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Pulsed Electric Field Technology for Preservation of Liquid Foods

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***Abstract* – Pulsed electric field technology is an emerging non-thermal technology with wide applications. This paper aims to provide a brief overview of PEF technology and its application for preservation of liquid foods. The basic mechanism of microbial inactivation by PEF, some important engineering aspects of the PEF system and its components as well as factors affecting the PEF treatment are described briefly. The advantages and limitations of the technology are also provided. An extensive review of some literatures on PEF pasteurization liquid foods are also included.**

***Keywords* – Pulsed Electric Field, Preservation, Pasteurization, Electroporation, Electric Field Strength.**

I. Introduction

Prevention of food spoilage and food-borne pathogens is a matter of prime importance to ensure food safety. For a long time liquid foods have been preserved by the use of preservatives and various thermal methods such as pasteurization, and sterilization. Excess use of preservatives is hazardous to health and leads to serious health consequences. Researchers have reported that artificial preservatives such as nitrates, benzoates, sulfites, sorbates, parabens, formaldehyde, BHT, BHA and several others can cause serious health hazards such as hypersensitivity, allergy, asthma, hyperactivity, neurological damage and cancer (Anand and Sati, 2013). Thermal processing can bring some unintentional undesired consequences, such as losses of certain nutrients, formation of toxic compounds (acrylamide, furan or acrolein), or of compounds with negative effects on flavour perception, texture or colour (Boekel *et al*., 2010). The heat-sensitive volatile compounds are evaporated during thermal processing and hence the flavor gets reduced. Heat-sensitive vitamins and bioactive compounds in food are also lost by heat. This has created low customer acceptance of heat-processed foods.

Consumers prefer minimally processed but microbiologically safe and nutritious food over the thermally processed ones. Non-thermal methods play an important role in this situation as they preserve the natural color, flavor, and nutrient compounds in foods. In the last two decades, several researchers have carried out experiments on the non-thermal processing of food materials and have reported that non-thermal methods preserve the quality of foods. Such methods include high-pressure processing, pulsed electric field, pulsed light, ultrasound, etc.

Pulsed electric field (PEF) technology applies a high-intensity pulsed electric field to foods for a very short time (less than a second). It causes irreversible permeabilization of cell membranes of biological cells and hence leads to pore formation and further leakage of cell constituents which ultimately leads to cell death. In PEF treatment, energy loss due to heating of food is minimal as compared to thermal pasteurization. Pulsed electric field technology has undergone tremendous advancements over the past years. Several companies are manufacturing PEF systems across the world now. The Pulsed Electric Field is applied to pasteurize fruit juices and those juices were available in the markets.

Pasteurization was considered as a thermal treatment by the Food and Drug Administration before 2002 in USA.

In September 2004, the USDA National Advisory Committee on Microbiological Criteria for Foods (NACMCF) redefined the term “pasteurization” as “any process, treatment, or combination thereof, that is applied to food to reduce the most microorganism(s) of public health significance to a level that is not likely to present a public health risk under normal conditions of distribution and storage” allowing methods such as PEF to be used (Nowosad *et al*., 2021).

II. PEF Technology

2.1. *History*

The concept of the application of electric current to food originated at the end of the 19th century. However, the application of pulsed electric fields to food were reported since the 1960s. The Pioneering work on PEF was done by German Engineer Heinz Doevenspeck in 1960 and he patented the technology describing the application of a pulsed electric field for disruption of cells in food material to improve phase separation (Fig.1 and Fig. 2). It was followed by the research work of Sale and Hamilton in UK. In the 1980s, Krupp Maschinentechnik, Germany developed two processes, ELCRACK and ELSTERIL based on Doevenspeck’s work (Toepfl *et al.,* 2007). The first commercial scale PEF system was built by Diversified Technologies, Inc. (DTI) for Ohio State University and the DUST Consortium in 2000. PEF pasteurization treatment was commercialized in 2005 by introducing the first commercial PEF-treated juices by Genesis Juice Corporation in the USA. Genesis and DTI were awarded the Food Technology Industrial Achievement award in 2007 by the Institute of Food Technologists (Kempkes, 2017).

Fig. 1. Heinz Doevenspeck (Sitzmann, 2017).

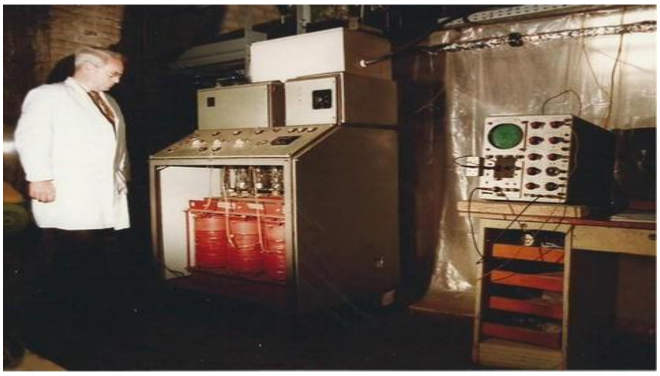

Fig. 2. Heinz Doevenpeck and his pulsed power generator at the facilities of Krupp Maschinenetechnik in the 1980s (Sitzmann, 2017).

