Advance Research in Agriculture and Veterinary Science
ISSN 2348-5353
Adv. Res. Agri. Vet. Sci. Vol. 1, No. 2, 2014: 54-61
Academy for Environment and Life Sciences, India
Available at www.aravs.org

REVIEW ARTICLE

A REVIEW OF APPLICATION OF PULSED ELECTRIC FIELD IN THE PRODUCTION OF LIQUID/SEMI-LIQUID FOOD MATERIALS

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KEYWORDS
non-thermal methods, pulsed electric field, current intensity, microbial and enzyme destruction.

Article History:
Received on
19 May 2014

Accepted on
1 May 2014

Published on
10 June 2014

ABSTRACT: Thermal methods are being used in the production of food materials generally.Aplication of heat to foods causes deterioration of food components so food manufacturers have begun searching for new methods that cause less damaging food components.Non-thermal methods are being used in the production of foods such as ultrasound, gamma radiation, high hydrostatic pressure and pulsed electric field treatment lately. Pulsed electric field treatment is a new method as non-thermal methods that being used in processing of liquid samples without any significant effects on physicochemical properties of food samples. The pulsed electric field method consists of pulse generator, switches, treatment chamber, cooling section and monitoring system. Microbial inactivation and enzyme destruction of fruit/vegetable juices, milk and liquid egg samples can be assured by pulsed electric filed treatment successfully. Increase in current intensity, pulse width causes higher microbial inactivation and enzyme destruction.

INTRODUCTION

The preservation of food materials are mainly based on the killing microorganism and inactivation of enzymes during the production. In many cases, heating process is being used for prevention microorganisms and inactivation of enzymes. Heat treatment causes pigment degradation and changes in chemical components of food materials due to thermal treatment. Non-thermal process are being used for prevention of microbial growth and enzyme inactivation such as ultrasound technology, pulsed electric field, high hydrostatic pressure and gamma radiation and etc. Common effects of non-thermal application is to eliminate the use of heat treatment during the process due to avoiding the adverse effects of heat on chemical components of materials. Heating process can causes lots of changes in foods such as flavor, color and texture that affect the final quality of the foods.

Non-thermal processing of food materials are being used such as ultrasound, gamma radiation, high hydrostatic pressure and pulsed electric field treatments succesfully and such treatments are least harmfull to the nutrient components of foods compared to the thermal process. Pigments are present in foods that rsponsible for color but also have an important antioxidant effect on health such as anthocyanin pigments. It is reported that pigment concentration decreases at low rates after pulse processing while other processes cause more pigment degradations (Mohammed and Ayman, 2012). Among the non thermal methods pulsed electric field is an alternative method which is being used in the production of liquid/semiliquid food materials. This techniques is thought to be an alternative thecnique to the pasteurization (thermal) process, enhancing drying procedure of food materials, modification of enzyme activity, increasing liquid extraction of plant cells (Barsotti *et al.*, 1999).

This method is superior to the thermal treatments such as pasteurization or sterilization due to application of pulsed electric treatment that avoids detrimental changes in quality attributes and physicocemical properties of food samples (Mohammed and Ayman, 2012). Among the 5-80 kV/cm generated electric fields applied within short of high voltage pulses between two electrodes that

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causes microbial inactivation for food safety which leads to the penneabilization of microbial membranes. Researchers reported that exposing to high current field pulses, cell membranes improves pores either by enlargement of existing pores or producing new pores (Mohammed and Ayman, 2012). Sensory properties of fruit juices are being conserved and shelf life of food samples is extended (Min *et al.*, 2003). Some of pulsed electric field treated food samples are milk, tomato juices (Min *et al.*, 2003), apple juice (Evrendilek *et al.*, 2000), pear, strawberry juice (Mosgueda-Melgar *et al.*, 2012), peach (Altunta *et al.*, 2011) apricot (Evrendilek *et al.*, 2013), longan juice (Zhang *et al.*, 2010), carrot juice (Vega-Mercado *et al.*, 1996), grape juice (Huang *et al.*, 2014), cranberry juice (Jin and Zhang, 1999), citrus juices (Cserhalmi *et al.*, 2006). Non-thermal treatment of foods are being investigated as an alternative preservation technology to the thermal treatment that inactivates the microorganisms without significant changes in sensory attributes of food materials.

