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EFFECT OF PULSED ELECTRIC FIELD PROCESSING ON FLAVOR AND COLOR OF LIQUID FOODS†

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ABSTRACT

This review shows that pulsed electric field (PEF) is a non-thermal preservation method that uses electric pulses to inactivate microorganisms and most especially high-intensity pulsed electric field (HIPEF) treatment involving application of pulses of high voltage (typically 20–80 kV/cm) to foods placed between two electrodes could achieve better flavor preservation and color retention in liquid foods than heat processing. HIPEF processing has been shown to deliver safe and chill-stable fruit juices with fresh-like sensory and nutritional properties. In addition, studies have shown that hurdle application of the different non-thermal treatments offers synergistic advantage over separate application of the individual treatment. PEF treatment in combination with other hurdles (such as microfiltration with large pore $\geq$1.2 μm, ultraviolet irradiation, high-intensity light pulses, etc.) has the potential to increase the preservation of liquid foods while retaining sensory attributes.

PRACTICAL APPLICATIONS

Non-thermal technology is one of the food processing and preservation methods that currently have been explored on a global scale. Pulsed electric fields (PEF) is a non-thermal preservation method that uses electric pulses to inactivate microorganisms and causes little or no change in food qualities. It is an efficient process that is employed to inactivate microorganisms and decrease the activity of enzymes without major undesirable effects on the organoleptic qualities of food products. PEF technology has not only proven to be effective in eliminating food microorganisms and inactivate enzymes, it also has a higher flavor and color retention properties than thermally processed foods.

INTRODUCTION

Thermal processing has been the traditional method of processing and preservation of food. During thermal processing, there is the inactivation of enzymes and microorganisms in food products. Unfortunately, this process also reduces the nutritional and flavor qualities and produces undesirable off-flavors (Nijssen 1991). Consumers these days are more concern about what goes into the production of their foods (Evans and Cox 2006). Thus, the increased demand for fresh-like foods has led to an emergent interest in alternative non-thermal processing technologies that will produce foods with high-quality flavor and color characteristics.

Non-thermal technology is one of the food processing and preservation methods that currently have been explored on a global scale. It is designed to eliminate the use of high temperatures during processing in order to avoid the adverse effect of heat on the flavor, color and nutritional values of foods (Barsotti *et al.* 2001). Non-thermal food preservation processes are considered to be more energy efficient and to promote better quality attributes than conventional thermal processes. Some of the non-thermal processes includes: irradiation, ultrasound, micro and ultrafiltration, high hydrostatic pressure (HHP), pulsed electric field (PEF), light pulse (LP) and ohmic heating.

Pulsed electric fields (PEF) is a non-thermal preservation method that uses electric pulses to inactivate microorganisms and causes little or no change in food qualities. It is an efficient process that is employed to inactivate microorganisms and decrease the activity of enzymes without major undesirable effects on the organoleptic qualities of food products (Ramos *et al.* 2006). PEF is basically used as an alternative method of pasteurizing liquid foods. This involves the application of electric pulses of high voltage to liquid or semi-solid foods placed in a treatment chamber between two electrodes to inhibit microorganisms' growth and thus to increase shelf life of food without any heat and chemical effects (Aguilar-Rosas *et al.* 2007). Pulsed electric technology has been reported by Zimmermann and Benz (1980) and Castro *et al.* (1993). When a pulse of higher voltage (typically 20–80 kV/cm) is used the pulsed electric technology is referred to as high-intensity pulsed electric field. High-intensity pulsed electric field (HIPEF) has been demonstrated to be an alternative pasteurization method. Although its efficiency in extending the shelf life of juice while maintaining the natural color and viscosity still remains a big challenge (Min *et al.* 2003).

Elez-Martinez *et al.* (2006) reported that HIPEF treatment was able to maintain the natural color of orange juice for 56 days of storage as compared to thermal processing. Flavor and color of food are some of the important quality parameters that may determine acceptability or rejection by consumers (Bermudez-Aguirre *et al.* 2010). For example, children often prefer beverages with attractive color and flavor to colorless foods (Bermudez-Aguirre *et al.* 2010). Gifford and Clydesdale (1986) showed that the degree of sweetness of cherry-flavored drinks was perceived differently by consumers because of the presence of red-colored pigments. Presently, there is little information in the literature dealing with the effects of PEF treatment on the volatile compounds and the possible color degradation in liquid foods

In this report, a brief review of the research studies on the effect of different pulsed electric field (PEF) processing methods on the flavor and color of liquid foods are outlined. In addition some direct comparison of PEF and high-temperature short time (HTST) pasteurization for some liquid foods is discussed.

APPLICATION OF PEF TECHNOLOGY

Due to its effective destruction of bio-membranes and inactivation of food enzymes, PEF technology is currently being used in different areas of science (Zimmermann 1986; Prassanna and Panda 1997). In addition to the inactivation of microorganisms, PEF minimal heat production during treatment has made it a better alternative process for pasteurization of liquid foods. PEF technology has been widely used for the processing of liquid foods and beverages, such as apple, orange, cranberry, tomato, peach juices, pea soups, milk, liquid egg and brine solutions (Qin *et al.* 1995a; Barbosa-Canovas *et al.* 1998; Bendicho *et al.* 2002; Góngora-Nieto *et al.* 2003; Min and Zhang 2003).

