cost analysis. A large-scale commercial PEF system was designed and the total pasteurization cost was estimated to be 3.7¢/L. The total PEF cost was 2.2¢/L more than that of traditional thermal processing. A thorough knowledge of the processing costs will provide companies with a better understanding of the pros and cons of PEF pasteurization.

This study aimed at determining the PEF processing conditions for orange juice pasteurization able to meet the US FDA and commercial shelf-life requirements and estimating the overall processing costs. Several bacterial composites involved previously in orange juice outbreaks with high acidic and PEF resistance were used to select the optimal processing conditions. The Lactobacillus composite was the most resistant to PEF processing followed by Salmonella and E. coli composites. Optimal process conditions that achieved 5 log reductions of composites with an additional safety margin (30 kV/cm, 60 °C) were used for the shelf-life study. PEF-treated orange juice had a shelf-life of 2 months at refrigeration conditions with lower microbial counts than fresh orange juice. The cost of PEF pasteurization of orange juice was estimated to be 3.7¢/L, where capital costs accounted for 54%, labor costs 35% and utility charges 11% of the total pasteurization costs. This study will allow companies a better understanding of the benefits and limitations of PEF nonthermal technology and aid them in deciding whether or not to implement the new process.

The main reason for the limited application of PEF technology may be the lack of systematic cost analysis studies of the commercial application of PEF processing. It has been stated that the low implementation of PEF in industry ismainly due to the high initial investment costs and elevated processing costs (Gongora-Nieto et al., 2002). However, only a few studies have been found in the scientific literatures that dealwith the cost analysis of PEF food processing. Some studies were performed a long time ago and are outdated in this rapidly developing technology (EPRI, 1998)whereas others barely discussed the cost of PEF processing (Huang and Wang, 2009). In a recent report, Hoogland and de Haan (2007) estimated the cost of PEF pasteurization without heat-recovery; however the study only reported the comparisonwith respect to thermal processing. Sufficient and up-to-date cost analysis information is urgently needed by commercial juice processors. A second reason for the low industrial success of PEF technology may be the lack of appropriate target microorganisms and the nonpathogenicsurrogates for designing commercial processing conditions and validation studies at the pilot-plant level. For pathogen inactivation challenge studies, the National Advisory Committee on Microbiological Criteria for Foods (NACMF) in a recent report (NACMF, 2010) recommended using resistant strains relative to the process and technology, representative as being expected to be present in the applicable foods or associated with an outbreak involving the product under study. The same report stated that using an inoculum composed of multiple strains (i.e., a cocktail) of a given pathogen would help to encompass the variability among organisms and reduce the number of required tests (NACMF, 2010). In addition, any new process for juice pasteurization needs to follow the U.S. Food and Drug Administration juice HACCP rules (21 CFR 120.24) that mandate processors to treat juice for a 5 log reduction of the pathogen of concern (FDA, 2009).

Mhemdi et al. (2013) studied the effects of pulsed electric field (PEF) (electric field strength, E, 100–1000 V; pulse duration, tp, 100 µs) on disintegration of potato slices treated between parallel plate electrodes by using a laboratory compression chamber equipped with a PEF-treatment system. The apparent density of slices (bed of particles), ρ, was varied within 0.313 g/cm3 and 1 g/cm3. The electrical conductivity $\sigma(\rho)$ of the packing of slices versus volume fraction of particles ϕ was approximated by the percolation law $\sigma \propto (\phi - \phi c)t$, where $\phi c \approx 0.290$, $t = ti \approx 0.46$ and $t = td \approx 1.39$ for the intact and completely damaged tissues, respectively. The impact of electric field strength and apparent density of slices on PEF-induced damage kinetics was studied. The more accelerated kinetics of damage was observed for more dense packing of slices. The approximated relation between the applied, E, and effective, Ee, electric field strengths accounting for the $\sigma(\rho)$ dependence was derived. Industrial relevance: The practical applications of PEF treatment (e.g., pressing, drying, extraction, etc.) demand operations with slices of food particles. In this study, research towards the electroporation efficiency of PEF applied to the porous packing of sliced food particles is provided.