COMPONENTS OF PULSED ELECTRIC FIELDS

The technic of pulsed electric field consists of high current generator, treatment unit, fluid handling system and controlling equipments. The generator of high current supplies electrical pulses of voltages, shapes and application time by using pulse forming systems. The system consists of power supplier, charging resistor, capacitor, switches, inductors and resistors. Power generator converts high voltage (50-60 Hz frequency) alternating current (AC) power to the high direct current power (DC). The energy produced by the generator (5-80 kV DC) is stored at capacitors and used to generate electric fields. The alternative current (AC) is raised in voltage through a voltage transformer and than rectified. The direct current (DC) high voltage supply then charges at capacitors through a series of resistors. The pulse generator sends a train of current voltage and the circuit serves to convert that to high voltage pulses by using rectifier. The system produces short duration pulses (micro or milisecond) within electric field strength up to 80 kV/cm.Systems have a switch that used to discharge high energy through the food materials in treatment chamber. Switching systems are the elements that connect storage device (capacitors) and energy load at treatment chamber.The switch is used to determine howmuch necessary pulse current and application time. It acts a bridge high energy suppliers and treatment unit (Zhang *et al.*, 2010; Pizzichemi, 2007; Mohammed and Ayman, 2012; Vallverdu-Queralt *et al.*, 2013).
Liquid or semi-liquid food materials are placed in treatment unit in which electrodes are connected together with non-conductive material to avoid electrical flow from one to another. The high electrical current is delivered to the electrodes which electrodes conduct the high electrical current to the food materials. The high electrical currents are supplied to the food materials by the generator at different current intensity and process time. The produced high current from the generator can be applied square wave, bipolar, exponentiallly and etc. It is reported that many different waveforms are being applied in pulsed electric field treatment.Pulse shapes are commonly being used either exponentially or square wave. Square wave producing systems require a switch with turn off capability or pulse forming network (Toepfl *et al.*, 2007).

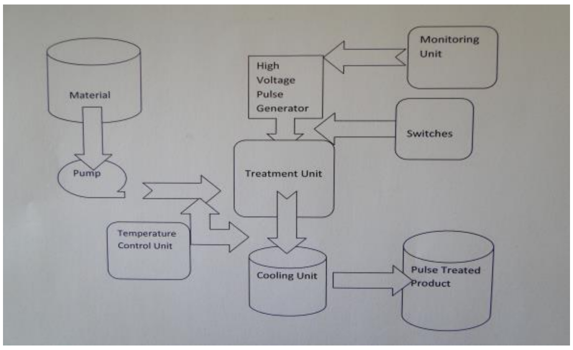

Figure 1: Components of pulsed electric field treatment and flow chart of process.

The pulsed electric fields generated by generator are used in treatment unit or chamber. Treatment units are designed to operate either batch or continuous manner. Semi-liquid or liquid food materials are pumped to the treatment chamber at a certain flow rate (5-100 ml/min) within coaxial or paralel plate types in chamber (Pizzichemi, 2007). The flow of paralel type is being used for batch system while coaxial flow systems are being used for continuous types. In both system liquid or semi-liquid materials are pumped through at a certain flow rate and the pulsed electric fields are applied at any pulse frequency. It is reported that treatment chamber consists of paralel plate electrodes and space insulater. The electrodes are seperated from the fluid materials by ion conductive membranes that made of sulfonated polystyrene and acrylic acid copolymers and electrolyte is being used to simplify electrical conduction between the electrodes and membranes (Dunn and Pearlman, 1987).