Recently, the effect of PEF technology on flavor, color and physicochemical changes have been reported in watermelon juice by Aguiló-Aguayo *et al.* (2010a), longan juice by Zhang *et al.* (2010) and grape juice by Marsellès-Fontanet *et al.* (2013). Some state universities (Washington and Ohio) have accomplished great success in PEF treatment of orange juice, apple juice, milk, eggs and green pea soups (Barbosa-Canovas *et al.* 2000). A system with a peak voltage of 20 kV and average power of 7 kW was used for the treatment of fruit mashes to facilitate subsequent unit operations (drying, extraction and freezing) to improve fruit and vegetable juice quality (Angersbach and Knorr 1998). Some important aspects of PEF technology are the generation of high electric field intensities, the design of chambers that impart uniform treatment to foods with minimum increase in temperature and the design of electrodes that minimize the effect of electrolysis (FDA 2015). Studies on energy requirements have concluded that PEF is an energy-efficient process compared to thermal pasteurization (Qin *et al.* 1995a). Other applications of PEF in food processing are listed in Table 1.

BASIC PRINCIPLES AND MECHANISM OF PULSED ELECTRIC FIELDS

Pulsed electric field technology involves the application of short pulses of high electric field with very short duration ranging from micro- to milliseconds. The intensity is generally in the order of 10–80 kV/cm. the process is usually carried out by pulsed electric currents delivered to a product placed between a set of electrodes. The processing time is achieved by multiplying the number of pulses with effective pulse duration. Food is capable of transferring electricity due to the presence of several ions. The presences of ions give the food a certain degree of electrical conductivity. Once an electrical field is applied, electrical current flows into the liquid food and is transferred throughout the liquid food (Zhang *et al.* 1995).

A pulsed electric field processing system is made up of a high-voltage power source, an energy storage capacitor bank, a charging current limiting resistor, a switch to discharge energy from the capacitor across the food and a treatment chamber. An oscilloscope is used to observe the pulse waveform. A high-voltage DC generator is used to convert voltage from the utility line (110 V) into high-voltage AC. This is subsequently rectified to a high-voltage DC. Energy from the power source is stored in the capacitor and is discharged through the treatment chamber (Fig. 1) to the food material. The maximum voltage across the capacitor is equal

TABLE 1. OTHER APPLICATIONS OF PULSED ELECTRIC FIELDS IN FOOD PROCESSING

Product	Treatment regime	Parameters improved compared with untreated samples	Chamber characteristics	References
Liquid egg	25.8 kV/cm; 37C; 100 pulses; 4 µs	Effective in processing egg product with shelf-life of 10 days	Continuous chamber, coaxial stainless steel electrodes; 0.6 cm gap, vol. of 28.6 cm^3	Martin-Belloso *et al*. (1997)
Pea soup	25–33 kV/cm; 53–55C; 10–30 pulses; 2 µs	Reduction of *E. coli* by log reduction of 6D	Ditto	Vega-Mercado *et al*. (1997)
Yoghurt	23–38 kV/cm; 63C; 20 pulses; 100 µs	Effectively reduced microorganisms by 2D	Static chamber; parallel stainless steel electrodes; 2 cm gap; vol. 157 cm^3	Dunn and Pearlman (1987)
Coconut	0.1–2.5 kV/cm; 60C; 0–200 pulses; 100 µs	More milk yield (20%)	Ditto	Ade-Omowaye *et al*. (2000)
Potato processing	0.4 kV/cm; 60C; 2 pulses; 575 µs	Freezing time reduced and the quality and rehydration of samples improved	Polypropylene cylindrical tube with inner diameter of 26 mm and an electrode at the bottom, 0.1 cm gap	Jalte *et al*. (2009)
Sugar beet	2.5 kV/cm; 20C, 20 pulses, 5 µF	Increased mass transfer rates and allows for reduced extraction temperature	Static chamber, parallel stainless steel electrodes, 3.8 cm gap	Eshtiaghi and Knorr (2002)
Soybean protein isolates	0–40 kV/cm; 500 pulses; 0–54 µs	Controlled PEF treatment was able to modify their structure and functions to produce desired products	Six co-field flow tubular chambers; 0.29 cm gap	Li *et al*. (2007)
Meat and fish treatment	2.5 kV/cm; 30C; 1–64 pulses, 100 µs	Effectively reduced microbial load by 6D	Continuous chamber, flat circular parallel stainless steel electrodes, 0.5 cm gap, vol. 5.7 mL	Barsotti *et al*. (2001)
Carrots	0.22–1.60 kV/cm; 18C, 5 pulses, 405 µs	Resulted in increased permeability index of carrots and mass transfer rate during osmotic dehydration	Static chamber, parallel stainless steel electrodes, 3 cm gap	Rastogi *et al*. (1999)
Apple slices	1.0 kV/cm; 24 or 45C; 20 pulses, 400 µs	Higher rehydration capacity was achieved in sample pre-dried with HIPEF	Ditto	Taiwo *et al*. (2002)

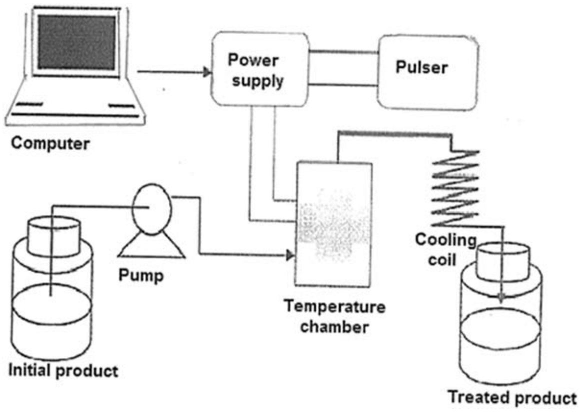

FIG. 1. SCHEMATIC DIAGRAM OF PEF OPERATION (ORTEGA-RIVAS *ET AL.* 1998)

to the voltage across the generator. The bank of capacitors is charged by a direct current power source obtained from amplified and rectified regular alternative current main source. An electrical switch is employed to discharge energy stored in the capacitor storage bank across the food in the treatment chamber.