A drastic increase in permeability re-establishes the equilibrium of the electrochemical and electric potential differences of the cell plasma and the extracellular medium forming a Donnan-equilibrium (Toepfl et al., 2007). Simultaneously, the neutralization of the transmembrane gradient across the membrane irreversibly impairs vital physiological control systems of the cell like osmoregulation and consequently cell death occurs. Microbial cells which are exposed to an external electrical field for a few microseconds respond by an electrical breakdown and local structural changes of the cell membrane. In consequence of the so called electroporation, a drastic increase in permeability is observed which in the irreversible case is equivalent to a loss of viability. This type of non-thermal inactivation of microorganisms by high intensity pulsed electric fields might be beneficial for the development of quality retaining preservation processes in the food industry. However, process safety, cost-effectiveness, and consumer benefits of pulsed electric field treatment have to be confirmed.

PEF offers the ability to inactivate microorganisms with minimal effects on the nutritional, flavor and functional characteristics of food products due to the absence of heat. PEF technology is based on the application of pulses of high voltage (typically 20– 80 kV/cm) delivered to the product placed between a set pair of electrodes that confine the treatment gap of the PEF chamber. The large field intensities are achieved through storing a large amount of energy in a capacitor bank (a series of capacitors) from a direct current power supply, which is then discharged in the form of high voltage pulses(Zhang et al., 1995).The pulse caused by the discharge of electrical energy from the capacitor is allowed to flow through the food material for an extremely short period of time (1–100 ls) and can be conducted at moderate temperatures for less than 1s (Deeth e al., 2007). When food is subjected to the electrical high-intensity pulses several events, such as resistance heating (Pereira and Vicente, 2010), electrolysis (Hulsheger and Niemann, 1980) and disruption ofcell membranes (Craven et al., 2008), can occur contributing to the inactivation of microorganisms. In fact, several theories exist for the destruction of bacterial cells by PEF, but they commonly describe damage on the cell membrane (electroporation) which affectsits functioning and may lead to cell death (Deeth et al.,2007). PEF technology is mainly intended for preservation of pumpable fluid or semi-fluid foods (Craven et al., 2008). In particular it could be used to improve the shelf-life of milk (Sampedro et al.,2005),green pea soups, liquid whole eggs (Barbosa-Canovas,2001) and fruit juices (Heinz et al.,2002). In fact, the adoption of PEF for commercial non-thermal pasteurization of fruit juices has been first implemented by Genesis Juices, Oregon, USA (Clark, 2006). A combination of mild heat and PEF mightalso be helpful to achieve sufficient enzyme inactivation to avoidthe necessity of refrigerated storage. When operating at high treatment temperatures and making use of synergetic heat effects, PE Fenergy input might be reduced close to the amount required for conventional thermal pasteurization, assuming 95% of heat recovery (Toepfl et al., 2006). Although the study of PEF technology has been focused on its ability to inactivate microorganismsin liquid food products at low temperatures, some other applications in the food industry have been explored as well, suchas the enhancement of drying efficiency and decontamination of liquid waste (Barbosa-Canovas and Sepulveda, 2005).The lack of understanding of the factors that can affect the efficacy of PEF-treatment, such as proper processing conditions and design of equipment, type of microorganism, suitability and properties. Properties of the treated food are currently limiting the validation of this technology for commercial application (Deeth et al., 2007).

Gerlach et al.(2008)the application of pulsed electric fields is a novel technique to preserve foods in a non-thermal way. One key component of this technology is the treatment chamber, in which the food is exposed to a pulsed electric field to induce permeabilization of biological cells, e.g. to inactivate microorganisms. For a high efficiency of the method and a high product quality a detailed knowledge of the electric field strength and temperature distribution in the chamber is necessary. The numerical simulation of the fluid dynamics coupled with the electric and thermal fields inside the treatment chamber can provide such information with high special and temporal resolution. An important goal of the simulations is the optimization of the treatment chamber geometry to improve the uniformity of the electric and thermal fields between the electrodes in order to avoid the over or under-processing of foods or dielectric breakdowns. Deeth et al. (2007) performed numerical investigations on the pulsed electric field process and presents numerical results of a treatment chamber optimization and the solution of coupled fluid dynamical, electrical and thermal problems. Industrial relevance: Numerical simulations of the pulsed electric field process provide detailed information of the fluid flow, the temperature and the electric field distributions in treatment chambers under various conditions. Such local information inside the electric field is difficult to obtain experimentally. For a further development of the pulsed electric field technology, numerical simulations can be applied to improve the fundamental understanding of the physical phenomena occurring and to optimize the process with respect to the chamber design and operating conditions.

