

Processing of Fruits and Fruit Juices by Novel Electrotechnologies

G. Akdemir Evrendilek · T. Baysal ·
F. Icier · H. Yildiz · A. Demirdoven ·
H. Bozkurt

Received: 4 March 2010 / Accepted: 3 November 2011 / Published online: 22 November 2011
© Springer Science+Business Media, LLC 2011

Abstract Recent demands from consumers for fresh-like quality foods with less and/or no artificial additives have introduced innovative processing technologies. These technologies due to their potential for food processing with preservation of important properties may cause to introduce new products in the market, to improve the competitiveness of the food, to eliminate the use of some artificial food additives, and to reduce energy cost. Pulsed electric fields for microbial and enzyme inactivation, shelf-life extension, moderate electric fields for yield and extraction, and ohmic heating are among these novel technologies that are based on the application of electric current on food materials. It has been well established that these technologies can successfully be applied to different food products. Among all, fruit juices have special importance due to the suitability of their physical properties to be processed by the electrotechnologies. This article covers the fundamentals of these technologies, their current use, research activities, and trends.

Keywords PEF · MEF · Ohmic heating · Fruit juices · Food quality

Introduction

The adverse effect on food products by heating processes on physical, nutritional, and sensory properties has led to explore in-depth alternative technologies, among them, those based on electrical based methods. Pulsed electric fields (PEF), moderate electric fields (MEF), and ohmic heating applications are among these new methods that can be used for improving the product quality in food processing and also for yield improvement.

The bactericidal effects of direct and alternating electrical current have been investigated as early as at the end of the nineteenth century [98]. The applicability of PEF to successfully achieve membrane permeabilization in plant, animal, or microbial cells have been shown in batch as well as in continuous operation, but research work was mainly conducted in a laboratory scale. Knowledge has been obtained regarding key processing parameters and impact of the treatment on microbial and plant cells; however, unfortunately no application in an industrial size could be achieved until 2006 [129].

All living cells contain cell membranes. These membranes are comprised of lipids (fatty molecules) and proteins [4]. Prokaryotes have an additional layer outside the membrane known as the cell wall. At low frequencies (50–60 Hz) and high field strengths most commonly associated with electrical current, the naturally porous cell walls can allow the cell membrane to build up charges, forming disruptive pores [29]. Electroporation occurs because the cell membrane has a specific dielectric

G. A. Evrendilek (✉)
Department of Food Engineering, Faculty of Engineering
and Architecture, Abant Izzet Baysal University, 14280 Golkoy
Bolu, Turkey
e-mail: gevrendilek@ibu.edu.tr; gevrendilek@yahoo.com

T. Baysal · F. Icier · H. Bozkurt
Department of Food Engineering, Faculty of Engineering,
Ege University, 35100 Bornova, Izmir, Turkey

H. Yildiz
Department of Food Engineering, Faculty of Engineering, Celal
Bayar University, Muradiye, Manisa, Turkey

A. Demirdoven
Department of Food Engineering, Faculty of Engineering and
Natural Sciences, Gaziosmanpaşa University, Taşlıçiftlik, 60240
Tokat, Turkey

strength, which can be exceeded by the electric field. The dielectric strength of a cell membrane is related to the amount of lipids (acting as an insulator) present in the membrane itself. The pores formed can vary in size depending on the electric field strength and can reseal after a short period of time. Excessive exposure causes cell death due to the leakage of intracellular components through the pores [69]. Therefore, electroporation is highly damaging the cells and would enhance the lethal effects of the self-generated heat [8].

In addition to microbial inactivation by electroporation, studies involving electrotechnologies of different food products also included preservation of nutritional and sensory properties, enzyme inactivation, enhancement of juice yield, and shelf-life extension. Among all other food products, fruit juices have special importance for processing by electrotechnologies. Information related to the application of electrotechnologies on fruit and fruit juices are reported in different studies. Recent applications and future needs on fruits and fruit juices are summarized in this study.

Pulsed Electric Fields

Inactivation Mechanism and Modeling

When the food sample having electrical conductivity properties was placed between a high voltage and a grounded electrode, the resulting electrical field can be calculated by Laplace equation ($\nabla^2\varphi = 0$, where φ denotes the electrical potential) [132, 158]. From the Laplace equation, the potential difference ($\nabla\varphi M$) for the biological cells with spherical shape and a radius (R) can be estimated by applied external electric field (E). A formula derived from Maxwell equation in ellipsoidal coordinates with several simplified assumptions provided the local membrane potential difference at the distance A_F from the center in direction of the external electric field. According to the formula, the potential difference can be expressed as [131]:

$$\nabla\varphi M = -f(A)A_F E \quad (1)$$

The shape factor in the equation is explained as a function of three semi-axis (A_1, A_2, A_3) of elliptical cells:

$$f(A) = \frac{2}{2 - A_1 A_2 A_3 \int_0^\infty \frac{1}{\left((s + A_F^2) \left(\sum_{n=1}^3 \sqrt{s + A_n^2} \right) \right)} ds} \quad (2)$$

where φ is electrical potential (V), M is membrane, $f(A)$ is shape factor, A_F is length of semi-axis in field direction (m), E is electric field strength (kV/cm) and A is the length of semi-axis of ellipsoid (m).

It is reported that [158] if applied electric field strength is 1 V above the membrane potential ($\nabla\varphi M$), the rapid electrical breakdown and local conformational changes occur at the lipid bilayer structure [131]. If the membrane thickness is considered as 5 nm, the critical electric fields that must be overcome for electrical breakdown formation is (E_{crit}) 2,000 kV/cm [131].

In addition to inactivation mechanism, microbial inactivation kinetics is also studied extensively. Different mathematical models have been proposed to explain the decrease in the microbial number as a function of applied electric field strength or treatment. The simplest approach at sufficiently high electric field strength for microbial inactivation was first-order kinetics. When semi-log inactivation data were plotted against electric field strengths of treatment time, the resulting graph would be a straight line. The survival fraction (S) is defined as the ratio between the number of survivors and the number of initial microorganism (N/N_0). According to first-order kinetics, the model has the following form:

$$S = e^{-kt} \quad (3)$$

where S is the survivor fraction, k is the kinetic constant that depends on the intensity of the electric field, and t is the treatment time [23, 116].