Apart from the aforementioned components, some adjunct devices are also necessary. For example, in a continuous system, a pump is required to transport the food through the treatment chamber. Also, a chamber cooling system may be introduced to reduce the ohmic heating effect and control food temperature during treatment. In addition, high-voltage and high-current probes are used to measure the voltage and current delivered to the chamber (Ho *et al.* 1995; Barbosa-Canovas *et al.* 1999; Floury *et al.* 2005).

CURRENT LIMITATIONS OF PULSED ELECTRIC FIELDS

Some of the most important technical drawbacks or limitations of the PEF technology are:

(1) The availability of few commercial units which is limited to those produced by PurePulse Technologies, Inc. and Thomson-CSE. Many pulse-power suppliers such as DIL/Elea, GeneZapper NY and Montena Technology are capable of designing and constructing reliable pulsers. The complete PEF systems must be assembled independently.

(2) The presence of bubbles, which may lead to non-uniform treatment as well as operational and safety problems. When the applied electric field exceeds the dielectric strength of the gas bubbles, partial discharges take place inside the bubbles that can volatize the liquid and therefore increase the volume of the bubbles. The bubbles may become big enough to bridge the gap between the two electrodes and this may produce a spark. Therefore, air bubbles in the food must be removed, especially with batch system. Vacuum degassing or pressurizing the treatment media during processing, applying positive back pressure, may minimize the presence of gas.

(3) Pulsed electric field processing has limited applications. It is used on food products that can withstand high electric fields. The electric property of a food is closely related to its physical structure and chemical composition. Homogenous liquids with low electrical conductivity provide ideal conditions for continuous treatment with PEF.

(4) The maximum particle size in the liquid must be smaller than the gap of the treatment region in the chamber in order to maintain proper processing operation

(5) The number and diversity in equipment, limits the validity of conclusions that can be drawn on the effectiveness of a particular process conditions.

PULSED ELECTRIC FIELDS EQUIPMENT AND MANUFACTURERS

About 20 research groups are currently working in the area of pulsed electric field processing. However, commercial PEF is limited to two produced by PurePulse Technologies Inc. and Thomson-CSF, respectively. Moreover, there are four pilot scale systems available at present for liquid food preservation. These systems are available at Ohio State University, USA, Stork Food and Dairy Systems (The Netherlands), SIK (Sweden) and the Berlin University of Technology (Germany) (Kumar *et al.* 2015).

CURRENT STATUS OF PEF TECHNOLOGY AND COMMERCIAL APPLICATIONS

The method of high-intensity pulsed electric fields used to inactivate microorganisms has been the focus of research for the past four decades. During this period, the technology has proved to be most effective in the inactivation of vegetative bacteria, yeast and molds (Qin *et al.* 1996). In addition, system components have been designed to effectively inactivate different species. PEF technology has been most widely applied to apple juice, orange juice, milk, liquid egg and brine solutions (Qin *et al.* 1995b). The increase in the market segment of fruit juices has led manufacturers to seek ways to overcome the thermal effects of processing while increasing the shelf-life of juices (Hodgins *et al.* 2002).

Pulsed electric field technology has recently been used in alternative applications including drying enhancement, enzyme activity modification and preservation of solid and semi-solid food products. In 2006, the first commercial installation of PEF for fruit juice preservation was achieved in the USA (Toepfl 2012). In 2009, an industrial juice preservation line was installed in Europe. This was followed by equipment for pre-treatment of vegetables in 2010 (Toepfl 2012).

IMPACT OF PEF PROCESSING ON FLAVOR AND COLOR OF FRUIT JUICES

Tomato Juice

Tomato is one of the most widely consumed vegetables in the world, either fresh or industrially processed. Its flavor is considered an important criterion for its acceptability (Aguiló-Aguayo *et al.* 2008a). Over 400 aroma compounds have been identified in tomato, but only (*E*)-2-hexenal, (*Z*)-3-hexenal, hexenal, (*Z*)-3-hexen-1-ol, hexenol, 2-isobutylthiazole and 6-methyl-5-hepten-2-one, have been reported to be the key odorants in tomato (Ruiz *et al.* 2005; Aguiló-Aguayo *et al.* 2010b). The best method of extending the shelf life of juices is by thermal process. However, thermal treatment also reduces the sensory (flavor and color) and the nutritional qualities of thermally processed products (Yeom *et al.* 2000).

Recently, the use of non-thermal processing technology for food preservation has been employed. For instance, Aguiló-Aguayo *et al.* (2010a) reported that high-intensity pulsed electric fields (HIPEF) treatment is as effective as thermal process in the destruction of microorganisms in fruit juices. In another study, Vallverdú-Queralt *et al.* (2013) showed that HIPEF (35 kV/cm for 1,500 µs) reduced the loss of (*E*)-2-hexenal when compared to the heat treated (90C, 60 s) tomato juice. This trend has also been reported by Aguiló-Aguayo *et al.* (2010b) and Min and Zhang (2003) for (*E*)-2-hexenal in juices treated with HIPEF at 40 kV/cm for 57 µs. Similar result was obtained for (*E,E*)-2,4-decadienal, which is responsible for the fatty and rancid notes in tomato juice. The presence of this compound was found to increase with storage time. However, the concentration was more in juices treated by thermal treatment and stored between 42 and 56 days (Vallverdú-Queralt *et al.* 2013).