CHEMICAL RISKS

Some authors have investigated if PEF processing could chemically induce changes in the quality of food or even cause harmful effects on the consumers. Hulsheger and Niemann, (1980)suggested that hypochloric acid, generated from chloride in buffers under the action of an electric field, could contribute to the lethality of PEF treatment. Nevertheless, Wouterset al. (1999)later demonstrated that the inactivation degree of L. monocytogenes in buffer systems containing chloride ions was no significantly higher than in buffers without chloride.They argued that the length of the pulse is a critical parameter when aiming at controlling undesirable electrochemical reactions.Some studies have identified the unintentional emission of metal as a significant risk (Heinz et al., 2002).Charged electrodes are in contact with the food and, therefore, the formation of electrolytic products and the release of electrode material into the product stream can hardly be controlled. Thus, the particular design of electrodes and treatment devices, as well as pulse shape definition, is critical to prevent these risks (Mastwijk et al.,2004).The amount of metals released depends on the type of product, the specific composition of the electrodes and pulse geometry. On the other hand, changes in food components could be induced due to the electrochemical action. Detailed information on the composition of foods can be obtained by chemical fingerprinting (Noteborn et al., 2001).Minor chemical changes have been demonstrated to be induced in PEF-treated tomato product after processing (Lelieveld et al., 2001).From a legal perspective, PEF treatment is subjected to the Novel Food Regulation (NFR) issued by the European Union. The NFR states that safety of food products can be assumed if during the novel process no additives are introduced, and the resulting product does not substantially differ from the untreated product.

FUTURE PERSPECTIVES FOR THE INDUSTRIAL IMPLEMENTATION OF PEF

Application of pulsed electric fields for food preservation offers excellent perspectives regarding the successful implementation of this environmentally friendly technology, in terms of energy consumption, at an industrial level. PEF have been shown to be an interesting technology to process acidic products such as fruit juices or even low acidic commodities, if properly combined with other processing techniques. Hence, high-quality, safe and shelf stable liquid foods can be obtained without significant depletion of their fresh bioactive potential. In-depth research is needed in order to study the factors involved in the generation/destruction of these compounds, as well as to elucidate the mechanistic insight of the changes. However, some challenges and bottlenecks still preclude the industrial implementation of PEF. On the one hand, many groups are currently studying the effects of PEF treatments with systems that greatly differ in building-up, way of operation, and construction materials. This greatly complicates the comparison of results. On the other hand, because of the intrinsic characteristics of the technology, it is not easy to on-time monitor the process conditions that determine the boundary regions delimiting areas in which the primary treatment effects, caused by the electrical treatment, outweigh the secondary effects, caused by temperature(Soliva-Fortuny et al.,2009). Furthermore, industrial equipment needs to be designed considering energy recovery systems, as well as operation conditions that minimize undesirable phenomena such as electrochemical reactions leading to electrode corrosion. The development of improved PEF systems capable of adapting working conditions to different fluid characteristics and flow rates represents a significant design challenge that needs to be overcome to facilitate the commercial exploitation of this non thermal technology.

Pulsed electric fields (PEF) technology provides the potential of ensuring safety and maintaining the physico-chemical quality of liquid food products without substantially impacting the content and composition of thermolabile compounds. This is especially relevant in the case of plant-based foods, because some of the features that are currently most appreciated by consumers, such as aroma or bioactive potential, are related to this heat-sensible fraction. Specifically, fruit juices and vegetable-based beverages exhibit a remarkable content in phytochemicals with health-promoting benefits, some of them with a significant antioxidant potential.Although the effectiveness of PEF treatments has been extensively studied during the past couple of decades, their impact on the bioactive composition of foods is still being researched. Through the presentation, some of the key factors that rule the inactivation/ destruction of health-related constituents in foods will be introduced and discussed. Recently published research results will be reviewed and compared with those obtained for other thermal and non-thermal processing technologies, with a special stress on the effect of PEF-processing variables on the bioactive composition of foods throughout their whole shelf-life. Furthermore, different examples will be presented to illustrate not only the potential but also the limitations of PEF technology when aiming at preserving the health-promoting features of plant-based foods.