Cooling section is another part of pulsed electric field application. Fluid samples are passes through a cooling coil section that connected to the treatment chamber. Cooling section is generally submerged in an ice-water bath for cooling purposes.

SOME APPLICATIONS OF PULSED ELECTRIC FIELD IN FOOD PRODUCTIONS

The pulsed electric field application is suitable for fruit juices, milk, beverages, soups, liquid eggs in order to prevent microbial growth and enzyme destruction process. The pulsed electric field is not suitable for solid containing food materials that are not pumpable. This method can be applied to enhance liquid phase of cellular system such as extracting the oils from the seeds, sugar from sugar beet or cane from plant cells and reducing the solid volume of wastewater.

According the results of high-intensity pulsed electric fields on carotenoids profile of tomato juice showed that carotenoid contents of juices increased (10-20 %) through the storage time (56 days at refrigerated condition) than compared to heat treated and untreated tomato juices. The operation conditions of pulsed electric field were 60 ml/min as flow rate, 35 kV/cm current intensity, for 1.5 milisecond by bipolar squared-wave pulses at 100 Hz frequency (Vallverdu-Queralt *et al.*, 2013).

It is reported that longan juices was treated by pulsed electric field and physicochemical properties, flavor compunds and microorganisms of longan juices were studied at an intensity of 32 kV/cm with bipolar pulse (3 µs wide) at a flow rate of 83 ml/min.In order to compare the pulsed electric field treatment with heat treatment, longan juices were heated at 100 °C for 1 min and cooled in an ice bath. Physicochemical properties of juices were as changes in color (L, a, b, b/a, ΔE), pH, titratable acidity (%), total soluble solids (brix), non-enzymatic browning indices, hydroxymethyfurfurol (mg/L), total phenol content (g/L) and vitamin C (g/L) (Table 1).The results pulsed electric field treated juices showed that there were no noticeable difference with untreated juice samples due to color parameters of L, a,b, b/a, total color differences (ΔE), pH, non-enzymatic browning indices, hydroxymethyfurfurol, vitamin C and total phenol contents of longan juices although well-visible differences were found between untreated juice samples and heat treated samples due to pyhsicochemical properties (Zhang *et al.*, 2010).

Table 1: Physicochemical properties of longan juices (Zhang *et al.*, 2010)

Treatment	Parameters											
	L	a	b	b/a	ΔE	pH	Titratable acidity (%)	Brix	Non-enzymatic browning indices	Hydroxymethyl furfurol (mg/l)	Phenol Content (g/l)	Vitamin C (g/l)
Untreated	19.56	3.52	6.14	1.74	-	6.82	0.45	18.7	0.322	0.08	1.13	1.42
Pulsed electric treatment	19.63	3.50	6.41	1.83	0.28	6.81	0.68	18.6	0.3278	0.08	0.93	1.37
Heat treated	16.30	2.98	5.72	1.92	3.31	6.80	0.71	18.7	0.5434	0.41	0.65	1.12

Due to results of pulsed electric fields longan juices had higher content of flavor compunds compared to thermally treated juices samples.Pulsed electric field treatment proved that more efficient in yeast inactivation and moderate inactivation in E. coli although thermal treatment most effective for E.Coli and yeast inactivation (Zhang *et al.*, 2010).

Phenol content and flavor compounds are present in many fruit and vegetables that heat sensitive compounds.Phenol contents are responsible for color and flavor development in many fruits (Aguilar-Rosas *et al.*, 2007) and also this compounds are being used as an indicators of physiological state and potential damages in fruit juice quality (Blanco *et al.*, 2001). Heat treatment causes considerable loss of phenol content in longan and apple juice (Zhang *et al.*, 2010; Aguilar-Rosas *et al.*, 2007) Pulsed electrical field treated juices have a higher content of phenol compared to the thermally treated fruit juices.Flavor compounds are heat sensitive materials which are affected by heating process but pulsed electric field treated fruit juices have significantly higher contents of flavor compounds compared to the thermally treated juice samples except for esters that are related with high temperature and thermal process (Shaw, 1986; Yeom *et al.*, 2000; Braddock, 1999; Zhang *et al.*, 2010).