In addition, there was a better retention of (*Z*)-3-hexenol and hexanol in HIPEF-processed samples than the heat-treated ones. The content of hexanol decreased progressively as the storage duration progresses from the 28th day to the 56th day. On the other hand there was an associated increase in (*Z*)-3-hexenol. The increase in (*Z*)-3-hexenol was associated with the changes in hydroperioxide lyase activity (Vallverdú-Queralt *et al.* 2013). The carotenoid-related volatile compounds 6-methyl-5-hepten-2-one and geranyl acetone that gives tomato its characteristic aroma were also found to be higher in HIPEF-treated juice than thermally processed tomato juice (Aguiló-Aguayo *et al.* 2010b; Vallverdú-Queralt *et al.* 2013). Alkylthiazole (2-isobutylthiazole) was also found to be well retained in HIPEF-treated tomato juice. The higher retention of flavor compounds have been attributed to the use of low temperatures (below 35C) during HIPEF processing (Min and Zhang 2003). Concentrations of *trans*-2 hexenal and 2-isobutylthiazole of PEF processed tomato juice were higher than those of control tomato juice at 0 day (Min and Zhang 2003).

In terms of color, the concentration of 5-hydroxymethyl-2-furfural (HMF) has been reported to be higher in thermally processed tomato juice than those produced by PEF (Min and Zhang 2003). The HMF has been used as an indicator of non-enzymatic browning reaction in juice (Lee and Nagy 1988; Porretta 1991). Generally, PEF treatments have been reported as a better method for color preservation in juices more than thermal treatment (Elez-Martinez *et al.* 2006). For instance, the effect of HIPEF processing (35 kV/cm for 1,500 µs using bipolar 4 µs pulses at 100 Hz) on color parameters, viscosity and enzyme activities were evaluated during 77 days of storage at 4C on tomato juice by Aguiló-Aguayo *et al.* (2008b). The research results revealed that HIPEF-treated tomato juice showed higher values for lightness than the thermally processed and untreated juice throughout the storage time.

Apple Juice

Apple juice is one of the widely consumed fruit juices in the world. It is traditionally pasteurized thermally either by batch or continuous methods prior to packaging in containers. In recent times, high-temperature short time (HTST) pasteurization is a method commonly used for preserving apple juice. The temperature employed is as high as 76.6–87.7C for 25–30 s (Moyer and Aitken 1980). Pasteurization by heat is quiet effective against microbial and enzymes activities, but may be detrimental to the sensory and nutritive qualities of the final product. Qin *et al.* (1994) reported that less than 10% of the electric energy for heat treatment was used by PEF to cause a seven log reduction of *Saccharomyces cerevisiae* in apple juice. Ortega-Rivas *et al.* (1998) also reported the use of 16 exponential decay pulses of PEF at 50 kV/cm to obtain a five log reduction of indigenous aerobic bacteria in apple juice. The use of PEF has been satisfactory not only in microbial inactivation, but also in preserving the nutritive and sensory attributes close to that of the untreated juice.

Eight key odorants (i.e., acetic acid, hexanal, butylhexanoate, ethylacetate, ethylbutyrate, methylbutyrate, hexylacetate and 1-hexanal) have been identified as the most important contributors to apple juice flavor (Cunningham *et al.* 1986). Aguilar-Rosas *et al.* (2007) observed that there was significant loss of flavor volatiles in apple juice treated by PEF and heat when compared to the untreated sample. Although, most of the compounds where better retained by

TABLE 2. PERCENTAGE OF VOLATILES LOSSES, COMPARED WITH UNTREATED SAMPLE IN APPLE JUICE TREATED BY TWO METHODS

Compound	Loss percentage for PEF	Loss percentage for HTST
Acetic acid	39.792 ± 20.84	100
Hexanal	7.042 ± 9.32	62.348 ± 5.35
Butyl hexanoate	18.108 ± 7.72	36.273 ± 24.86
Ethyl acetate	77.458 ± 29.23	67.126 ± 39.33
Ethyl butyrate	60.190 ± 17.80	88.398 ± 12.46
Methyl butyrate	30.081 ± 31.37	51.200 ± 19.56
Hexyl acetate	8.408 ± 16.12	22.910 ± 21.99
1-hexanal	14.101 ± 7.65	69.307 ± 5.62

Note: Differences by a Student's *t*-test for independent samples ($P < 0.05$, $n = 3$) (Aguilar-Rosas *et al*. 2007).

PEF treatment than the thermally processed apple juice. For instance, hexanal, hexyl acetate and 1-hexanal were better retained in PEF treated apple juice than the HTST treated apple juice (Table 2). However, low molecular weight and low boiling compounds such as ethylbutyrate, ethylacetate produced significant losses of 60–77%, respectively, in PEF treated apple juice. Surprisingly, acetic acid was completely lost in HTST treated juice.

In terms of color, apple juice treated with PEF showed a tendency of becoming lighter as the electric pulse field increases. The value of *L* and *b* followed the same trend, while *a* value showed no significant change after PEF treatment (Bi *et al*. 2013). Earlier, Charles-Rodriguez *et al*. (2007) reported statistically significant color changes for both PEF and conventional HTST pasteurized apple juice. However, the natural color of apple juice was better conserved by the PEF treatment. Recently, Torkamani (2011) showed that PEF-treated apple juice had brighter color more than the HTST-treated juice. In addition, the author reported that the sensory and visual qualities of the PEF-treated apple juice were similar to that of the fresh apple juice. Finally, apple juice treated with ten 2.5 µs pulses at 36 kV/cm and had over 3 weeks of shelf-life extension at both 4 and 25C of storage (Qin *et al*. 1995b). The shelf-life of PEF-processed reconstituted apple juice at 35 kV/cm and 94 µs was more than 67 days at 4C (Evrendilek *et al*. 1999).