However, inactivation curves explained above are not usually linear; therefore, different kinetic models have been proposed. A model known as Hülshager's model [54] provides a linear relationship between the logarithm of survivor microorganisms and the logarithm of treatment time for a given electric field intensity, and a linear relationship between the logarithm of survivor microorganisms and the electric field intensity for a given treatment time. The model is expressed as:

$$S = \left(\frac{t}{t_c} \right)^{-(E-E_c)/k} \quad (4)$$

where S is the survivor fraction, t is the treatment time, t_c is the critical treatment time, E is the electric field intensity, E_c is the critical electric field and k is a constant. The parameters E_c , t_c , and k are proposed to be dependent on the microorganism when limits on experimental conditions are observed [54, 116]. Although the model defined a linear relationship between the logarithm of survival fraction and logarithm of treatment time at any given electric field intensity or linear relationship between logarithm of survival fraction and logarithm of electric field intensity at any given treatment time, it can have deviations from the linearity. The limitations posed by this model promoted searching for alternative ones capable of better predicting microbial inactivation. Model proposed by Peleg [93] based on Fermi's equation was used to explain microbial inactivation:

$$S(V) = \frac{1}{1 + \exp((V - V_c)/a)}. \quad (5)$$

According to this model, S is the survivor fraction, V is the electric field strength, V_c is a critical level of V where the survivor fraction is 0.5, and a is a parameter related to the steepness of the curve around V_c [93, 116].

With recent attempt to explain microbial inactivation kinetics better, studies more focused on Weibull distribution model. In this approach, it is accepted that microbial inactivation kinetics does not fit the normal distribution, and it is addressed that Weibull is more appropriate to explain the inactivation data [94]. The formula is given by:

$$\log_{10}(S) = -\left(\frac{t}{a}\right)^b, \quad (6)$$

where S is survival fraction (N/N_0) at a treatment time (t) or electric field strength (k), a (μ s) and b are scale and shape parameters, respectively. The b factor interprets the shape of the survival curve; thus, when $b < 1$, the survival curve is concave; when $b > 1$, the survival curve is convex; and when $b = 1$, the survival curve is a straight line.

Our findings regarding the inactivation of different microorganisms as a function of electric field strength and treatment time also fit log logistic model expressed as:

$$\log_{10}(S) = \frac{1}{1 + (\chi + \alpha)^{-\beta}} \quad (7)$$

where S is survival fraction (N/N_0) at a treatment time or electric field strength (χ), ($\alpha > 0$) and ($\beta > 0$) are scale and shape parameters, respectively.

In order to compare the different models, the root mean squared error (RMSE) is used. The smaller the RMSE values, the better the fit of the model to the data [94]

$$\text{RMSE} = \sqrt{\frac{\sum(\text{fitted} - \text{observed})^2}{n - p}}, \quad (8)$$

where n is the number of observations and p is the number of parameters to be estimated. The accuracy factor parameter (A_f) described by Ross [112] is defined by the following expression

$$A_f = 10^{\frac{\sum |\log(\text{predicted}/\text{observed})|}{n}}, \quad (9)$$

where n is the number of observations used to make the calculations. The *predicted/observed* ratio refers to the relationship between the survival fraction fitted by the model and the one obtained experimentally. The larger the A_f , the less accurate the average estimate, while A_f value of 1 indicates that the model produces a perfect fit for the data [96].

The basic principle of PEF is based on the application of high-intensity short-duration pulses to food samples

carrying ions that transmit the electric current through the food [54, 113, 152, 153]. Therefore, PEF mostly applied to the food samples that can conduct the electricity. Foods processed by PEF should have certain levels of ions that deliver conductivity of foods. Another requirement for food samples to be processed by PEF is viscosity. Especially for the continuous PEF system, food should be pumped through the system by a certain flow rate during the PEF processing. Sometimes application of moderate heat in combination with PEF was applied to food product to help pumping it through the PEF fluid handling system.

Inactivation mechanism of PEF on microorganisms is based on changes or disruption in the cell membrane and electrochemical instability [31]. Applied electric current causes membrane instability due to membrane compression and pore formation [133]. Microbial inactivation by PEF is affected by several factors such as microbial factors, food factors and factors that depend on electric application. Microbial factors include cell size, cell shape, cell wall construction, growth stage of microorganisms, and initial cell count [55]. Factors related to PEF-processed food include acidity, conductivity, viscosity, particle size, and composition (fat, protein, carbohydrate, mineral, and water content). The PEF-processing variables are number of pulses, magnitude of applied electric field strength, frequency, pulse width, and treatment time [10].

Although there are different food products such as soups, yogurt drink, plain milk (2%, 1% and nonfat), chocolate milk, rice pudding, beer and liquid egg, PEF studies mostly focused on processing of orange, apple, cranberry, tomato, melon, watermelon, and orange–carrot juice mixtures for microbial inactivation (Table 1), preservation of chemical, physical, nutritional, and sensory properties and shelf-life extension [18, 33, 36, 39, 51, 53, 79, 80, 87, 102, 107, 124, 130, 134, 152, 154, 155, 157] as well as enzyme inactivation (Table 2) [24, 52, 135, 136, 142].

PEF Processing of Different Fruit Juices

Orange juice is one of the most studied fruit juice by PEF. In a study performed to determine the effects of PEF (35 kV/cm for 59 μ s) with heat treatment (94.6 °C for 30 s) on the quality of orange juice, it was revealed that PEF treatment provided greater amounts of vitamin C retention and better flavor than heat pasteurization during storage at 4 °C ($p < 0.05$). Moreover, PEF treatment caused lower browning index, higher whiteness (L) and higher hue angle values during storage at 4 °C ($p < 0.05$). °Brix and pH values were not significantly affected by both PEF and heat treatment ($p > 0.05$) [127]. PEF treatment of squeezed citrus juices (grapefruit, lemon, orange, tangerine) with pH, °Brix, electric conductivity, viscosity,

Table 1 Overview of the inactivation of microorganisms in fruit juices by PEF treatment