REFERENCES

[1] Ade-Omowaye, B. I. O., Angersbach, A., Taiwo, K. A and Knorr, D. 2001. Use of pulsed electric field pre-treatment to improve dehydration characteristics of plant based foods. Trends in Food Science and Technology.12(8):285–295.

[2] Mastwijk, H.C and Pol-Hofstad, I.E. 2004.Pulsed electric field (PEF) processing in the fruit juice and dairy industries. Food Safety Magazine 10(3).

[3] Noteborn, H.P.J.M., Lommen, A., van der Jagt, R.C., Weseman, J.M. 2001.Chemical fingerprinting for the evaluation of unintended secondary metabolic changes in transgenic u food crops. Biotechnology 77:103–114.

[4] Heinz, V., Alvarez, I., Angersbach, A., Knorr, D. 2002.Preservation of liquid foods by high intensity pulsed electric fields-basic concepts for process design. Trends Food Sci Technol. 12:103–111.

[5] Wouters, P.C., Dutreux, N., Smelt, J.P.P.M., Lelieveld, H.L.M.1999.Effects of pulsed electric fields on inactivation kinetics of Listeria innocua. Appl Environ Microbiol .65(12):5364–5371.

[6] Aguilo-Aguayo I, Soliva-Fortuny R, Martın-Belloso O. 2010. Impact of high-intensity pulsed electric field variables affecting peroxidase and lipoxygenase activities of watermelon juice. LWT-Food Sci Technol. 43(6):897–902.

[7] Amami, E., Khezami, L., Vorobiev, E., &Kechaou, N. 2008. Effect of pulsed electric field and osmotic dehydration pretreatment on the convective drying of carrot tissue. Drying Technology. 26(2):231–238.

[8] Anna Vallverdu-Queralt, Alessandra Bendini, Sara Barbieri, Giuseppe Di Lecce, Olga Martin-Belloso, and TulliaGallinaToschi. 2013.Volatile profile and sensory evaluation of tomato juices treated with pulsed electric fields. Journal of Agricultural and Food Chemistry.61(8):1977.

[9] Barbosa-Canovas, G. V., & Sepulveda, D. 2005.Present status and the future of PEF technology.In Gustavo V. Barbosa-Canovas, María S. Tapia, M. Pilar Cano, Olga Martin-Belloso, & Antonio Martínez (Eds.), Novel food processing technologies. Boca Raton, USA: CRC Press.

[10] Barbosa-Canovas, G. V.2001.Developments in pulsed electric fields – USA research and consortium activities.In Proceedings of electric field processing the potential to make a difference.Chipping Campden: Campden and Chorleywood Food Research Association.

[11] Cai, Z., Riedel, H., Thaw Saw, N. M., Kutuk, O., Mewis, I., Jager, H., et al. (2011). Effects of pulsed electric field on secondary metabolism of Vitisvinifera L. cv. GamayFreaux suspension culture and exudates. Applied Biochemistry and Biotechnology.164:443–453.

[12] Clark, J. 2006. Pulsed electric field processing.Food Technology. 60(1):66–67.

[13] Craven, H., Swiergon, P., Ng, S., Midgely, J., Versteeg, C., Coventry, M. 2008.Evaluation of pulsed electric field and minimal heat treatments for inactivation of pseudomonads and enhancement of milk shelf-life.Innovative Food Science and Emerging Technologies, 9, 211–216.

[14] De Vito, F., Ferrari, G., Lebovka, I., Shynkaryk, V., &Vorobiev, E. N. 2008.Pulse Duration and Efficiency of Soft Cellular Tissue Disintegration by Pulsed Electric Fields. Food and Bioprocess Technology.1:307–313.

[15] Deeth, H., Datta, N., Ross, A., & Dam, X. 2007. Pulsed electric field technology: Effect on milk and fruit juices. In G. Tewari& V. Juneja (Eds.), Advances in thermal and non-thermal food preservation. Oxford, UK: Blackwell Publishing.

[16] Donsi, F., Ferrari, G ansPataro, G. 2010.Applications of pulsed electric field treatments for the enhancement of mass transfer from vegetable tissue. Food Engineering Reviews, 2(2), 109–130.

[17] Donsi, F., Ferrari, G., &Pataro, G. 2010.Applications of pulsed electric field treatments for the enhancement of mass transfer from vegetable tissue. Food Engineering Reviews.2(2):109–130.