2.2. *Mechanism of Microbial Inactivation by PEF*

The basic principle behind microbial inactivation by PEF is electroporation. Electroporation is defined as the electrically induced reversible permeabilization of cells. The cell membrane in a biological cell acts as an insulator shell to the cytoplasm. When a cell suspension is exposed to an electrical field, ions inside the cells move along the field until they are held back by the membrane. This leads to the accumulation of free charges on both membrane surfaces. The accumulation of more surface charges increases the trans-membrane potential. Due to the attraction of opposite charges induced on the inner or outer surface of the cell membrane, compression pressures occur resulting in a decrease in the membrane thickness. When the electric field strength exceeds a threshold value called critical field strength, pore formation or membrane breakdown occurs. With an increase in exposure times and field intensities beyond the threshold, more and more areas of the membrane are subjected to breakdown. This leads to the physical destruction of the cell. (Qin *et al*., 1996; Rastogi., 2007; Nowosad *et al*., 2021). Fig. 3 represent the electroporation mechanism. Electric field strength ranging from 0.1-1kV/cm causes reversible permeabilization of plant cells. 0.5-3 kV/cm causes irreversible permeabilization of plant and animal tissue while 15-40 kV/cm causes irreversible permeabilization of microbial cells (Nowosad *et al*., 2021).

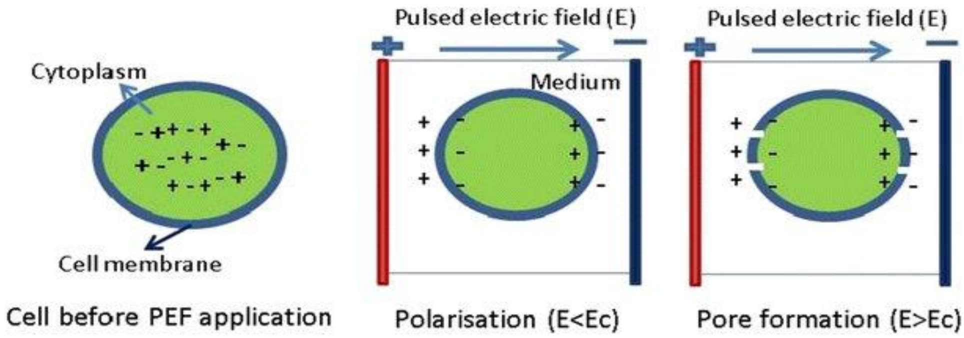

Fig. 3. Schematic representation of electroporation mechanism in biological cell membrane exposed to an electric field E. Ec represents critical electric field strength. (Bibha *et al*., 2018).

2.3. *PEF Treatment Process*

PEF technology relies on the application of short pulses of high electric fields with a duration of microseconds to milliseconds and intensity in the order of 10-80 kV/cm (Mohamed and Amer Eissa, 2012). Batch and continuous are two types of PEF systems. Continuous systems with a flow rate ranging from 400-6000 L/h are used for commercial applications (Sampedro and Rodrigo, 2015). A typical continuous PEF unit is composed of high voltage pulse generator, treatment chamber, fluid handling system and control and monitoring devices (Nowosad *et al.*, 2021). The treatment parameters are set by the control and monitoring unit. The high voltage pulse generator apply short electric pulses to the treatment chamber which consist of two electrodes with an insulator placed between them. The liquid food is pumped from the storage tank to the treatment chamber. Sometimes heating is done before PEF treatment to increase the process efficiency. The electrodes in treatment chamber are cooled by cooling system to avoid temperature rise. After PEF treatment the product is cooled and aseptically packed and stored in refrigerator at 4^0 C. Fig. 4 shows a continuous PEF treatment process.

The most commonly applied electric field pulses are of two types. They are exponential decay waves and square waves. An exponential decay voltage wave is a unidirectional voltage that rises rapidly to the maximum value and decays slowly to zero. In the square waveform, voltage increases quickly from zero to the maximum value, where it remains for the given time period and then decreases instantly to zero (Rastogi, 2007). The circuits for the generation of exponential decay pulses and square wave pulses are shown in Fig. 5.

Exponential decay pulses have a long tail with a low electric field, during which excess heat is generated in the food without bactericidal effect. On the other hand, the square pulse maintains a peak voltage for a longer time than the exponential decay pulse. Since both waveforms effectively inactivate microorganisms, square wave pulses will save energy and require less cooling effort (Zhang *et al.*, 1995).

2.4. *PEF System Components*

2.4.1. *Electric Power Source*

The power supply converts the AC power available from the utility into high-voltage DC power (Kempkes, 2017).