Non-enzymatic browning indices are important factors for the quality of fruit juice samples.Pulsed electric field treated fruit juices had lower browning indices than termally treated juice samples such as longan juice (Zhang *et al.*, 2010), peach (Altunta *et al.*, 2011) apricot nectar (*Evrendilek et al.*, 2013), orange juice (Yeom *et al.*, 2000) and citrus (Cserhalmi *et al.*, 2006) samples. It is reported that the effect of pulsed electric field treatment on non-enzymatic browning indices is not significantly different but thermal process indicates significant difference compared with untreated juice samples.

In a similar study of processing of peach nectar with pulsed electric fields with respect to physical,chemical and microbial inactivation, treatment conditions of pulsed electric fields were current intensity 17, 20, 23, 27 and 30 kV/cm with square wave bipolar pulse, at a flow rate of 50 ml/min, 3 µs pulse duration and 131 µs process time. Measurement of physical and chemical properties were as pH, titration acidity (%), conductivity, color (L,a,b), non-enzymatic browning indices, metal ion concentration, ascorbic acid content and beta carotene concentration. On the other hand, the microorganisms were as E.coli, S. aureus, L. monocytogenes, E. carotowora, P. syringia and P. expansum in pulsed electric field treatment. It was reported that there was no difference in pH, brix, titration acidity (%), conductivity, color parameters of L,a,b, non-enzymatic browning indice, metal ion concentration, ascorbic acid content and beta carotene contents compared to the untreated peach samples. Increased pulse treatment time caused an increase on inactivation of microorganism and fungi inactivation was higher than bacterial inactivation by pulse treatment. Increasing current intensity caused higher microbial inactivation n pulsed treatment for peach nectar. According to results of physical, chemical properties and microbial inactivation pulsed electric field was successfully used up to 30 kV/cm current intensity without significant adverse effect on the important quality parameters of peach nectar (Altunta *et al.*, 2011).

In a study of apricot processing by pulsed electric field, physical, chemical properties and microbial inactivation of some microorganisms were studied. Pulsed electric field conditions were as at a current intensity of 17, 20, 23, 27 and 30 kV/cm with square wave bipolar pulse, at a flow rate of 50 ml/min, 3 µs pulse duration and 66-210 µs process time. In this study, test microorganisms were E.coli, S. aureus, L. monocytogenes, E. carotovora, P. syringia and P. expansum. It was reported that there was no difference in pH, brix, titration acidity (%), conductivity, color parameters of L,a,b, non-enzymatic browning indice, metal ion concentration, ascorbic acid content (g/l) and total beta carotene contents (mg/l) compared to the untreated peach samples. According to the results of pulsed electric treatment, increase in current intensity did not affect chemical, physical properties and mineral contents of apricot nectar significantly. Increase in electric current intensity caused an increase on inactivation of microorganism (L. monocytogenes, S. aureus, E. carotovora, P. syringia, P. expansum) and increasing current intensity caused higher microbial inactivation in pulsed treatment for apricot nectar (Evrendilek *et al.*, 2013).