[18] Elez-Martınez P, Martın-Belloso O. 2007. Effects of high intensity pulsed electric field processing conditions on vitamin C and antioxidant capacity of orange juice and gazpacho, a cold vegetable soup. Food Chem. 102:201–9.

[19] Elez-Martinez, P., Escola-Hernandez, J., Espachs-Barroso, A., Barbosa-Canovas, G.V., MartinBelloso, O. 2005.Inactivation of Lactobacillus brevis in orange juice by high intensity pulsed electric fields. Food Microbiol. 22(4):311–319**.**

[20] Elez-Martinez, P., Suarez-Recio, M., Martin-Belloso, O. 2007. Modeling the reduction of pectin methyl esterase activity in orange juice by high intensity pulsed electric fields. J Food Eng. 78(1):184–193.

[21] Elez-Martinez, P., Escola-Hernández, J., Soliva-Fortuny, R.C., Martin-Belloso, O. 2004. Inactivation of Saccharomyces cerevisiae suspended in orange juice using high-intensity pulsed electric fields. Journal of Food Protection.67(11):2596-2602.

[22] EPRI.1998. Pulsed electric field processing in the food industry: A status report on PEF. Report CR-109742. Palo Alto, USA: Industrial and Agricultural Technologies and Services.

[23] F. Sampedro , A. McAloon , W. Yee , X. Fan , H.Q. Zhang, D.J. Geveke. 2013. Cost analysis of commercial pasteurization of orange juice by pulsed electric fields. Innovative Food Science and Emerging Technologies 17:72–78.

[24] Food and Drug Administration. 2009. Title 21 — Food and drugs. Part 120 — Hazard analysis critical control point (HACCP) systems. Subpart 24 — Process controls Code of Federal Regulations. Washington, DC: U.S. Government Printing Office.

[25] G. Barbosa-Canovas, & H. Zhang (Eds.), Textbook of Food Preservation.Journal of Applied Microbiology, 98, 1387−1399.

[26] Galindo, F., Dejmek, P., Lundgren, K., Rasmusson, A., Vicente, A. n., & Moritz, T. 2009.Metabolomic evaluation of pulsed electric field-induced stress on potato tissue.Planta, 230, 469–479.

[27] Gerlach, D., Alleborn, N., Baars, A., Delgado, A., Moritz, J., Knorr, D. 2008. Numerical simulations of pulsed electric fields for food preservation: A review.Innovative Food Science and Emerging Technologies. 9:408–417.

[28] Giner, J., Gimeno, V., Espachs, A., Elez, P., Barbosa-Canovas, G.V., Martin, O. 2000. Inhibition of tomato (Licopersiconesculentum Mill.) pectin methylesterase by pulsed electric fields. Innovative Food SciEmerg Technol. 1:57–67.

[29] Gongora-Nieto, M. M., Sepulveda, D. R., Pedrow, P., Barbosa-Cánovas, G. V and Swanson, B. G. 2002. Food processing by pulsed electric fields: Treatment delivery, inactivation level, and regulatory aspects. Lebensmittel-Wissenschaft und Technologie.35: 375–388.

[30] Grimi, N., Mamouni, F., Lebovka, N., Vorobiev, E., &Vaxelaire, J. 2010.Acoustic impulse response in apple tissues treated by pulsed electric field.BiosystemsEngineering.105(2): 266–272.

[31] Grimi, N., Praporscic, I., Lebovka, N., &Vorobiev, E. 2007. Selective extraction from carrot slices by pressing and washing enhanced by pulsed electric fields. Separationand Purification Technology, 58(2), 267–273.

[32] H. Mhemdi , N. Grimi , O. Bals , N.I. Lebovka, E. Vorobiev.2013. Effect of apparent density of sliced food particles on the efficiency of pulsed electric field treatment.Innovative Food Science and Emerging Technologies. 18:115–119.

[33] Heinz, V., Toepfl, S., & Knorr, D.2002.Impact of temperature on lethality and energy efficiency of apple juice pasteurization by pulsed electric fields treatment.Innovative Food Science and Emerging Technologies. 4:167–175.

[34] Heinz, V., Toepfl, S., & Knorr, D.2003.Impact of temperature on lethality and energy efficiency of apple juice pasteurization by pulsed electric fields treatment.Innovative. Food Science and Emerging Technologies.4:167−175.