2.4.2. *Energy Storage Capacitor*

A capacitor is an electrical device used to store energy. The capacitance (C_0) of a capacitor is calculated as,

$$C_0 = \frac{t}{R} = \frac{t\sigma A}{d} \tag{1}$$

Where t is the pulse duration, R is the resistance, σ is the conductivity of the food, A is the area of the electrode surface, and d is the distance between electrodes.

The energy stored in the capacitor (Q) is calculated from values of capacitance (C_0) and charging voltage (V) as,

$$Q = 0.5\ C_0\ V^2 \tag{2}$$

2.4.3. *Resistor*

Resistors are used to regulate the current flow and impose a voltage reduction.

2.4.4. *Switches*

A switch is used to connect or disconnect the electric current and discharge the stored energy in a capacitor through the pulse-forming network (Taha *et al.*, 2022).

2.4.5. *Treatment Chamber*

The treatment chamber is one of the most important components of a pulsed electric field system. The major function of the treatment chamber is to transfer the high-voltage Pulsed electric field to the food. A treatment chamber consists of two electrodes held in position by insulating material that also forms an enclosure containing food materials (Zhang *et al*., 1995). The electrode gap ranges between 0.1-1.0 cm.

Proper design of the treatment chamber is important to ensure treatment homogeneity, prevent dielectric breakdown, and hence to increase the process efficiency (Arshad *et al*, 2020). Static chambers are used for batch processing in laboratories, whereas continuous chambers are used for industrial-scale applications (Taha *et al.*, 2022). The three most widely used chamber configurations are parallel plate, coaxial and co-linear chambers as shown in Fig. 6.

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Parallel plate configuration is the simplest in design. The two electrodes are kept in parallel. This configuration provides the most uniform electric field distribution. Due to the large surface area, the electrical resistance is lower in this configuration. The lower resistance and higher current favor undesirable electrochemical reactions at the electrode liquid interface which leads to electrode corrosion and the release of minerals to treated food (Arshad *et al.*, 2020).

The coaxial chamber is composed of two hollow cylinders with an electric field acting radially and the food moving axially between the two electrodes. In this configuration, the distribution of the electric field decreases radially from the internal towards the external cylinder. However, the homogeneity of electric field distribution can be increased by increasing the radius of the electrodes at a given gap (Arshad *et al.*, 2020).

In the co-linear configuration, couples of tubular electrodes are spaced with insulator spacer tubes. This configuration provides high treatment capacity and high electrical resistance due to low surface area. Hence this configuration requires a lower current and avoids electrode corrosion. The main disadvantage of this system is the non-uniform electric field distribution during processing.

Parallel and coaxial configurations are commonly used for batch processing, whereas co-linear configuration is used in continuous processing (Taha *et al.*, 2022).

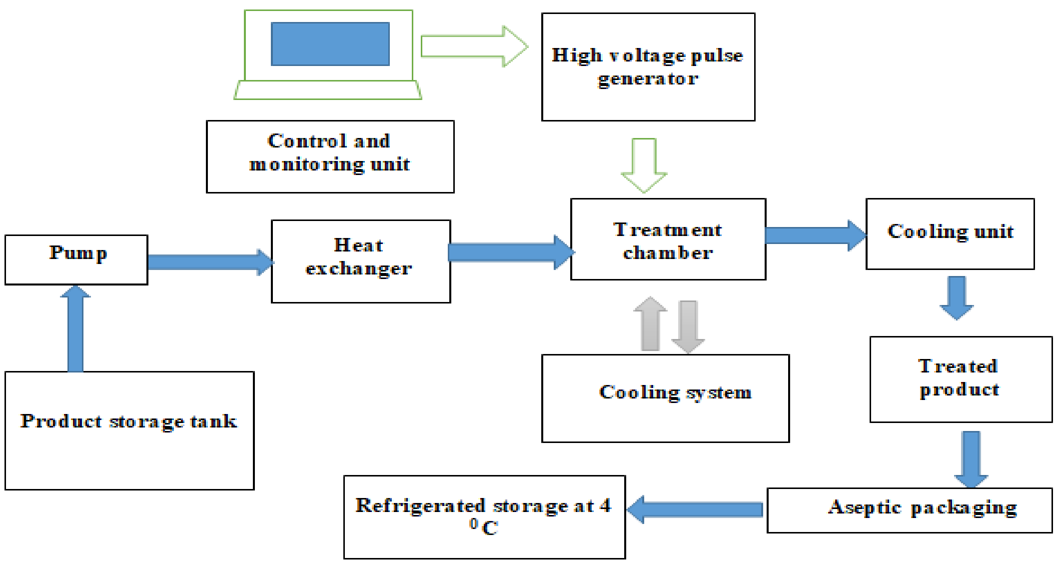
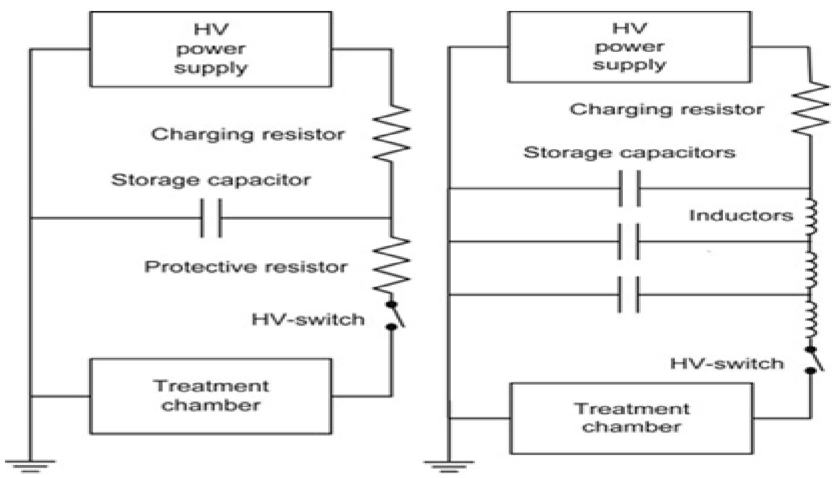