In the study of microbiological shelf life and sensory evaluation of fruit juices treated by high-intensity pulsed electric fields within antimicrobial substances pulse treatment conditions were as current intensity of 35 kV/cm, 1000-1700 µs of process time, at a flow rate of 90-110 ml/min, 4 µs for pulse width at 100-235 Hz pulse frequency. The juices of apple, tomato, pear, strawberry and orange were treated by pulsed electrical field with citric acid and cinamon bark oil as antimicrobials additive. For thermal process juices samples were heated at 90 ºC for 1 min. and stored at 5 ºC within polyprophylene caps.Shelf-life of fruit juices were estimated due to mesophlic, mold, yeast and psychrophlic populations for untreated, heat treated, high intensity pulse treated, and high intensity pulse treated with antimicrobials fruit samples. Shelf life of fruit juices treated by high intensity pulsed electric field with antimicrobials were higher (> 91 days) than untreated and pulsed electric field (< 41 days) treated juices samples due to microbiologic safety. It is accepted that electroporation produced by pulsed electric treatment allows the antimicrobial agents to enter the cells so lethality of microorganisms increases.Sensory evaluations of fruit juices for untreated, thermally treated, pulsed electric field treated, pulsed elctric field treated within antimicrobial subtances were done in a hedonic scale from 0 (dislike extremely) to 10 (like extremely) according to sensory attributes as color, aroma, taste,sourness and overall acceptability. The results showed that the use of citric acid and cinnamon bark oil as an antimicrobial additives increased the microbial shelf life of tomato, pear, strawberry,orange and apple juices. Although the microbial shelf life of juices that treated by pulsed electric field with antimicrobial substances were higher, significant changes on some sensory properties were detected for fruit juices of pulsed electric field treated within antimicrobial substances (Mosgueda-Melgar *et al.*, 2008).

Some researchs show that microorganisms can be inactivated succesfully by the treatments of pulsed electric fields and inactivation of microorganisms strongly depends on the conditions of pulsed electric field treatment and the type of microorganisms. P. expansum and B. cinerea are inactivated by pulsed electric field treatment in sour cherry juice, peach and apricot juices (Evrendilek *et al.*, 2008, Evrendilek *et al.*, 2009). Melon and water melon juice that inoculated with S. enteridis, E. coli and L. monocytogenes shows that the population of these microorganisms decreases due to the pulsed electric field treatment. It is reported that L. monocytogenes are more resistant to the pulse treatment compare to others in both melon and water melon juices at the same treatment condiditons (Mosgueda-Melgar *et al.*, 2007).

Pulsed electric field treatment at moderate or high intensity current is a non-thermal treatment which is proving to kill microorganisms, inactivate enzymes and increase the shelf-life of liquid/semiliquid food materials without significant loss of sensory attributes. Although the pulsed electric field treatment is non-thermal food treatment method to inactivate microorganisms for fruit juices, milks and etc, electric field applications at different current intensity are still at laboratory or pilot scale.Further studies should be carried out from laboratory scale to the industrial applications.But it is still there are some issues that need to be clarified such as temperature monitoring, the applied energy requirement per unit volume of food samples and breakdown of food materials inside in treatment chamber.

The viscosity of fruit juices is important physical factor which affect consumer demands. This physical factor is affected by thermal application that related with pectin methyl esterase (PME) and polygalacturonase (PG) enzymes present in food samples. In order to decrease viscosity of juices samples, heating process is being used in general.Due to application of heating process, the depolymerization of pectin occurs during fruit juice processing (Rodrigo *et al.*, 2007). The conditions of high intensity pulsed electric field at inactivation of pectolytic enzymes of tomato and strawberry juices were as current intensity of 35 kV/cm, 50-250 Hz pulse frequency, 1-7 pulse width and 1 milisecond treatment time.In order to prevent the enzymes in fruit juices, pulsed electric field treatment is being used at different inactivation level successfully. Inactivation level of pectin methyl esterase was among 55 % and 90 % (Rodrigo *et al.*, 2003; Elez-Martinez *et al.*, 2007; Yeom *et al.*, 2000; Aguilo-Aguayo *et al.*, 2008) for fruit systems and inactivation level of polygalacturonase was among 12 % and 26.7 % (Aguilo-Aguayo *et al.*, 2008; Aguilo-Aguayo *et al.*, 2009a) for tomato and strawberry juices. Lpoxygenase and hydroperoxide inactivation of tomato juice by high intensity pulsed electric fields, the treatment conditions were same as strawberry juice and the results show that residual lipoxygenase and hydroperoxide liyase activites decreased (Aguilo-Aguayo *et al.*, 2009b). It is reported that to reduce enzyme activity adequately, the variables of high intensity pulsed electric field are important factors such as pulse frequency, pulse width, polarity and current intensity (Aguilo-Aguayo *et al.*, 2009a). Another important factor is required energy input to achieve enzyme destruction at laboratory or pilot scale.So required energy input supplied to the samples of tomato and strawberry juices was computed through an equation (Martin *et al.*, 1994):