[35] Hoogland, H., & de Haan, W. 2007.Economic aspects of pulsed electric field treatment of food. In H. L. M. Lelieveld, S. L. H. Notermans, & S. W. H. de Haan (Eds.), Food preservation by pulsed electric fields.257–265. New York: CRC Press.

[36] Huang, K., and Wang, J.2009. Designs of pulsed electric fields treatment chambers for liquid foods pasteurization process: A review. Journal of Food Engineering.95:227–239.

[37] Jaeger, H., Schulz, M., Lu, P and Knorr, D.2012. Adjustment of milling, mash electroporation and pressing for the development of a PEF assisted juice production in industrial scale. Innovative Food Science & Emerging Technologies.14:46–60.

[38] Jalte, M., Lanoiselle, J. -L., Lebovka, N. I., &Vorobiev, E. 2009. Freezing of potato tissue

[39] Kempkes, M. A.2011.Pulsed electric field (PEF) systems for commercial food and juice processing. In C. J. Doona, K. Kustin, & F. E. Feeherry (Eds.), Case studies in novel food processing technologies.73–102.Cambridge: Woodhead Publishing.

[40] Lebovka, N. I., Praporscic, I., &Vorobiev, E. 2004.Effect of moderate thermal and pulsed electric field treatments on textural properties of carrots, potatoes and apples. Innovative Food Science and Emerging Technologies.5(1):9–16.

[41] Lebovka, N. I., Shynkaryk, M. V., El-Belghiti, K., Benjelloun, H., &Vorobiev, E. 2007. Plasmolysis of sugarbeet: Pulsed electric fields and thermal treatment. Journal of Food Engineering.80(2):639–644.

[42] Lebovka, N., &Vorobiev, E. 2010.Advanced electroporation techniques in biology and medicine. In A. G. Pakhomov, M. Damijan, & M. S. Markov (Eds.), Series: Biological effects of electromagnetic. CRC Press .463–490.

[43] Loginova, K. V., Lebovka, N. I., &Vorobiev, E. 2011a. Pulsed electric field assisted aqueous extraction of colorants from red beet. Journal of Food Engineering. 106(2):127–133.

[44] Loginova, K. V., Vorobiev, E., Bals, O., &Lebovka, N. I. 2011b. Pilot study of countercurrent cold and mild heat extraction of sugar from sugar beets, assisted by pulsed electric fields. Journal of Food Engineering.102(4):340–347.

[45] Lopez, N., Puertolas, E., Condon, S., Raso, J., & Alvarez, I. 2009.Enhancement of the extraction of betanine from red beetroot by pulsed electric fields. Journal of Food Engineering.90(1):60–66.

[46] Luciano Jose Quintao-Teixeira, Robert Soliva-Fortuny, AfonsoMota Ramos, and Olga Mart ın-Belloso. 2013. Kinetics of Peroxidase Inactivation in Carrot Juice Treated with Pulsed Electric Fields. Journal of Food Science.78(2):222-228.

[47] M.M.G ongora-Nieto, P.D. Pedrow, B.G. Swanson, G.V. Barbosa-Canovas. 2003. Impact of air bubbles in a dielectric liquid when subjected to high electric field strengths, Innov. Food Sci. Emerg. Technol. 4:57–67.

[48] Manas, P and Pagan, R. 2005. A review: Microbial inactivation by new technologies ofMartinez Viedma, P., Sobrino Lopez, A., Ben Omar, N., Abriouel, H., Lucas Lopez, R., Martin Belloso,O., Galvez, A.2010.Increased inactivation of exopolysaccharide-producing Pediococcusparvulus in apple juice by combined treatment with enterocin AS-48 and high-intensity pulsed electricfield. J **Food** Prot . 73(1):39-43.

[49] Min, S., Jin, Z. T., and Zhang, Q. H.2003b. Commercial scale pulsed electric field processing of tomato juice. Journal of Agricultural and Food Chemistry. 51:3338–3344.

[50] Morales-de la Pena, M., Salvia-Trujillo, L., Rojas-Grau, M.A., Martin-Belloso, O.2011. Changes on phenolic and carotenoid composition of high intensity pulsed electric field and thermally treated fruit juice-soymilk beverages during refrigerated storage. Food Chemistry. 129(3):982-990.