Fig. 4. Flow chart of continuous PEF treatment process.



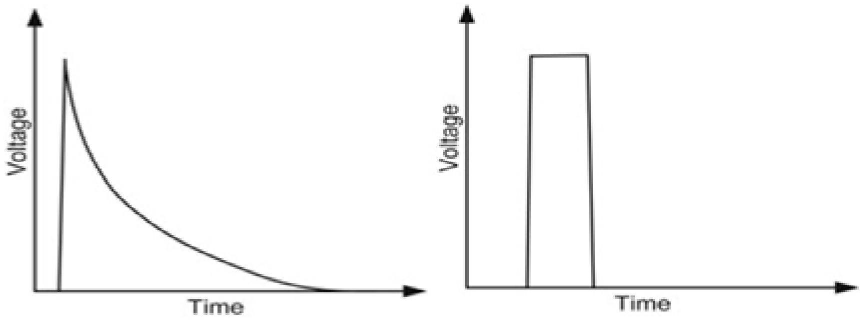


Fig. 5. Simplified electrical circuits of impulse generation systems and ideal voltage patterns of exponential decay and square wave pulses (Toepfl *et al.*, 2014).

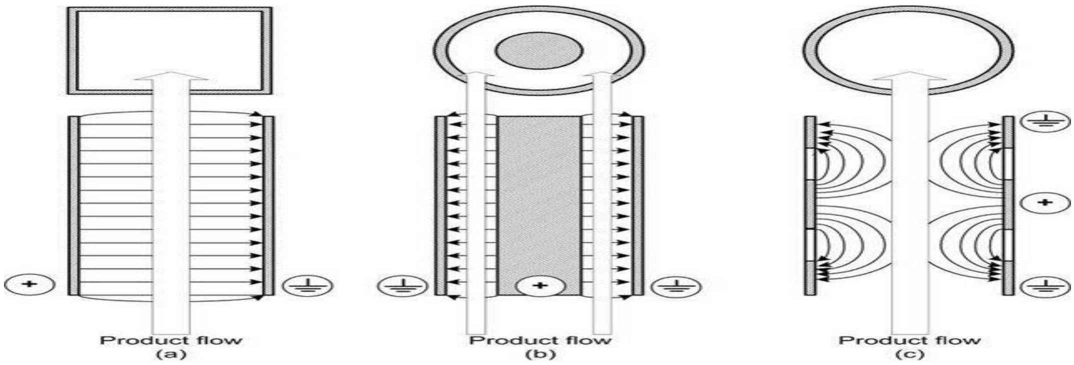


Fig. 6. Configurations of treatment chambers for continuous PEF treatment; (a) Parallel plate, (b) Coaxial, and (c) Co-linear configuration (Toepfl, 2006).

Important factors to be considered while design of treatment chamber are as follows.

1. The material of construction of treatment chamber should be washable and autoclavable. The recommended insulation materials are polysulfone, polyvinyl chloride (PVC), pyrex glass, polyethermide, and polypropylene. Carbon electrodes were used earlier as they are not reactive and can withstand intense heat. But they have very short lifespans. The best materials for electrode construction are platinum, gold etc. as they have high corrosion resistance. But their use is uneconomical. The most widely used material is stainless steel due to their lower prices and high corrosion resistance (Arshad *et al*., 2020).
2. Expelling of air bubbles during filling is necessary to prevent dielectric breakdown (Qin *et al*., 1996).
3. To maintain low temperature operation, circulation of cold water through jackets built in the electrodes is necessary (Qin *et al*., 1996).
4. A pressure release device is provided in treatment chamber to prevent potential pressure breakage (Qin *et al*., 1996).

2.5. *Factors Influencing Effectiveness of PEF Treatment*

The factors affecting PEF treatment can be divided in to process factors and product factors (Taha *et al.*, 2022). The most typical process parameters that characterize PEF technology are electric field strength, treatment time, pulse shape, pulse width (pulse duration), number of pulses, pulse specific energy, and pulse repetition frequency.