Orange Juice

Over 200 flavor compounds have been reported in orange (Maarse and Visscher 1989; Shaw 1991), with hydrocarbons contributing between 75 and 98%. There are several compounds that contribute to the orange juices' flavors such as acetaldehyde, citral, ethyl butyrate, limonene, linalool, octanal and α-pinene (Ortega-Rivas 2011). Among all these, limonene is the key flavor compound. Jia *et al*.'s (1999) study showed loss of 40% decanal, 9.9% octanal and 22.4% ethylbutyrate after heat treatment at 90C for 3 min (Table 3). However, application of PEF technology at 30 kV/cm electric field intensity showed no loss for decanal and octanal at 240 or 480 µs; however, ethylbutyrate was reduced by 5.1 and 9.7 at 240 or 480 µs, respectively. Besides that, Ayhan *et al*. (2002) investigated the flavor and color changes in PEF-treated orange juice at electric field intensity of 35 kV/cm and 59 µs. They revealed that d-limonene, α-pinene, myrecene and valencene contents of the juice were not affected after storage at 4 and 22C for 112 days; but, compounds like octanal, decanal, ethylbutyrate and linalool contents reduced significantly in 14 days at 4C and 2 days of 22C.

Several studies have shown that PEF-treated orange juice maintained lighter color than thermally processed juice (Knorr *et al*. 2004; Valero *et al*. 2007; Walkling-Ribeiro *et al*. 2009). For instance, Timmermans *et al*. (2011), subjected orange juice to three different treatments (i.e., mild heat pasteurization, high-pressure processing and PEF) and the authors reported no color changes in the PEF-treated juice and high-pressure processed juice after one month of storage. Similar results have also, been reported for other citrus juices like grape, lemon and tangerine treated with PEF (Cserhalmi *et al*. 2006). Qiu *et al*. (1998) employed PEF treatment (29.5 kV/cm, 60 µs, at 30C) on orange juice and aseptically bottled the juice. The bottled juice had a shelf stabled life of 7 months at 4C, whereas untreated juice could only store for 30 days. In addition, the PEF-treated juice retained greater amounts of vitamin C. Approximately 82% of vitamin A and *β*-carotene (98%) were retained after 40 days at 4C in opaque tubes with nitrogen headspace (Plaza *et al*. 2011). Lower browning index, higher whiteness (*L*) and higher hue angle (*Ø*) values than the heat-pasteurized juice were also obtained during storage at 4C (Yeom *et al*. 2000).

Strawberry Juice

Strawberries are known for their exquisite flavor and aroma and are used to prepare juice (Bood and Zabetakis 2002). Over 300 complex mixtures of flavor components have been

TABLE 3. THE EFFECTS OF 240, 480 µS PEF AND HEAT PROCESS AT 90C FOR 1 MIN ON THE VOLATILES IN FRESH SQUEEZED ORANGE JUICE (JIA *ET AL*. 1999)

Compound	Control	240 µs PEF	480 µs PEF	Heat process
Ethyl butyrate (loss %)	0	5.1	9.7	22.4
α-pinene (loss %)	0	0.8	5.8	21.9
Octanal (loss %)	0	0.0	0.0	9.9
Limonene (loss %)	0	2.8	7.5	20.5
Decanal (loss %)	0	0.0	0.0	41.7

identified in strawberry (Latrasse and Fruits 1991). Strawberry juice flavor is made up of; esters, furanones, lactones, alcohols, carbonyls and sulfur compound (Zabetakis and Holden 1997). Lipoxygenase (LOX) and β-glucosidase (β-GLUC) have been identified as some of the enzymes involved in the biosynthesis of some aroma components of strawberry (Leone *et al.* 2006). For example, "fresh green" odor of strawberry fruit is catalyzed by LOX. Aguiló-Aguayo *et al.* (2009) investigated the effect of HIPEF on the LOX and β-GLUC activities in strawberry juice as indicated by residual activity (RA) during storage. They showed that after 14 days of storage, the RA of LOX in the fresh strawberry juice reduced by 50% whereas HIPEF-treated juice retained it for 21 days. The decrease in hexanal concentration in HIPEF treated and heat-treated strawberry juices were associated with the inactivation of LOX just after juice processing (Aguiló-Aguayo *et al.* 2009). However, the LOX inactivation was attributed to β-GLUC activity. HIPEF treatment showed little effect on β-GLUC inactivation. For 1-butanol and linalool, there were no differences in the treated and un-treated juices at day 0. However, linalool concentration decreased steadily in heat-treated juice beyond day 14, while, the initial concentration in HIPEF-processed juice was maintained throughout storage. The high retention of linalool concentration in HIPEF-processed juice was associated with the high levels of β-GLUC activity observed during storage.