Food	Microorganism	PEF system	PEF treatment condition	Log reduction	Source
Apple juice	<i>S. cerevisiae</i> , <i>E. coli</i>	Batch parallel plate	12 kV/cm, 20 pulses, exponential decay, <30 °C	<i>S. cerevisiae</i> : 3–4, <i>E. coli</i> : 3	Qin et al. [100]
Apple juice	<i>S. cerevisiae</i>	Batch parallel plate	25 kV/cm, 558 J, exponential decay, <25 °C	3–4	Zhang et al. [153]
Apple juice	<i>S. cerevisiae</i>	Continuous flow coaxial	50 kV/cm, square wave, 29.6 °C	6.3	Qin et al. [101]
Apple juice	<i>S. cerevisiae</i>	Continuous recirculating parallel plate	40 kV/cm, 64 pulses, exponential decay, 15 °C	3.3	Harrison et al. [49]
Apple juice	<i>E. coli</i> O157:H7	Co-field flow tubular	29 kV/cm, square wave	5	Evrendilek et al. [37]
Apple juice	Laboratory scale: <i>E. coli</i> O157:H7, Pilot plant scale: aerobic microorganisms, yeasts and molds	Co-field flow tubular	Laboratory scale: 34 kV/cm, 166 µs of tr.time, 1.5 mL/s, 800 pps Pilot plant scale: 35 kV/cm, 94 µs of tr. time, 85 L/h, 952 Hz	Laboratory scale: 4.5 Pilot plant scale: aerobic microorganisms – 2.1, yeasts and molds – 1.5	Evrendilek et al. [39]
Apple juice	<i>S. cerevisiae</i>	Co-field flow tubular	20 kV/cm, 10.4 pulses, square wave	4	Cserhalmi et al. [32]
Apple juice	<i>E. coli</i>	Bench scale, bipolar or unipolar square wave	12, 24,36 kV cm 21, 400, 600 and 800 pps	>5	Charles-Rodriguez et al. [28]
Apple juice	<i>E. coli</i>	Co-field flow continuous	PI: 60 kV/cm, 11.3 pulses P2: UV (50 cm length 2.94 s tr. time, 8 mL/min flow rate) + PEF (60 kV/cm, 162 J/mL specific energy, 11.3 pulses)	4.87 5.35	Gachovska et al. [45]
Apple juice (AJ), orange juice (OJ), grape juice (GJ), pineapple juice (PJ), cranberry juice (CJ)	<i>Zygosaccharomyces bailii</i> ascospores Vegetative cells (V), ascospores (A)	Coaxial	AJ: 32.3 kV/cm, 19 °C OJ: 34.3 kV/cm, 20 °C GJ: 35.0 kV/cm, 20 °C PJ: 33.0 kV/cm, 20 °C CJ: 36.5 kV/cm, 22 °C	AJ (V): 4.8 AJ (A): 3.6 OJ (V): 4.7 OJ (A): 3.8 GJ (V): 5.0 GJ (A): 3.5 PJ (V): 4.3 PJ (A): 3.4 CJ (V): 4.6 CJ (A): 4.2	Raso et al. [105]
Apple cider	Naturally occurring yeast and molds	Concentric chamber	PI: 27–33 kV/cm, 200 pulses/s, 3 L/h flow rate, 50 °C P2: 27–33 kV/cm, 200 pulses/s, 10 L/h flow rate, 50 °C+ nisin (27.5 U/mL) and lysozyme (690 U/mL) P3: 27–33 kV/cm, 200 pulses/s, 10 L/h flow rate, 50 °C + 3 or 5 mL/100 mL clove oil 36.5 kV/cm, 22 °C	PI: 3.10 P2: 4.22–4.88 P3: 5.09	Liang et al. [71]
Cranberry juice	<i>Byssoschlamys fulva</i> canidiospores	Coaxial	36.5 kV/cm, 22 °C	5.9	Raso et al. [104]
Cranberry juice	<i>Neosartorya fischeri</i>	Coaxial	51.0 kV/cm, 34 °C	Not inactivated	Raso et al. [104]

Table 1 continued

Food	Microorganism	PEF system	PEF treatment condition	Log reduction	Source
Cranberry juice	Total aerobic bacteria (TAB), total mold and yeast (TMY)	Co-field flow tubular, square wave bipolar pulse	40 kV/cm for 150 μ s, 1,000 Hz, 2 μ s pulse duration	TAB: 4.8 TMY: 4.87	Jin and Zhang [65]
Longan juice	<i>E. coli</i> and yeast	Laboratory unit, square wave bipolar pulse	32 kV/cm, 90 s tr. time, 3 μ s pulse duration, 10 Hz	<i>E. coli</i> : 2–3 Yeast: 6–7	Zhang et al. [152]
Orange juice	Initial microorganisms	Thyratron-based pulse power supply	P1: 120 pulses/mL, 46 kV/cm P2: 120 pulses/mL, 46 kV/cm 45 °C	P1: 2 P2: 3	El-Hag et al. [35]
Orange juice	<i>S. cerevisiae</i>	Gene Pulsar II Electroporation system exponential decay pulses	40 pulses, 12.5 kV/cm, 1 μ F capacitance, 0.02 ms/pulse pulse decay time	6	Molinari et al. [87]
Orange juice	<i>Salmonella</i> Typhimurium	Concentric treatment chamber	90 kV/cm, 50 pulses, 55 °C	5.9	Liang et al. [72]
Orange-carrot juice mixture	Aerobic microorganisms, yeasts and molds	Co-field flow tubular, bipolar wave	P1: 25 kV/cm, 280 μ s P2: 25 kV/cm, 330 μ s	TPC P1: 2.46 \pm 0.35 P2: 3.26 \pm 0.29 TMY P1: 2.67 \pm 0.61 P2: 2.85 \pm 0.30	Rivas et al. [109]
Orange juice	Aerobic microorganisms	Co-field flow tubular, square wave	29.5 kV/cm, 60 μ s of tr. time	4.2	Qui et al. [102]
Whey protein fortified orange juice	Aerobic microorganisms, yeasts and molds	Pilot plant scale system, co-field flow tubular	32 kV/cm, 92 μ s of tr. time, 3.3 μ s of pulse width, 800 Hz, 79 L/h	Aerobic microorganisms: 0.5 Yeasts and molds: 3.5	Sharma et al. [125]
Orange juice	Aerobic microorganisms, yeasts and molds	Pilot plant scale system, co-field flow tubular	30 kV/cm, 240 μ s of tr. time, 2 μ s of pulse width, 1,000 Hz, 2 mL/s	Aerobic microorganisms: 2.5 Yeasts and molds: 2.5	Jia et al. [64]
Orange juice	<i>L. mesenteroides</i> , <i>E. coli</i> , <i>L. innocua</i> , <i>S. cerevisiae</i> ascospore	CPS1 system, cathode (PurePulse Tech)	30 kV/cm or 50 kV/cm (<i>S. cerevisiae</i> ascospores), 100 L/h	<i>L. mesenteroides</i> , <i>E. coli</i> , <i>L. innocua</i> : 5, <i>S. cerevisiae</i> ascospore: 2	McDonald et al. [80]
Orange juice	Aerobic microorganisms, yeasts and molds	Pilot plant scale system, co-field flow tubular	35 kV/cm, 59 μ s of tr. time, 1.4 μ s of pulse width, 600 pps, 98 L/h	Aerobic microorganisms: 7 Yeasts and molds: 7	Yeom et al. [144]
Orange juice	Aerobic microorganisms, yeasts and molds	Commercial-scale system, co-field flow tubular	40 kV/cm, 97 μ s of tr. time, 2.6 μ s of pulse width, 1,000 pps, 500 L/h	Aerobic microorganisms: 6 Yeasts and molds: 6	Min et al. [83]
Orange-carrot juice	<i>L. plantarum</i>	Co-field flow tubular, square wave bipolar pulses	28.6, 32.0, and 35.8 kV/cm with tr. time changing from 10.2 to 46.3 μ s	2.5	Rodrigo et al. [111]
Orange-milk mixture	<i>L. plantarum</i>	Bench scale, co-field flow chambers	P1: E:40 \times 10 ⁵ V/m, t: 130 \times 10 ⁻⁶ s, and T < 55 °C P2: E: 40 \times 10 ⁵ V/m, t: 130 \times 10 ⁻⁶ s, 2.5 \times 10 ⁻⁶ s, and 1,358 \times 10 ³ J/L	P1: 2.12 P2: 2.46	Sampedro et al. [115]