[51] Morris, C., Brody, A.L., Wicker, L.2007.Non-thermal food processing and preservation technologies: a review with packaging implications. PackagTechnolSci 20(4):275–286.

[52] National Advisory Committee on Microbiological Criteria for Foods.2010. Parameters for determining inoculated pack/challenge study protocols. Journal of Food Protection.73(1): 140–202.

[53] Odriozola-Serrano, I., Soliva-Fortuny, R., Hernández-Jover, T., & Martín-Belloso, O. (2009). Carotenoid and phenolic profile of tomato juices processed by high intensity pulsed electric fields compared with conventional thermal treatments. Food Chemistry. 112:258–266.

[54] Ortega-Rivas, E. (2011). Critical issues pertaining to application of pulsed electric fields in microbial control and quality of processed fruit juices. Food and Bioprocess Technology.4: 631–645.

[55] P.C. Wouters, N. Dutreux, J.P.P.M. Smelt, H.L.M.1999. Lelieveld, Effects of pulsed electric fields on inactivation kinetics of *Listeria innocua*, Appl. Environ. Microbiol. 65:5364–5371.

[56] Pereira, R. N and Vicente, R. N.2010. Environmental impact of novel thermal and non-thermal technologies in food processing Food Research International 43 (2010) 1936–1943.

[57] Pereira, R., Martins, R and Vicente, A. 2008. Goat milk free fatty acids characterization during conventional and ohmic heating pasteurization. Journal of Dairy Science, 91, 2925–2937.

[58] Porras-Parral, G.,Miri, T., Bakalis, S., & Fryer, P. J. 2012. The effect of electrical processing on mass transfer in beetroot andmodel gels. Journal of Food Engineering, 112(3), 208–217.

[59] Puertolas, E., Luengo, E., Alvarez, I., &Raso, J. 2012. Improving mass transfer to soften tissues by pulsed electric fields: Fundamentals and applications.In M. P. Doyle, & T. R. Klaenhammer (Eds.), Annual Review of Food Science and Technology. Palo Alto: Annual Reviews. 3: 263–282.

[60] Qian Sui., Jason Wan and Kai Knoerzer.2012.Numerical Evaluation of Lactoperoxidase Inactivation During Continuous Pulsed Electric Field Processing.Biotechnology Progress.28:(5) 1363–1375.

[61] R.K. Simpson, R. Whittington, R.G. Earnshaw, N.J. Russel, Pulsed high electric field causes ‘all or nothing’ membrane damage *in Listeria monocytogenes* and *Salmonella typhimurium*, but membrane H+-ATPase is not a primary target, Int. J. Food Microbiol. 48 (1999) 1–10.

[62] R.N. Pereira and A. A. Vicente.2010.Environmental impact of novel thermal and non-thermal technologies in food processing.Food Research International. 43:1936–1943.

[63] Rivas, A., Rodrigo, D., Martınez, A., Barbosa-Canovas, G.V., Rodrigo, M. 2006.Effect of PEF and heat pasteurization on the physical-chemical characteristics of blended orange and carrot juice. LWT-Food SciTecnol 39:1163–70.

[64] Rodrigo, D., Barbosa-Canovas, G.V., Martinez, A., Rodrigo, M. 2003. Pectin methyl esterase and natural microflora of fresh mixed orange and carrot juice treated with pulsed electric fields.Journal of Food Protection.66(12):2336-2342.

[65] S.Toepfl, V. Heinz , D. Knorr. 2013. High intensity pulsed electric fields applied for food preservation. Chemical Engineering and Processing. 46 (2007) 537–546.

[66] Sampedro, F., Rodrigo, M., Martinez, A., Rodrigo, D and Barbosa-Canovas, G.2005.Quality and safety aspects of PEF application in milk and milk products.Critical Reviews in Food Science and Nutrition. 45:25–42.

[67] SanjaSeratli; BrankoBugarski ; Viktor Nedovic; ZoricaRadulovic; Lars Wadso; PetrDejmek and Federico Gomez Galindo .2013. Behavior of the surviving population of Lactobacillus plantarum 564 upon the application of pulsed electric fields.Innovative Food Science and Emerging Technologies.17 : 93–98.