$Q=[V_o.I.t]/v$

where V_o: peak voltage, I: current intensity, t: treatment time and v: volume of treatment chamber and required energy for microbial inactivation of grape juice was computed an equation as below (Huang *et al.*, 2014) at laboratory scale;

$Q_{spec}=[\ _{av}.E^2.\ .f.V]/m$

where $_{av}$: average electrical conductivity of media, E: electric field strength, : pulse width, f: pulse frequency, V: treatment volume and m: mass flow rate

The results of studies show that pulsed electric field at moderate or high intensity current have an significant effect on decreasing pectolytic enzyme activity. Pulsed electric field treatment can be applied successfully for inactivating enzymes that present in foods without significant adverse effects on quality properties of fruit juices as an alternative method to the thermal treatment (Aguilo-Aguayo *et al.*, 2009b). If applied electric field transcend the dielectric strenght of bubbles, partial discharges occur inside the bubbles that means evaporation takes places. Due to this bubbles may become so big, breakdown takes place at the insulation level among the polarities of electric field source (Bastaki *et al.*, 2012). Due to this it is important to control the applied electric field level and dielectric strenght of gas bubbles in food samples. Due to breakdown of food materials, the design of treatment chamber is most important factor. The other factors are homogenity of electrical field, electrical resistance, reduction and generation of field areas in design of treatment chamber in pulsed electric field applications (Barbosa-Canovas and Sepulveda, 2005).

The monitoring the temperature of liquid food systems is another important parameters in pulsed electric field treatment. Changes in physicochemical properties of food samples are temperature depentent events.So treatment temperature should be controlled at nonthermal range, many physicochemical changes can be prevented.Some researchers monitored the inlet and outlet temperatures of pulsed electric filed chambers. Evrendilek and Zhang, (2005) monitored the temperatures by using K-type dual-channel temperatures for pasteurization of E. coli by pulsed electric fields. The method used in pulsed field treatment can not measure the actual temperature of foods in treatment chamber due to inlet and outlet temperature monitoring process. Qin used the fibre-optic sensors that installed inside treatment chamber to measure the liquid temperatures for inactivation of microorganisms at different waveforms. In order to prevent temperature raising, electrically non-cunductive cooling systems around the treatment chamber may be used.It is reported that many studies of pulsed electrical filed treatment are occured at room temperature or slightly lower or higher than this temperature (Evrendilek *et al.*, 2013; Zhang *et al.*, 2010; Toepfl *et al.*, 2007; Huang *et al.*, 2014; Aguilo-Aguayo *et al.*, 2009a).

CONCLUSION

Pulsed electric field treatment at moderate or high current intensity can be applied successfully for killing microorganisms and enzyme inactivation without significant effects on physicochemical properties for fruit juices samples instead of tradational thermal treatment.Moderate or high intensity pulsed electric field affect the enzyme activities and viscosity at different current intensity, pulse width and frequency. Increase in current intensity, pulse width causes higher microbial inactivation and enzyme destruction.So microbial and enzyme safety of juices/liquid food samples can be assured by pulsed electric filed treatment. Using some of antimicrobial substances prolongs the shelf life of foods within pulsed electric fields. Organoleptic properties of food samples shouldn't be overlooked so further studies should be carried out based on the sensory attributes of fruit juices or liquid food materials. Further studies are needed to develop an industrial model and also energy cost of commercial application of pulsed electric field treatment.

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