Table 1 continued

Food	Microorganism	PEF system	PEF treatment condition	Log reduction	Source
Tomato juice	Aerobic microorganisms, yeasts and molds	Commercial-scale system, co-field flow tubular	40 kV/cm, 57 μ s of tr. time, 2 μ s of pulse width, 1,000 pps, 500 L/h	Aerobic microorganisms: 6 Yeasts and molds: 6	Min et al. [84]
Tomato juice	Naturally occurring microorganisms	Circular treatment chamber, square, exponential decay or bipolar shape	80 kV/cm, 20 pulses, 50 °C + nisin (100 U/mL)	4.4	Nguyen and Mittal [90]
Sour cherry juice	<i>E. coli</i> O157:H7 <i>S. aureus</i> <i>L. monocytogenes</i> <i>P. syringae</i> subs. <i>E. carotovora</i> <i>P. expansum</i> <i>B. cinerea</i>	Batch scale, co-field flow tubular	30 kV/cm, 3 μ s pulse duration, 20 μ s pulse delay time, 500 pps frequency, bipolar square wave pulses	4.53 3.82 3.17 4.69 4.90 5.68 6.62	Altuntas et al. [6]
Apricot nectar	<i>E. coli</i> O157:H7 <i>S. aureus</i> <i>L. monocytogenes</i> <i>P. syringae</i> subs. <i>syringae</i> <i>E. carotovora</i> <i>P. expansum</i> <i>B. cinerea</i>	Batch scale, co-field flow tubular, bipolar square wave pulses	30 kV/cm, 3 μ s pulse duration, 20 μ s pulse delay time, 500 pps frequency	3.10 2.69 2.91 4.07 4.73 5.04 5.74	Altuntas et al. [5]
Peach nectar	<i>E. coli</i> O157:H7 <i>S. aureus</i> <i>L. monocytogenes</i> <i>P. syringae</i> subs. <i>syringae</i> <i>E. carotovora</i> <i>P. expansum</i> <i>B. cinerea</i>	Batch scale, co-field flow tubular, bipolar square wave pulses	30 kV/cm, 3 μ s pulse duration, 20 μ s pulse delay time, 500 pps frequency	4.11 4.02 4.07 3.59 4.27 4.73 4.28	Altuntas et al. [7]
Sour cherry juice, peach and apricot nectar	<i>P. expansum</i> <i>B. cinerea</i>	Batch scale, co-field flow tubulars, bipolar square wave pulses	30 kV/cm, 3 μ s pulse duration, 20 μ s pulse delay time, 500 pps frequency	100% inactivation in spore germination rate and germination tube elongation	Evrendilek et al. [40, 41]
Melon juice	<i>E. coli</i> O157:H7 <i>S. Enteritidis</i> <i>L. monocytogenes</i>	Batch scale, bipolar and square wave	35 kV/cm for 1,709 μ s at 217 Hz, 1,440 μ s and 4 μ s pulse duration	3.71 3.70 3.56	Mosqueda-Melgar et al. [88]

Table 1 continued

Food	Microorganism	PEF system	PEF treatment condition	Log reduction	Source
Watermelon juice	<i>E. coli</i> O157:H7	Batch scale, bipolar and square wave	PEF (35 kV/cm for 1,727 μ s at 188 Hz and 4 μ s pulse duration)	3.56	Mosqueda-Melgar et al. [88, 89]
	<i>S. Enteritidis</i>			3.60	
Pomegranate juice	<i>L. monocytogenes</i>	Bench scale, bipolar square wave pulses	17, 23, 30 kV/cm at 5, 15, 25, 35 °C	3.41	Evrendilek et al. [38]
	<i>E. coli</i> O157:H7			<i>E. coli</i> O157:H7:1.1, 1.7, 2.3 (5 °C)	
	<i>S. aureus</i>			1.5, 2.0, 2.8 (15 °C) 2.0, 2.6, 3.6 (25 °C) 3.3, 4.3, 5.3 (35 °C) <i>S. aureus</i> : 1.0, 1.4, 2.1 (5 °C) 1.4, 1.9, 2.5 (15 °C) 1.9, 2.2, 2.8 (25 °C) 2.0, 2.6, 3.0 (35 °C)	
Carrot juice	<i>E. coli</i>	Parallel-plate electrodes, exponentially decaying wave	1.5 μ s pulse duration, 10 Hz pulse frequency, 0.029 μ F capacitor, 6-mL tr. chamber, 52.5 mL/min flow rate	3.8	Zhong et al. [156]
Formulated carrot juice	Total aerobic mesophilic bacteria	Batch scale, co-field flow tubular, bipolar square wave pulses	27 kV/cm, 3 μ s pulse duration, 20 μ s pulse delay time	4.30	Akin and Evrendilek [3]
	Total mold and yeast			3.42	
	Total enterobacteriaceae			4.46	
Grape juice	<i>E. coli</i> O157:H7	Bench scale, bipolar square wave pulses	4 μ s pulse width 35 kV/cm, 1,000 Hz, 1 ms tr. time	3.57	Garde-Cerdán et al. [46]
	<i>S. cerevisiae</i>			4.0	
Grape juice	<i>K. apiculata</i> ,	Bench scale, bipolar square wave pulses	35.0 kV cm, 303 Hz, pulse width for 1 ms	3.88	Marselles-Foantet et al. [77]
	<i>S. cerevisiae</i> ,			3.94	
	Mix. of <i>LAB</i> (<i>L. plantarum</i> + <i>L. hilgardii</i>)			3.54	
Red and white grape juices	<i>G. oxydans</i>	Circular treatment chamber, triangular shaped pulses	P1: 20 pulses 65 kV/cm (peak-to-peak), 50 °C with 2-h incubation of the juice with 1:3 lyso/chrisin (1:3 ratio of lysozyme and nisin; 0.4 g/100 mL). P2: 51 °C, 20 pulses of 80 kV/cm (peak-to-peak) with nisin (400 U/mL) P3: 20, 65 kV/cm (peak-to-peak), 50 °C to white grape juice with (0.4 g/1,000 mL)	2.24	Wu et al. [141]
	<i>S. cerevisiae</i>			P1: 5.9 P2: 6.2 P3: 4.4	