2.5.1. *Electric Field Strength*

Electric field strength refers to the field strength locally present in the treatment chamber during the sample treatment. (Raso *et al*., 2016). It can be estimated by dividing the voltage (V) measured across the electrodes and the distance between electrodes (d): $E = \frac{V}{d}$

With a fixed number of applied pulses, the rate of microbial inactivation increases with an increase in the electric field strength (Qin *et al*., 1996).

2.5.2. *Treatment Time*

Treatment time refers to the product of the number of pulses applied and the pulse width or pulse duration (Raso *et al*., 2016). An increase in any of these variables leads to an increase in microbial inactivation. But a large pulse duration may cause an undesirable increase in temperature of food (Rastogi, 2007).

2.5.3. *Pulse Shape*

Square wave pulses are more energy efficient and lethal than exponential decaying pulses. Bipolar pulses are more lethal than mono-polar pulses (Rastogi, 2007).

2.5.4. *Pulse width*

The pulse width of exponential decay pulse is the time needed to decrease the voltage to 37% of its peak value. Pulse width of a square pulse is the time for which the voltage is kept at the maximum value. A high pulse width require high energy input requirement and results an effective irreversible electroporation. However, localized thermal effect and electrolysis limit the pulse width to microseconds (Arshad et al., 2020).

2.5.5. *Pulse Specific Energy*

Pulse specific energy or energy density (kJ/kg/pulse) is the electrical energy received by the treated product per each pulse.

2.5.6. *Pulse Repetition Frequency*

Frequency refers to the number of pulses applied by unit of time. PEF processing with a frequency of a kilohertz is commonly required in the industrial treatment of liquid foods (Arshad et al., 2020).

Product factors that affect the effectiveness of PEF treatment include electrical conductivity, pH, chemical composition and temperature.

2.5.7. *Conductivity*

The conductivity of the food should be lower to obtain greater microbial inactivation for the same applied field (Rastogi, 2007).

2.5.8. *pH*

A decrease in pH or ionic strength results in higher microbial inactivation.

2.5.9. *Temperature*

PEF treatment and moderate temperature exhibit a synergistic effect on the inactivation of microorganisms. Microbial inactivation increases with an increase in temperature at a constant electric field strength.

The characteristics of microorganisms such as the type of organism, concentration and growth stage also affect the effectiveness of PEF treatment (Rastogi, 2007).

2.5.10. *Type of Microorganisms*

Gram positive organisms are more resistant to PEF than gram negative organisms. Yeasts are more sensitive to PEF than bacteria due to their larger size.

2.5.11. *Initial Concentration*

Higher initial concentration of organisms results in lower inactivation.

2.5.12. *Growth Stage*

The cells in logarithmic phase are more sensitive to PEF than those in lag phase or stationary phase.

2.6. *Advantages of PEF Treatment*

1. *Reduced Treatment Temperature and Time:*

The main advantage of PEF pasteurization over conventional thermal processing is the reduced treatment temperature and processing time (Siemer and Toefl, 2020). The thermal impact of a PEF process versus thermal pasteurization is shown in Fig. 7.

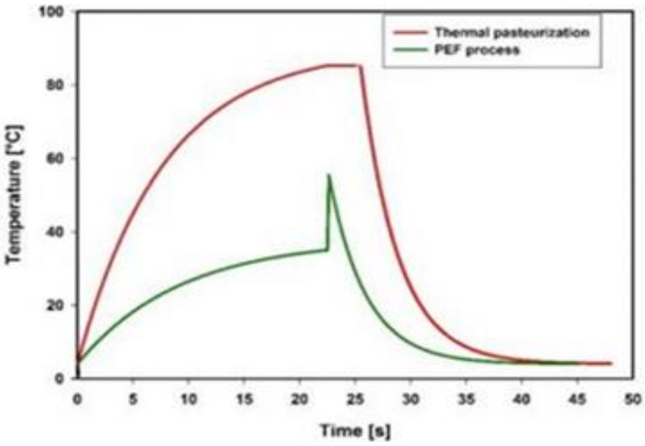


Fig. 7. Thermal impact of a PEF process versus thermal pasteurization (Siemer *et al*., 2020).

2. *Superior Quality Fruit Juices:*

Heat-sensitive colors, nutrients and flavour are not affected by PEF treatment.

3. *Inactivation of Microbes and Enzymes:*

PEF have successfully inactivated microorganisms such as *E.coli, Bacillus subtilis*. *Saccharomyces cerevisiae*, and *Listeria monocytogenes*, among others (Rastogi, 2007).

4. *Diverse Applications:*

PEF can be applied to increase extraction rate and drying rate. It is also used for tissue softening of potato which will allow easy cutting to make french fries. PEF is also used for waste water disinfection (Nowosad *et at.* 2021).

2.7. *Limitations of PEF Treatment*

1. *High Capital Cost:*

The investment costs of an industrial scale PEF system is estimated to be in the range of 2 to 3 million US $ at of 5 t/h capacity and high field strength ranging from 20-40 kV/cm and an energy input of 100 to 1000 kJ/kg (Toepfl *et* al., 2006).