Dimethyl hydroxyl furanone (DMHF) is another key flavor compound in strawberry (Zabetakis and Holden 1997). It was found to increase from 0.75 mg/100 mL for untreated juice to 1.41 mg/100 mL after being treated with HIPEF. When compared to the thermally treated juice at 90C, DMHF content was significantly reduced to 0.56 mg/100 mL after 30 s of heating at 90C; a further decrease to 0.45 mg/100 mL was observed after 60 s. On the 14th day of storage, the DMHF decreased to 0.42 mg/100 mL. HIPEF-treated juices, however, did not change throughout the storage. Besides that, esters contribute a lot to fruity, green and other flavor notes to strawberry. In Aguiló-Aguayo *et al.*'s (2009) study, methyl butanoate and ethylbutanoate were found in higher concentrations in HIPEF-treated samples than in thermally processed juice. Also, 0.28 mg/100 mL of methyl butanoate and 1.20 mg/100 mL ethylbutanoate were obtained in HIPEF-treated juice while 0.16 mg/100 mL methyl butanoate and 1.02 mg/mL ethylbutanoate were found in thermally treated juice at 90C for 60 s. High retention of flavor compounds was also reported by Yeom *et al.* (2000) and Cserhalmi *et al.* (2006) in HIPEF-treated orange juices. Odriozola-Serrano *et al.* (2008) used bipolar squared-wave pulses through a continuous flow bench scale system (OSU-4F, Ohio State University Columbus, OH) to evaluate the effect of HIPEF treatment (35 kV/cm, 1,700 μs in bipolar 4 μs pulses at 100 Hz) on phenolic compounds of strawberry juices. They found that higher contents of ellagic and β-coumaric acid were retained in HIPEF-treated strawberry juice as compared to pasteurized juices. Application of PEF treatment (35 kV/cm, 1,700 μs) on strawberry juice was able to achieve a shelf-life of 63 days (Odriozola-Serrano *et al.* 2008). Strawberry juice submitted to bipolar pulses showed higher vitamin C, anthocyanin content and antioxidant capacity than that processed by applying monopolar mode (Odriozola-Serrano *et al.* 2009).

Watermelon Juice

Watermelon aroma is a complex mixture of about 75 compounds (Nijssen 1991). Yamija *et al.* (1985) identified alcohols and aldehydes as the major contributors to watermelon aroma. The most abundant compounds are hexanal (green) (*Z*)-2-nonenal, nonanal, (*Z*)-6-nonenal, 1-nonanol and (*Z*)-3-nonen-1-ol (Yamija *et al.* 1985; Lewinsohn *et al.* 2005). However, geranylacetane and 6-methyl-5-hepten-2-one were the potent odorants of watermelon (Yajima *et al.* 1985). The effect of HIPEF and thermal pasteurization on flavor retention in watermelon juice during cold storage has been studied by Aguiló-Aguayo *et al.* (2010a). The authors observed that hexanal concentration was significantly enhanced (25%) after treatment with PEF. The retention of (*E*)-2-nonenal was 17% for HIPEF-treated juice while a 6.8% reduction occurred in samples treated at 90C for 60 s. Nonanal also had similar pattern of retention, with up to 27% increase in concentration when treated with HIPEF and 17% increase when treated thermally at 90C for 30 s. However, (*Z*)-6-nonenal remained constant in all samples regardless of the treatment applied. The retention of 6-methyl-5-hepten-2-one was higher in thermally treated (90C for 30 s) watermelon juice (30%) than in PEF-processed juice which had 20% retention. It has been suggested that high temperature may induce thermal hydrolysis of fruit glycosides causing 6-methyl-5-hepten-2-one formation (Sucan and Russell 2002). In addition, geranylacetone was slightly retained (1.8%) after the application of heat (90C for 60 s) to the fresh sample. Whereas, increments of 35 and 24% were obtained from HIPEF-treated and heat-treated juices at 90C for 30 s, respectively. However, there was no change in 1-nonanol and (*Z*)-3-nonen-1-ol contents after treatment with HIPEF or heat treatments. Data from storage studies also showed that HIPEF-processed samples retained flavor compounds better than thermally processed samples for a period of 21 days.

Watermelon like tomato is rich in lycopene, which is responsible for its red color (Perkins-Veazie *et al.* 2001). It also contain small amount of phenols, vitamins C and antioxidant compounds (Gardner *et al.* 2000). Lycopene and vitamin C are generally susceptible to degradation by oxidation during thermal processes. Vitamin C content of watermelon was retained up to 99.9% when treated with HIPEF (35 kV/cm, 50 μs, 50 Hz) using mono- or bipolar 1 μs (Oms-Oliu *et al.* 2009). However, at higher electric field strength, frequency and pulse width, up to 50% of vitamin C was lost. Undesirable changes in color and flavor of watermelon juice are catalyzed by enzymes such as peroxide (POD), LOX, PME and polygalacturonase (PG). HIPEF treatment (35 kV/cm, 1,727 μs applying 4 μs pulses at 188 Hz in bipolar mode) proved effective in preserving the red color of watermelon juice when compared to thermally treated ones (Aguiló-Aguayo *et al.* 2010c). The authors also showed that HIPEF treatment induced a slight but significant increase in L^* and hue angle (h°), compared to untreated and thermally processed watermelon juices over time. Since the L^* value measures the color in the light-dark axis, it means that the HIPEF-processed juice produces a brighter color throughout the storage period. Similarly, increase in the values of h° signifies an increase in the intensity of the red chromaticity of the HIPEF-treated juices. Different authors have also observed higher redness in HIPEF-processed juices such as; tomato juice (Min and Zhang 2003), orange juice (Cortés *et al.* 2008) and strawberry juice (Oms-Oliu *et al.* 2009).

In conclusion, Mosqueda-Melqar *et al.* (2008) applied HIPEF (35 kV/cm, 1,682 μs, 193 Hz and 4 micro pulse duration) on watermelon juice and their results showed that the juice achieved a shelf stabled life of 91 days at 5C.