Table 1 continued

Food	Microorganism	PEF system	PEF treatment condition	Log reduction	Source
Cranberry juice	<i>Byssoschlamys fulva</i> conidiospores	Pilot size, continuous coaxial treatment chamber, exponential decay pulses	30, 35, 40 kV, 19–34 °C, 2–3.3 μs pulse width	<i>B. fulva</i> conidiospores inactivation	Raso et al. [104]
Grape juice	<i>Neosartoria fischeri</i> ascospores			6 log cranberry juice	
Pineapple juice				<1 log tomato juice	
Orange juice				Negligible <i>N. fischeri</i> inactivation	
Apple juice					
Tomato juice					

nonenzymatic browning index (NEBI), hydroxymethylfurfural (HMF), color, organic acid content, and volatile flavor compound measurements showed no significant changes between control and PEF-treated samples [34]. Blended orange–carrot juice mixture processing by PEF (25 kV/cm and 280 μs, and 25 kV/cm and 330 μs) and conventional high temperature short time (HTST 98 °C, 21 s) revealed that even though heat process provided more microbial inactivation, PEF preserved the important quality properties of the juice better [96]. The degradation kinetics of ascorbic acid and shelf-life studies of orange–carrot juice stored at 2 and 10 °C resulted in lower ascorbic acid degradation by PEF with shelf-life extension of 50 days at 2 °C [132]. Commercial-scale PEF treatment of orange juice at 40 kV/cm for 97 μs compared with thermal treatment at 90 °C for 90 s for microbial inactivation and quality parameters showed that retention of important quality parameters were higher with PEF than that with heat treatment [85]. Changes in the color values were less affected by PEF. There was no significant change in HMF content of the juice pasteurized or treated by PEF compared to untreated orange juice [30].

In a study conducted to determine the effect of different processing methods including high pressure, PEF, low pasteurization (LPT), high pasteurization (HPT), HPT plus freezing (HPT + F), and freezing (F) on bioactive compounds (vitamin C, carotenoids, and flavanones) and DPPH radical scavenging capacity (RSC) of orange juice, PEF treatment did not modify individual or total carotenoid content and did not modify flavanone content [117]. The combination of PEF (4-μs-wide bipolar pulse, 35 kV/cm electric field strength, and 1,200 pps frequency) and HTST (90 °C for 30 s) on processing of apple juice revealed that these measured variables were less affected by the PEF treatment than by the thermal pasteurization [1]. When the effect of PEF and HSTS was compared to each other for the changes in pH and color, it was presented that pH was preserved better with PEF than HTST [28]. Changes in color, pH, acidity, and soluble solids of apple juice samples were compared with ultra-high temperature (UHT; 115, 125 and 135 °C for 3 and 5 s) and PEF (between 33 and 42 kV/cm with frequencies of 150, 200, 250, and 300 pps), and it was found that measured characteristics were all less affected by PEF than by UHT when compared with the untreated juice [118].

In order to determine the effect of PEF alone and in combination with cinnamon essential oil on the physical properties of apple juice, PEF processing at 0, 17, 20, 23, 27, and 30 kV/cm electric field strengths and cinnamon essential oil at 0, 10, and 20 μL/mL concentrations was applied. PEF application alone did not cause any changes in physical properties ($p > 0.05$). Depending on cinnamon essential oil concentration, some physical properties

Table 2 Overview of the inactivation of enzymes in fruit juices by PEF treatment

Enzyme	Medium	PEF system	PEF treatment condition	Reduction (%)	Source
PFO	Apple juice	Bench scale, rectangular shape bipolar pulse, 0.65 cm gap distance	38.5 kV/cm and 300 pps combined with 50 °C	70%	Sanchez-Vega et al. [118]
POD, PPO	Apple juice	P1: Bench scale P2: Pilot plant scale	P1: 60 °C + PEF (30 kV/cm, 100 kJ/kg) P2: 40 °C + PEF	P1: 100% for POD and P2: 48% for PPO	Schilling et al. [123]
PME	Orange juice	Pilot plant scale system, co-field flow tubular PEF treatment chamber, stainless steel tubular electrode, electrode gap: 1.0 cm	35 kV/cm, 59 µs of treatment time, 1.4 µs of pulse width, 600 pps, 98 L/h	88%	Yeom et al. [144]
PME	Orange juice	Co-field flow tubular PEF treatment chamber, stainless steel electrode, electrode gap: 0.2 cm	20–35 kV/cm, 2.0 or 2.2 of pulse width, 700 pps, 0.42, 0.31 mL/s	90%	Yeom et al. [143]
Pectin methyl esterase (PME)	Tomato juice	Gene electroporator (Bio-Rad Laboratories)	24 kV/cm, 800 µs of treatment time, exponential decay	93.8%	Giner et al. [47]
PG PME	Tomato juice	Circular treatment chamber, square, exponential decay or bipolar shape	40 pulses of 87 kV/cm at 50 °C	No inactivation for PG 55% for PME	Nguyen and Mittal [90]
Lipoxygenase	Tomato juice	Commercial-scale system, co-field flow tubular PEF treatment chamber, boron carbide tubular electrodes, electrode gap: 1.27 cm	40 kV/cm, 57 µs of treatment time, 2 µs of pulse width, 1,000 pps, 500 L/h	54%	Min and Zhang [82]
Lipoxygenase	Tomato juice	Co-field flow tubular PEF treatment chamber, electrode gap: 0.292 cm	30 kV/cm, 60 µs of treatment time, 3 µs of pulse width, 1 mL/s, 50 °C	88.1%	Min et al. [84]
Lipoxygenase	Tomato juice	Pilot plant scale, continuous, co-field flow, square wave bipolar	40 kV/cm for 57 µs	53%	Min et al. [86]
PPO Lipoxygenase	Tomato juice	Coaxial treatment chamber	24 kV/cm for 320 and 962 µs	69% for PPO 88% for lipoxygenase	Luo et al. [75]
Peroxidase (POD), PME, PG	Tomato juice	Bench scale, co-field flow treatment chamber, square wave bipolar pulses	35 kV/cm, 1,500 µs 4 µs pulses at 100 Hz	97% for POD 82% PME 12% PEG	Aguiló-Aguayo et al. [2]
POD	Carrot juice	Continuous flow bench-scale PEF unit, co-field flow treatment chamber with 0.29 cm gap distance, square wave bipolar pulse	35 kV/cm for 1.000 µs applying 6 µs pulse width at 200 Hz	73%	Quitão-Teixeira et al. [103]
PPO, POD	White grape juice	Bench scale, co-field flow treatment chamber, square wave bipolar pulses	25–35 kV/cm, 200–1,000 Hz, 1–5 ms treatment time	100% for PPO 50% POD	Marselles-Fontanet et al. [78]