2. *Dielectric Breakdown:*

An electric field strength of 30-40 kV/cm and pulse width beyond 20 μs may result in gas bubble formation after one pulse. As air is a poor conductor of electricity, the application of PEF through air results in dielectric breakdown which can cause sudden equipment failure and fire hazard. The breakdown strength (BS) of a solid, liquid, or gas dielectric is the maximum electric field strength in V/m withstood before undergoing an 'insulator-to-conductor' transition, evidenced by an electric spark. The BS of gases (i.e. Air BS: 30 kV/cm at atmospheric pressure) is much smaller than for liquids (oil: 100 kV/ cm at atmospheric pressure, thus the presence of gas in a liquid medium reduces its electrical strength. The presence of gas also distorts the field, leading to the breakdown of the liquid at relatively lower voltages (Gongora-Nieto *et al*., 2003). To reduce the probability of dielectric breakdown in foods, the following is suggested by Zhang *et al*. (1995):

- Use of a smooth electrode surface to minimize electron emission.
- Providing round electrode edges to prevent field enhancement.
- Design of the treatment chamber to provide uniform electric field strength so that the actual applied field strength does not exceed the dielectric strength of the fluid foods under the test conditions.
- Degassing prior to treatment to eliminate gas bubble formation.
- Pressurizing the fluid food within the treatment chamber to prevent gas bubble formation.

3. *High Energy Consumption at Low Treatment Temperatures:*

At low treatment temperatures, energy consumption is very high in PEF processing as compared to thermal pasteurization. This results in high costs of operation. By using a combination of heat and PEF-treatment the energy consumption and the maximum temperature can be reduced. Using synergistic effects of elevated treatment temperature of 35-65 ^{0}C on microbial inactivation the energy consumption could be reduced from above 100 to less than 40 kJ kg^{-1} for a reduction of 6 log cycles. The use of treated juice to preheat untreated juice provided a possibility to recover the dissipated electrical energy after treatment, leading to a drastic reduction in operation costs. (Heinz *et al*., 2003).

4. *Unfavourable Electrochemical Reactions:*

Large currents used in PEF may cause unfavourable electrochemical reactions at the electrode- solution interface. It leads to production of toxic chemicals in food, electrode fouling and electrode corrosion. Electrode corrosion can be avoided by applying short pulses and bipolar pulses (Morren *et al*., 2003).

2.8. *Preservation of Liquid Foods by PEF*

Several studies on Pulsed electric field treatment of liquid foods have been reported in the past. According to

FDA, the processes of production should meet a performance standard of 5 log reduction of the most resistant pathogen.

Studies on milk (Table 1) have shown that PEF treatment have achieved microbial reduction of milk with a shelf life similar to that of HTST pasteurized milk (Sampedro and Rodrigo, 2015). An increase in shelf life of milk is achieved by a combination of thermal treatment and PEF.

Researches on fruit juices revealed that PEF pasteurization extended the shelf life while preserving the nutritional value and fresh like characteristics (Table 2). PEF can also be used for preservation of coconut water and liquid egg without affecting the quality (Table 3 and table 4). The combination of PEF with heat, natural antimicrobial compounds and ultrasound reported better performance (Table 5).

Genesis Juice Corporation introduced the first FDA approved, PEF processed juice to the US market in 2005. The shelf-life of these juices was 4 weeks at storage temperatures of 4°C. Genesis was shuttered in 2004 following FDA's warnings of "serious deviations" in Juice Hazard Analysis Critical Control Point regulations. The company was missing HACCP plans and had no sanitation control records. Genesis successfully introduced a PEF treated line of FDA-compliant juices in 2005, but was unable to overcome the financial impact of the shutdown, and was subsequently sold in 2007 to another company, without the PEF process.

Hoogesteger is Europe's leading supplier of fresh, cold pressed juices. Since 2012 the company has installed PEF systems in its production facilities. PEF pasteurization has increased product shelf life from 6-7 days up to 21 days (Fig. 8). The market share as well as the production planning of the company have been enhanced by the use of PEF technology. Hoogesteger offers juices such as orange, strawberry-kiwi, apple pear raspberry, apple, and orange mango as well as a number of others.

PEF process lines should follow CIP cleaning and the compliance to HACCP is very important to ensure safety of PEF treated foods. Three critical control points identified for the PEF products are receiving and storage section, PEF treatment section, and aseptic packaging section. The main factors considered and monitored for each CCP are handling and processing time, temperature of material, and cleanliness of equipment and utensils. Standard operating procedures (SOPs) should be defined for reception, storage, and preparation of raw materials, to ensure proper handling and reduce the risk of contamination (Vega-Mercado *et al*., 2007).

Fig. 8. PEF-treated Genesis juice on sale in 2006 (Kempkes, 2017).

Fig. 9. Hoogesteger smoothies.

Table 1. Summary of some selected studies on PEF treatment of milk.