Longan Juice

Longan is a tropical fruit commercially grown in Southeast Asian countries like China, Malaysia, Vietnam and India (Li *et al.* 2009). It is consumed for its unique, delicate and desirable flavor. Longan also contains vitamin C, mineral and phenolic compounds with chemo-preventive properties (Chaikham and Apichartsrangkoon 2012; Lasekan and Abbas 2012). Zhang *et al.* (2010) investigated the effect of PEF processing on the physicochemical properties, flavor compounds and microorganisms in longan juice. They reported that thermal processing caused considerable loss of phenols up to 42%, while only 18% reduction was caused by PEF treatment. Phenols have earlier been reported as secondary metabolites in plants which play an important role in flavor and color development in fruit juices (Aguilar-Rosas *et al.* 2007). Ethanol, (*E*)-*β*-ocimene, *E,E*-2,6-dimethyl-1,3,5,7-octateraene,e,e-, allo-ocimene and 2-hydoxybenazoic acid, methyl ester were the key five volatile compounds identified in longan juice. They were all significantly higher for PEF-processed juice than heat-treated samples when compared to the untreated juice. Esters however were more retained in thermally treated longan juice than PEF-treated samples. Some esters were found to be more concentrated than in untreated juice. Recently, Zhang *et al.* (2010) reported that PEF-treated (bipolar pulse 3 μs wide, at an intensity of 32 kV/cm) longan juice retained greater amounts of vitamin C and flavor compounds than thermally treated juice. In addition the juice was able to store for 40 days at 4C.

Pomegranate Juice

Apart from those common fruit juices like apple juice and orange juice, pomegranate juice was treated with HIPEF (35 and 38 kV/cm, 281 μs at 55C with a flow rate of 100 L/h) (Guo *et al.* 2014). The authors observed that the HIPEF-treatment did not change the total phenolic content and anthocyanin content. Anthocyanins are responsible for the bright red color of pomegranate juice (Alighourchi and Barzegar 2009; Patras *et al.* 2010). In terms of color changes, pomegranate juice was found to have lower L^* values (darker) and higher a^* values (redder) and unchanged b^* value (yellowness) after HIPEF treatment. On the other hand, from the sensory evaluation, HIPEF-treated juice had higher overall flavor (6.3) and overall acceptability (6.4) compared to untreated juice which recorded an overall flavor of 6.0 and overall acceptability of 6.2, respectively. Jin *et al.* (2014) processed pomegranate juice using bench top (7.2 L/h flow rate, 35 kV/cm field strength and 72 μs total treatment time) and pilot scale (100 L/h flow rate, 35 kV/cm field strength and 281 μs total treatment time) continuous pulsed electric field processing system. The treated juice was packaged in PET bottles. Juice treated with PEF using the bench top, had a shelf-life of 21 days, while those treated on the pilot scale stored for 84 days

Grapefruit Juice

Different treatment temperatures, electric field intensity and treatment time were combined to study the effect of PEF on pectin methyl esterase (PME) inactivation in red grapefruit juice (Riener *et al.* 2009). The deactivation of PME was needed to prevent cloud loss. Combination of treatment temperature (23, 25 and 50C), electric field intensities (20, 30 and 40 kV/cm) and treatment times (25, 50, 75 and 100 μs) were applied on grapefruit juice on the PME inactivation. All three factors above were found to have significant effect on PME inactivation in grapefruit juice. Higher electric field intensity, higher treatment temperature and longer treatment time enhanced PME inactivation in the juice. Highest PME inactivation as much as 96.8% was obtained at temperature of 50C, for 100 μs time at 40 kV/cm pulses.

Carrot Juice

Besides fruit juices, PEF have been used to stabilize and preserve vegetable juices to prolong their shelf lives (Ramos *et al.* 2006). Color is the major characteristic in juices' selection among the consumers. The orange color in carrots is greater influenced by its carotenoids content (Quitão-Teixeira 2008). Besides carotenoid, phenolic acids and oxidative enzymes like polyphenol oxidase (PPO) and peroxidase (POD) that can cause non-enzymatic browning of juices by forming melanoidins that are dark substances (Talcott and Howard 1999) can also affect color. This will definitely affect the appearance and overall acceptability of juices. Therefore, Quitão-Teixeira (2008) studied the effect of optimizing different pulse polarities (mono or bipolar mode), pulse widths (from 1 to 7 μs) and pulse frequencies (50–250 μs) on color and POD inactivation of HIPEF-treated carrot juice by using response surface methodology (RSM). POD activity was measured by the percentage of residual POD activity (RA), $RA = 100 \times (A_t/A_o)$ where A_t and A_o were the POD activity of treated and untreated juices, respectively. Longer pulse width and stronger electric field strength were found to accelerate POD. Quitão-Teixeira (2008) concluded that bipolar pulses (27% RA) were more effective in inactivating POD activity compared to monopolar mode (47.8% RA of POD). Similar observation was reported by Elez-Martínez *et al.* (2007) on PME inactivation in orange juice. In terms of color, no significant differences were found between untreated and treated carrot juice (Quitão-Teixeira 2008).

INFLUENCE OF PULSE ELECTRIC FIELD PROCESSING ON FLAVOR COMPOUNDS OF MILK

Milk is a widely consumed beverage due to its nutritious, sensory and aroma characteristics. Chugh *et al.* (2014) recently studied the effect of PEF and HTST on color and volatile compounds in skim milk. The authors applied PEF at 28 or 30 kV/cm for 1122–2805 μs, while HTST treatments were applied at 75 or 95C for 20 and 45 s, respectively. The authors did not observed, noticeable color changes in the PEF-treated milk. Similarly, the skim milk volatiles were not significantly ($P > 0.05$) changed. However, HTST caused considerable changes in volatiles. For instance, concentrations of ketones, free fatty acids, hydrocarbons and sulfur compounds were significantly ($P < 0.05$) increased in HTST-treated milk. These findings indicate that PEF would be a useful technology for producing skim milk of high sensory quality (Chugh *et al.* 2014). In another study, Zhang *et al.* (2011) showed that PEF-treatment resulted in an increase in aldehydes formation in PEF milk. For example, milk treated with PEF at 30 kV/cm showed the highest content of pentanal, hexanal and nonanal, while heptanal and decanal contents were lower than the pasteurized milk. In addition, all the methyl ketones detected in PEF milk were lower than the pasteurized milk. There were no significant differences in the concentrations of acids, lactones and alcohols of PEF and pasteurized milk samples.