changed, but inactivation of *E. coli* O157:H7 increased with added cinnamon essential oil and electric field strength (Table 3).

Processing of sour cherry juice, apricot, and peach nectars by different electric field strengths (0, 17, 20, 23, 27, and 30 kV/cm) and different treatment times (0, 66, 105, 131, 156, and 210 µs) caused no significant difference in pH, TA, °Brix, conductivity, color (L^* , a^* and b^*), NEBI, metal ion concentration, ascorbic acid, and

beta-carotene retention as well as in the metal ion concentrations ($p > 0.05$) [5–7].

The effects of PEF (pulse polarity, pulse width, and frequency) on oxidative enzymes and color of fresh carrot juice were studied by response surface methodology (RSM). There was a linear relationship between electrical conductivity and temperature of the carrot juice. The color coordinates did not change significantly [103]. PEF processing of formulated carrot juice-based beverage

containing freshly squeezed carrot juice, 70% demineralised whey protein concentrate, oligofructose, sugar, and citric acid reported that PEF processing did not cause any significant change in physical properties and vitamin C concentration ($p > 0.05$) [3].

Combination of different hurdles such as moderately high temperatures (<50 °C), antimicrobial compounds, and PEF was tested for tomato juice processing. No reduction was detected in vitamin C content due to the treatments [90]. It was shown that PEF-processed juice retained more ascorbic acid than thermally processed juices at 4 °C for 42 days, and no significant difference was observed in the concentration of lycopene, °Brix, pH, or viscosity between thermally and PEF-processed juices during the storage. Sensory evaluations indicated that flavor and overall acceptability of PEF-processed juice were preferred to those of thermally processed juice ($p < 0.05$) [87]. In another study, it was explained that PEF-treated tomato juice showed higher values of lightness than thermally processed and untreated juice throughout storage time ($p < 0.05$) [2].

The pomegranate juice was processed with PEF processing (0, 17, 23, and 30 kV/cm electric fields strengths) at 5, 15, 25, and 35 °C, and it was found that the amount of total phenolic substances (TPS), antioxidant capacity, and total anthocyanin content decreased with increasing processing temperature (Fig. 1). Especially, the amount of microbial inactivation at 25 and 35 °C was significantly lower than that at 5 and 15 °C ($p < 0.05$) (Fig. 2) [38].

Changes in several physicochemical properties were studied on the grape juice processed by thermal and PEF treatments. No significant changes were noticed on physicochemical properties; however, the concentration of lauric acid diminished after PEF processing and the concentration of some amino acids varied after both treatments [46].

Cranberry juice was processed by either PEF (20 kV/cm and 40 kV/cm for 50 and 150 μ s) or thermal treatment (at

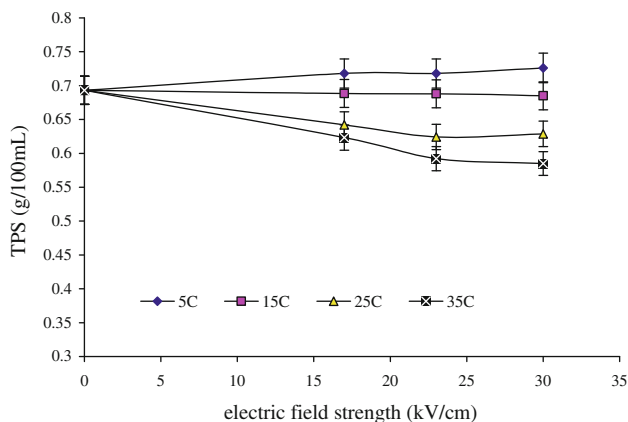


Fig. 1 Changes in the total phenolic content of pomegranate juice processed with 17, 23, 27, and 30 kV/cm electric field strengths

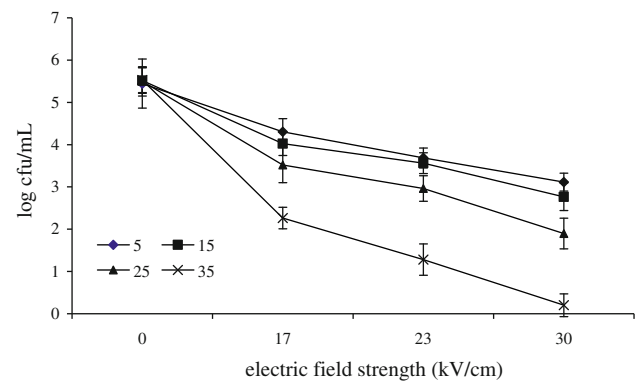


Fig. 2 Survival of *E. coli* O157:H7 on pomegranate juice processed with 17, 23, 27, and 30 kV/cm electric field strengths

90 °C for 90 s). Higher field strength and longer treatment time reduced more viable microbial cells, and the overall volatile profile of the juice was not affected by PEF treatment, but it was affected by thermal treatment [65].