[68] Sentandreu, E., Carbonell, L., Rodrigo, D., Carbonell, J.V. 2006. Pulsed electric fields versus thermal treatment: equivalent processes to obtain equally acceptable citrus juices. J Food Prot. 69(8):2016-2018.

[69] Shohael, A. M., Ali, M. B., Yu, K. W., Hahn, E. J., Islam, R., &Paek, K. Y. 2006. Effect of light on oxidative stress, secondary metabolites and induction of antioxidant enzymes in Eleutherococcussenticosus somatic embryos in bioreactor. Process Biochemistry:41:1179–1185.

[70] Soliva-Fortuny, R., Balasa, A., Knorr, D., & Martin-Belloso, O.2009.Effects of pulsed electric fields on bioactive compounds in foods: A review. Trends in Food Science & Technology.20:544–556.

[71] T. Grahl, H. Markl.1996. Killing of microorganisms by pulsed electric fields.Appl.Microbiol.Biotechnol. 45:148–157.

[72] Toepfl, S., & Heinz, V. 2011.Pulsed electric field assisted extraction — A case study. In pressure and pulsed electric fields for energy efficient and environmentally friendly food processing. Food Reviews International.22:405−423.

[73] Toepfl, S., Heinz, V., Knorr, D.2007. High intensity pulsed electric fields applied for food preservation. Chemical Engineering and Processing 46:537–546.

[74] Toepfl, S., Mathys, A., Heinz, V., and Knorr, D. 2006. Review: Potential of high hydrostatic

[75] U. Zimmermann, J. Schulz, G. Pilwat. 1973. Transcellular ion flow in *E. coli* and electrical sizing of bacteria, Biophys. J. 13:1005–1013.

[76] Vallverdu-Queralt, A., Oms-Oliu, G., Odriozola-Serrano, I., Lamuela-Raventós, R. M., Martín-Belloso, O., &Elez-Martínez, P. (2012b).Effects of pulsed electric fields on the bioactive compound content and antioxidant capacity of tomato fruit.Journal of Agricultural and Food Chemistry. 60:3126–3134.

[77] Vallverdu-Queralt,A., Odriozola-Serrano,I., Oms-Oliu,G., Lamuela-Raventos, R.M., Elez-Martinez, P., Martin-Belloso, O.2013. Impact of high-intensity pulsed electric fields on carotenoids profile of tomato juice made of moderate-intensity pulsed electric field-treated tomatoes.Food Chemistry.141(3):3131-3138.

[78] Vorobiev, E., &Lebovka, N. 2010.Enhanced extraction fromsolid foods and biosuspensions by pulsed electrical energy. Food Engineering Reviews. 2(2):95–108.

[79] Vorobiev, E., &Lebovka, N. 2012.New and promising application of pulsed electric field treatments in bio and food processing. In G. Ferrari (Ed.), Proceeding of the International Conference Bio & Food Electrotechnologies BFE 2012, book of full papers. Fisciano, Italy: ProdAlScarl, c/o University of Salerno.

[80] Vorobiev, E., and Lebovka, N.2010. Enhanced extraction fromsolid foods and biosuspensions by pulsed electrical energy. Food Engineering Reviews. 2(2):95–108.

[81] VVC. 2012.American Institute of Chemical Engineers Biotechnol. Prog.28: 1363–1375.

[82] Waite-Cusic, J.G., Diono, B.H., Yousef, A.E.2011.Screening for Listeria monocytogenes surrogate strains applicable to food processing by ultrahigh pressure and pulsed electric field.Journal of Food Prot.74(10):1655-1661.

[83] Xiufang Bi, Fengxia Liu, Lei Rao, Jing Li, Bingjing Liu, Xiaojun Liao, Jihong Wu. 2013. Effects of electric field strength and pulse rise time on physicochemical and sensory properties of apple juice by pulsed electric field. Innovative Food Science and Emerging Technologies 17:85–92.

[84] Zhang, Q., Barbosa-Canovas, G., & Swanson, B.1995.Engineering aspects of pulsed electric field pasteurization. Journal of Food Engineering.25(2):261–281.

[85] Daniela Bermúdez-Aguirre., Jaime, A., Yanez, C., Patrick Dunne., Neal, M., Davies., Gustavo, V., Barbosa-Canovas. 2010.Study of strawberry flavored milk under pulsed electric field processing.Food Research International 43: 2201–2207.