Type of milk	Processing conditions	Variables studied	Major results	Reference
Skim milk	Temp: 20, 30, 40 ^{0}C Electric field intensity: 30.76, 38.46, 46.15, and 53.84 kV/cm Number of pulses: 0,12,24 and 30 (2µs each)	Microbial analysis, pH, electrical conductivity, density, SNF, color, fat and protein	Higher microbial inactivation at higher temperatures, minor variation in physicochemical properties, some reduction in SNF, protein, and fat	Bermudez-Aguirre *et al.*, 2011
Whole milk	Temp: 20, 30, 40 ^{0}C, Electric field intensity: 30.76, 38.46, 46.15, and 53.84 kV/cm Number of pulses: 0, 12, 21 and 30			
Whole Milk	HTST: 75 ^{0}C, 15s PEF: 15, 20, 25, and 30 kV/cm for 800 µs, 200Hz, 2µs pulse width	Volatile compounds	Heat treatment resulted in an increase in aldehydes and methyl ketones of milk while PEF resulted in an increase in aldehydes alone. No significant changes of acids, lactones, and alcohols.	Zhang *et al.*, 2011
Whole milk	Thermal treatment: 15s, at either 63 or 72^{0}C PEF treatment: 30kV/cm, 22µs, at either 53 or 63 ^{o}C outlet temperature)	Microbiology, Composition pH Color, Rennetability Plasmin activity Volatile compounds	PEF processing for 22 µs at 30 kV/cm and 63^{o}C outlet temperature can extend the refrigerated shelf life of whole milk similar to thermal pasteurization without any adverse effect on physicochemical properties.	McAuley *et al.*, 2016
Whole milk	Traditional pasteurization: LTLT, UHT, and Microfiltration (MF) PEF conditions: Electric field strength: 24kV/cm Pulse duration: 25µs, Number of pulses: 20	Bacterial activity, Whey protein content, β-Lactoglobulin	2.43 log reduction in total bacterial viability, 0.9 log reduction of coliforms, whey protein content (4.98mg/mL) was not affected by PEF, β-Lactoglobulin (3.28mg/mL) was unaffected	Salasevicius *et al.*, 2021

Table 2. Summary of some selected studies on PEF treatment of fruit juices.

Type of Juice	Processing Conditions	Variables Studied	Major Results	Reference
Orange juice	Heat pasteurization: 94.6 ^{0}C for 30 s PEF treatment: 35 kV/cm for 59µs	Microbial count, ME activity, Vitamin C, flavour compounds, Browning index, color, particle size, pH, TSS.	PEF treatment prevented the growth of microbes at 4, 22 and 37 ^{0}C for 112 days. 88% reduction in PME activity was observed, PEF treated juice retained greater amount of vitamin C and flavour compounds during storage at 4 ^{0}C, PEF-treated juice showed lower browning index, higher whiteness and higher hue angle during storage, TSS and pH were not significantly affected	Yeom *et al.*, 2000
Apple juice	Conventional HTST	pH, total acidity, phenolic	Minimum variation in pH, no significant	Aguilar-

Type of Juice	Processing Conditions	Variables Studied	Major Results	Reference
	pasteurization : 90^0C for 30 s. PEF treatment: 35 kV/cm, 4us pulse width, 1200 pulses per second frequency	content volatile compounds	changes in acidity, HTST caused 32.2% loss of phenols while PEF caused only 14.49% reduction. The loss of volatile compounds were lesser in PEF treatment	Rosas *et al*., 2007
Mango juice	Thermal treatment: 90^0C, 60 s. HIPEF treatment: 35kV/cm, 200 Hz, pulse width 4µs, Treatment time 50, 100, 200, 400, 800, 1200, 1600, 1800, and 2000µs.	*L. innocua* inactivation, enzyme activity(PPO, LOX, POD), storage stability, physicochemical analysis (Electrical conductivity, pH, TSS, Viscosity, color), Total phenols, total carotenoids, antioxidant activity, sensory evaluation.	HIPEF treatment for 800 µs ensured 5 log reductions of *L. innocua. Enzyme* activities were significantly reduced at treatment times of 1800 µs. Fresh mango juice colour was preserved after HIPEF treatment throughout storage. Microbial count in HIPEF-treated (1800 µs) mango juice remained below 6 log cycles CFU/mL up to 2 months of refrigerated storage. Phenolic compounds in HIPEF-treated increased from 333 to 683 µg of GAE/mL from day 0 to the end of storage.	Salinas-Roca *et al.*, 2017
Pineapple juice	9kV/cm, 11kV/cm, 13kV/cm and 1000 Hz	Microbial count, Total phenolic content (TPC), total flavonoid content, ascorbic acid, β-carotene, antioxidant activity.	Highest microbial inactivation at 13 kV/cm. During storage microbes grew in PEF treated juice since the applied field intensity is less than the critical value. Flavonoid and ascorbic acid content diminished at a similar rate to that of untreated juice. Total Phenolic Count and β-carotene of treated juice reduced at a slower rate than the untreated juice	Yousuf *et al.*, 2020

Table 3. Summary of some studies on PEF treatment of Coconut juice.