It can be concluded from the previous studies that generally PEF treatment alone does not adversely affect the physical, chemical, and sensory properties of fruit juices. In most cases, PEF provides better sensory properties and longer and/or equal shelf-life compared to heat processing. However, temperature increase during PEF processing must be monitored, because studies revealed that depending on the temperature increase, physical, chemical, and sensory properties of food products can be adversely affected.

Moderate Electric Fields (MEF)

Application of electric fields on biological materials has gained popularity in food and bioproduct technology. These applications, which are based on either the non-thermal effects of electricity or the combined effects of electrical and thermal phenomena, are described as MEF treatment, to distinguish them from PEF treatment. MEF is usually used for the processes that involve electric fields less than or equal to 1,000 V/cm, which would be too low to fall in the pulsed electric field (PEF) or electroporation ranges, with or without heating effect. It is known that high electric fields can cause either reversible or irreversible rupture of cell membranes [15–17, 43, 122], and it affects the extraction yield on fruit juice processing [50].

The moderate electric field application (MEF) with field strengths under 100 V/cm enhances extraction and expressing processes in different food materials [67, 97, 138, 145, 147, 156, 158]. Previous studies reported [44, 149] that alternating electric field application at 220 V voltage and at 50 Hz (industrial frequency) increased the juice yield of prunes, apples, and grapes and also enhanced the juice extraction from sugar beet [68].

Table 3 Inactivation of *E. coli* O157:H7 inoculated into apple juice treated by PEF and cinnamon essential oil

	Cinnamon essential oil concentration ($\mu\text{L/mL}$)		
	0	10	20
Control	8.051 ± 0.61^a	7.57 ± 0.08^b	8.44 ± 0.42^a
Control + cinnamon e.o	0.00 ± 0.00^a	0.15 ± 0.05^b	0.48 ± 0.30^b
17 kV/cm	0.55 ± 0.12^a	1.47 ± 0.07^b	1.42 ± 0.38^b
20 kV/cm	1.32 ± 0.35^a	2.19 ± 0.23^b	2.78 ± 0.55^b
23 kV/cm	3.1 ± 0.39^a	3.58 ± 0.35^a	3.56 ± 0.37^a
27 kV/cm	4.02 ± 0.43^a	4.43 ± 0.32^a	5.36 ± 0.32^b
30 kV/cm	4.48 ± 0.24^a	5.58 ± 0.03^b	6.29 ± 0.15^c

Data in the same row with different superscript letters are significantly different ($p \leq 0.05$)

Table 4 Effects of moderate electric fields on yield

Material	Type of electroporation unit	Application conditions	Control yield (%)	Conventional mash heating yield (%)	Electroporation yield (%)	Increase in extraction yield (%) by EP	Authors
Orange (Valencia)	Drum type	27 V/cm, 10 s	47.02 ± 1.31	–	51.13 ± 1.25	8.74	(Demirdoven and Baysal [35])
Carrot (Nantes)	Drum type	22 V/cm, 60 s	49.57 ± 0.69	–	52.3 ± 1.28	5.5	(Baysal et al. [12])
Pomegranate (Hicaz)	Drum type	60 V/cm, 15 s	58.53 ± 0.3	–	62.67 ± 0.4	7.0	(Baysal et al. [13])
Grape (Foça Karası)	Box type	75 V/cm, 70 °C	79.2 ± 0.9	83.32 ± 1.16	87.21 ± 1.2	10.11	(Baysal et al. [14])
Sour cherry (Kütahya)	Box type	75 V/cm, 60 °C	79.19 ± 0.8	82.75 ± 0.54	86.47 ± 0.45	9.19	(Baysal et al. [13])
Kiwi (Hayward)	Box type	75 V/cm, 65 °C	80.45 ± 0.9	87.43 ± 1.16	86.47 ± 1.2	7.48	(Baysal et al. [14])
Tomatoes (Rio grande)	Continuous pipe type	68 V/cm, 1.5 s, 32 mm electrode gap	–	18.82	19.35	–	(Yildiz [144])

Electrotechnologies used for the extraction of juice from fruits and vegetables have been reported since the late 1940s [44] where the permeability of the biological tissue cells increases after the application of the electric field. This phenomenon is known as electroporation [91]. The microstructure of plant and animal tissues changes considerably during electrical treatment as a result of contraction and gapping of cell vacuoles [42].

MEF treatment can be used in extraction processes with the aim of improving yield of juice or pulp by destroying the plant tissue. In addition to the application in fruit juice production, it also reduces the time required for the extraction of beet juice and improves the juice yield of sugar beet. In tomato paste industry, pulp yield is increased and evaporation time is reduced [50]. Researches have been continued intensively on the effects of increasing yield and enhancing the quality characteristics of juice in fruit and vegetable juice production (Table 4).

Juice extraction is a slow and highly energy-consuming step in the production of fruit and vegetable juices; thus,

various methods have been tried to improve efficiency and increase yield. These techniques include variation of particle sizes in press materials or process speed variation; vacuum-assisted pressing enzymatic treatment, and press-aids [48]. In previous studies, MEF application improved juice yield by 10% in citrus juice production compared to conventional method. This method facilitates pressing and increases the yield by 1.5–4.5% in apple juice production; also, filtration and separation processes became easier. MEF was used in apple juice production as pretreatment before pressing, and the yield of juice increased by 10–15% [44, 81, 126]. In grape juice production, this application increases the yield by 0.5–2% [119].

Most of the researches indicated that in juice processing, thermal treatment significantly increases the juice yield. However, there is an additional effect on juice yield caused by the electric current. Table 4 shows the fruit and vegetable juice yields and MEF application conditions for different treatment samples. Different types of electroporation units could be used for the structure of fruits or vegetables

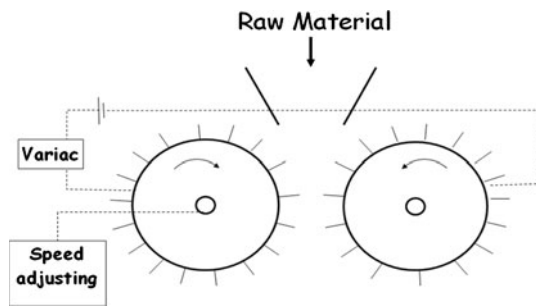


Fig. 3 Drum-type moderate electric field system

and also according to the production method. Drum-type MEF systems can be used for whole materials, and box-type MEF system can be used for fruit mashes. For example, a pilot-scale drum-type MEF system (Fig. 3) was used for whole materials, and no significant temperature increase ($<2\text{ }^{\circ}\text{C}$) was measured during MEF application. In orange juice production, oranges were subjected to a drum-type MEF system; after extraction processes, the yield of orange juice (27 V/cm–10 s) was calculated as 51.13% in MEF group and 47.02% in control group. MEF application increased juice yield 8.74% in orange juices [35]. In carrot juice production, yield was calculated as 52.3% in a drum-type MEF application and 49.57% in control samples. Thus, yield was increased by 5.5% with MEF treatment in carrot juice (22 V/cm–60 s) production [11]. In pomegranate juice, yield increased by 7.0% with a drum-type MEF application at 60 V/cm voltage gradient for 15 s [13]. It was reported that at lower processing temperatures, the permeabilization of cells, which is desirable in juice extraction, occurs mainly by the electrical effect.