INFLUENCE OF PULSE ELECTRIC FIELD PROCESSING ON FLAVOR COMPOUNDS OF GREEN TEA BEVERAGE

Tea is one of the most widely consumed beverages in the world. There are three main types of commercial tea, namely; green tea (i.e., unfermented), Oolong (semi-fermented) and black tea (fully fermented) (Arts *et al.* 2001). A recent study of the effect of PEF on the flavor compounds of green tea infusions showed no significant ($P > 0.05$) changes on the volatiles at the application of PEF at 20 or 40 kV/cm (Zhao *et al.* 2009). When the PEF treatment was applied at 40 kV/cm for 200 μs, the flavor compounds decreased remarkably (Zhao *et al.* 2009). For instance, 2-pentanol was significantly reduced (30%) and decanal remained constant. In addition, *cis*-3-hexenol and β-ionone the two key odorants of green tea were reduced by 13.8 and 2.8%, respectively, after PEF treatment at 40 kV/cm. Interestingly, indole which elicit animal-like note was decreased by 13.5% in PEF tea. The importance of this is that indole has been confirmed as one of the volatiles that exhibited the highest flavor dilution factor (FD) in green tea (Kumazawa and Mauda 1999). Therefore, its decrease was beneficial for green tea.

PULSED ELECTRIC FIELD TREATMENT IN COMBINATION WITH OTHER NON-THERMAL HURDLES

Studies have shown that PEF treatment in combination with other non-thermal hurdles such as UV, microfiltration, high-intensity light pulses (HILP), high-pressure and others have the potential of increasing the preservation of liquid foods while retaining their sensory attributes (Noci *et al.* 2008; Caminiti *et al.* 2011; Chugh *et al.* 2014). For example, the influence of UV and PEF on microbial inactivation and selected quality attributes (color, pH and non-enzymatic browning index) of apple juice was studied by Noci *et al.* (2008). The authors showed that the combination of UV and PEF produced a greater microbial reduction than PEF and the juice color and flavor were less affected.

In another study, Caminiti *et al.* (2011) processed a blend of apple and cranberry juice using a combination of UV (5.3 J/cm^2) or high-intensity light pulses (HILP) (3.3 J/cm^2) in combination with PEF (34 kV/cm, 18 Hz, 93 μs) or manothermosonication (MTS) (5 bar, 43C, 750 W, 20 kHz). They observed no significant changes in terms of color and total phenolic content between untreated sample and treated

HILP+PEF and UV+PEF sample. However, juices treated with combination HILP+MTS and UV+MTS treatment showed visible color changes indicating that application of MTS darkened the juices. According to Caminiti *et al.* (2011), non-enzymatic browning index (NEBI) is a measurement of color changes, off-flavors and nutrient losses. Higher NEBI indicates development of browning compounds from degradation processes. All combinations of non-thermal technologies showed no significant changes in the NEBI in apple and cranberry blend juice. Similarly, at 35 kV/cm for 1,700 μs bipolar mode treatment, no significant browning phenomenon was found in the strawberry juice. In terms of flavor, the apple and cranberry blend juice with combination treatment of HILP+PEF was the most desirable among the sensory panelists (5.8) followed by UV+PEF and pasteurized juice (5.6) and lastly UV+MTS (4.7) and HILP+MTS (4.6). Chugh *et al.* (2014) reported similar observation with skim milk when they combined PEF with microfiltration (MF) using pore sizes $\geq$ 1.2 μm.

POSSIBLE NEGATIVE CHANGES AFTER APPLYING PEF

In the last few years problem due to electrochemical reactions at the electrode/medium interfaces have been discussed (Morren *et al.* 2003; Roodenburg *et al.* 2003). The current challenges faced by the electro-engineers are (1) modifying pulse generator systems to reduce the amount of electrochemical reactions and (2) alternatively replacing commonly used stainless steel electrodes with other materials. Application of carbon electrodes may be one solution to overcome this problem (Toepfl *et al.* 2004) and application of shorter pulses or switching systems without leak current have been discussed (Mastwijk 2004) to avoid electrochemical reactions. Apart from a reduction in electrode life time, the release of particles and heavy metals from the electrodes may cause toxicity problems. Reyns *et al.* (2004) reported the generation of bactericidal and mutagenic compounds by a PEF treatment, even if they operated with 300 pulses at a pulse width of 2 s and 26.7 kV/cm.

CONCLUSION AND FUTURE TRENDS

Pulsed electric field (PEF) is a non-thermal food preservation technique that is been given more attention in the recent years. PEF technology has not only proven to be effective in eliminating food microorganisms and inactivate enzymes, it also has a higher flavor and color retention properties than thermally processed foods. PEF is applied mostly in liquid foods such as fruit juices, milk, milk product and other liquid foods. PEF uses very short pulses (micro to milliseconds) with range of 10–80 kV/cm electric field strength. PEF treatment in combination with other hurdles (such as UV, high-pressure processing and larger pore size microfiltration) has the potential to increase the preservation of liquid foods while retaining sensory attributes. Although the knowledge presented in this article is insufficient by itself for ensuring the production of liquid foods with higher-quality flavor, further research is required to examine the mechanism of flavor loss and color degradation during PEF.

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CONFLICT OF INTEREST

The authors declare that they do not have conflict of interest.

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