Type of Juice	Processing Conditions	Variables Studied	Major Results	Reference
Tender coconut water (TCW)	Pulse width: 2.5µs ,Field strength: 17 kV/ cm and 35kV/cm, Treatment time: 2, 4, 6 min	pH, Acidity and TSS standard plate count and *E. coli*, sensory attributes such as taste, colour and overall acceptability	No significant difference in pH, acidity and TSS before and after processing. SPC count was less than 5000 cfu/mL and *E. coli* was found to be absent. sensory attributes did not change after PEF processing. The shelf life was extended to 18 to 25 days at 5^oC.	Saranya and Sujatha., 2016
Coconut juice	Conventional thermal pasteurization(CTP) : 68.2^0C for 30 minutes. PEF treatment: 40kV/cm, 20-100 number of pulses	Microbial analysis, TSS, pH, color, vitamin C, sugars, minerals	Total plate count, yeast and mould count were less than 1 cfu/ml after PEF treatment, PEF treatment preserved more vitamin C compared to CTP, No significant difference in color, pH, and TSS, sugars and minerals.	Kantala *et al.*, 2021

Table 4. PEF treatment of liquid egg.

Type	Processing Conditions	Variables Studied	Major Results	Reference
Whole egg liquid	20-45 kV/cm 3-150 µs	Inactivation of *Salmonella Typhimurium* and *Staphylococcus*	4 log reduction of *Salmonella Typhimurium* was achieved with 45 kV/cm, 30 µs and 419 kJ/kg.	Monfort *et al.*, 2010

Type	Processing Conditions	Variables Studied	Major Results	Reference
		aureus	3 log reduction of *Staphylococcus aureus* was achieved with 40 kV/cm for 15µs and 166 kJ/kg.	

Table 5. Summary of some studies on PEF treatment combined with other methods.

Type of Juice	Treatment Combinations	Variables Studied	Major Results	Reference
Apple juice	Heat treatment + PEF: 35-75 ^{0}C, 34 kV/cm	Inactivation of *E.coli*, energy consumption	The energy consumption for 6 log cycle reduction of *E. coli* reduced from 100 kJ/kg to 40 kJ/kg when temperature is increased from 20-30^{0}C to 55-65^{0}C	Heinz *et al.*, 2003
Whole milk	Heat treatment +PEF: 65^{0}C for 10s, 35kV/cm, 2.3 µs, 5 pulses	Shelf life and quality assessment	Shelf life of milk was extended by a minimum of 24 days	Sepulveda *et al.*, 2009
Strawberry, Orange, apple, pear, tomato juices	Untreated, PEF alone (35kV/cm, 4µs), PEF + citric acid (0.5 - 2 %) or cinnamon bark oil (0.05 - 0.1%), Thermal	Microbiological shelf life, sensory properties	Both PEF alone and combined treatments extended shelf life of strawberry and oranges up to 91 days in refrigerated storage. Only combined treatment extended shelf life of apple, pear and tomato juices up to 91 days.	Mosqueda-Melgar *et al.*, 2012
Sour cherry juice	Ultrasound+ Pulsed electric field : Electric field intensity: 5-10 kV/cm, time: 5-35 µs Ultrasound power: 100-200 W, time: 3-9 min	*E.coli count*, Total phenolic content, Total anthocyanin content, Vitamin C, Energy consumption	Total phenolic content, anthocyanin and vitamin C ere maintained compared to conventional method	Samani *et al.*, 2020
Cantaloupe juice	Control: 90 ^{0}C, 3 min, PEF alone: 30 kV/cm for 400 µs, PEF+ temperature: 20kV/cm for 200µs + 55 ^{0}C. PEF+ tea polyphenols: Tea polyphenols 400mg/kg +30 kV/cm for 400µs	*S. cerevisiae* inactivation, pH, conductivity, TSS, colour, Vitamin C	Similar effects on microbial inactivation to thermal pasteurization. Two PEF-combined methods better preserved the quality of cantaloupe juice	Li *et al.*, 2021

III. Summary and Conclusion

Pulsed electric field technology is a highly promising technology for liquid food preservation. It has proven 5 log reduction of many spoilage organisms in liquid foods which satisfy the standard requirements by FDA. PEF treatment is affected by many factors and process parameters for each food application are different and have to be optimized. PEF treated fruit juices are healthy as they are preservative free and minimally processed. It also preserves the nutrient compounds and fresh like flavor of liquid foods. A combination of heat, natural antimicrobial compounds, pulsed electric field and other non-thermal technologies such as ultrasound along with aseptic packaging offers significant advantages including long refrigerated shelf life, low energy consumption and higher microbial and enzyme inactivation. An increase in process efficiency can be achieved by combining PEF with other non- thermal technologies such as ultrasound and high hydrostatic pressure. As more and more companies are producing commercial PEF systems now, the availability of PEF pasteurized fruit juices are expected in near future.

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