Box-type MEF systems can be used with the combination of heat for fruit mashes. In our researches, moderate temperatures between 60 and 70 $^{\circ}\text{C}$ were used for MEF applications. Grape (75 V/cm, 70 $^{\circ}\text{C}$), sour cherry (75 V/cm, 60 $^{\circ}\text{C}$), and kiwi (75 V/cm, 65 $^{\circ}\text{C}$) mashes were subjected to a box-type MEF unit (Table 4) [12, 13].

MEF treatments also affected the functional components as a result of electroporation. Previous studies indicated that a significant increase was found in ascorbic acid and total phenolic contents of samples after MEF application. In orange juice production, nearly 4.0% increase in ascorbic acid content and 14% increase in total phenolic content were observed after MEF application. In addition, 18% increase in pectin content of orange juices was determined after MEF application [35]. Thus, serum separation, which is an important problem of orange juice production, can be decreased. Similarly, pectin content was also increased by 7.73% in carrot juices with MEF application. Nutritive value of juices increased as a result of improved disintegration of the plant cells [11].

Fruits that are rich in antioxidant activity, such as pomegranate, red grape, and sour cherry, were used as raw material, and the effects of MEF application on total phenolic and anthocyanin contents were studied, and the highest antioxidant capacities evaluated for pomegranate juices after MEF process [13]. In addition, phenolic content of pomegranate juices nearly increased by 9% with MEF application compared to control samples. Also, the total anthocyanin content of MEF-applied grape juice increased more than 100%, and more than 25% increases were determined for phenolic contents of grape juices [12]. And similar results are available in the literature for sour cherry juices. Compared to thermal heating treatment, the MEF-processed samples had nearly 2.8% higher total anthocyanin content for sour cherry juices [13]. In tomato puree production, lycopene content was found higher for MEF-processed samples (273.9 $\mu\text{g/g}$) than the conventionally heated tomato puree samples (186.0 $\mu\text{g/g}$) [146].

Effects of MEF applications on microbiological load were also investigated. Orange samples were subjected to MEF application (27 V/cm voltage gradient for 10 s) and compared with untreated ones. Total viable microbial count (TVC) was found as 2×10^2 cfu/mL for MEF-treated and 4×10^2 cfu/mL for control samples. There was no significant temperature increase during electrical application [35]. In addition, initial number of *Aspergillus niger* was significantly reduced after MEF application in tomato puree production [144]. As a result of electroporation, the microstructure of plant tissues changes considerably during electrical treatment as a result of contraction and gapping of cell vacuoles [35, 44, 91]. According to these results, it seems that microbial reduction can be achieved by MEF application. As a result, besides increase in yield, MEF application also provides increase in cell wall permeability so that functional components can be transferred to juice easier. It was concluded that in order to obtain optimum fruit juice yield, designing of electroporation equipments for different fruits and vegetables and also determining process conditions for MEF treatment (voltage gradients and time) are important factors that need to be considered.

Ohmic Heating

Theory and Implementation

Ohmic heating is an electroheating method that is based on the passage of electrical current through a food product that serves as an electrical resistance. Electrical energy applied is converted to heat instantly inside the food, the amount of which is directly related to the current induced by the voltage gradient in the field and the electrical conductivity

[121]. Ohmic heating has a fast heating mechanism, and its rate depends on the resistance of the food and the voltage gradient applied. It could serve as homogeneous heating for food materials when homogeneous electrical current is passed through their homogeneous structure. The key to the successful implementation of an ohmic process is the knowledge on the rate of heat generation and the overall electrical conductivity changes in the food material [70]. It is crucial to evaluate the influence of key variables such as electrical field strength and sample conductivity to ensure a completely safe ohmically heated product [76, 151]. The heating time decreases as a result of higher heating rates resulting from the higher voltage gradient applied [59].

Ohmic process is not applicable to the food product having electrical conductivity values below 0.01 S/m and above 10 S/m [95]. Electrical conductivities of fruits and vegetables are high enough in general to obtain efficient heating during ohmic treatments [59, 60]. Since many foods are multicomponent in nature, studies on the effect of composition on overall electrical conductivity changes are required to characterize the ohmic heating behavior of such systems better [20].

Ohmic heating can be applied to different foods, such as blanching of vegetables [62], heating of fruit juices [58, 59, 70, 92, 148], nectars, and purees [19, 60, 149], and cooking [21, 76, 95, 151] and thawing of meat products [22]. Its application especially to liquid food materials is practical

and commercially applicable. Fruit purees are to be potentially used in baby food productions. The thermal processes applied to the baby foods are critically important to guarantee their microbiological safety. The data on the electrical conductivity changes of fruit purees during ohmic heating are very important in designing ohmic heating systems to be used in baby food lines [62]. Palaniappan and Sastry [92] reported that the electrical conductivities of juices increased linearly by decreasing insoluble solid contents. Castro et al. [26, 27] suggested that electrical conductivity decreases with increase in solids and sugar content of strawberry-based products. Moreover, it was reported that the rate of temperature change for the apricot puree was higher than the peach puree at all voltage gradients applied due to the acidity and pulp content differences between the purees [60]. In addition, the heating times of fruit juice concentrates (orange, apple, and sour cherry juice concentrates having 20–60% soluble solids) increased as a result of decreasing heating rates at high concentrations [58, 59].

The typical basic ohmic heating device consists of a power supply, an isolating transformer, a variable transformer, treatment chamber, and a microprocessor board (Fig. 4) [57]. The ohmic heating treatment chambers can be cylindrical or rectangular in shape in different dimensions. Treatment chamber can be operated in continuous or in static modes. Continuous ohmic heating

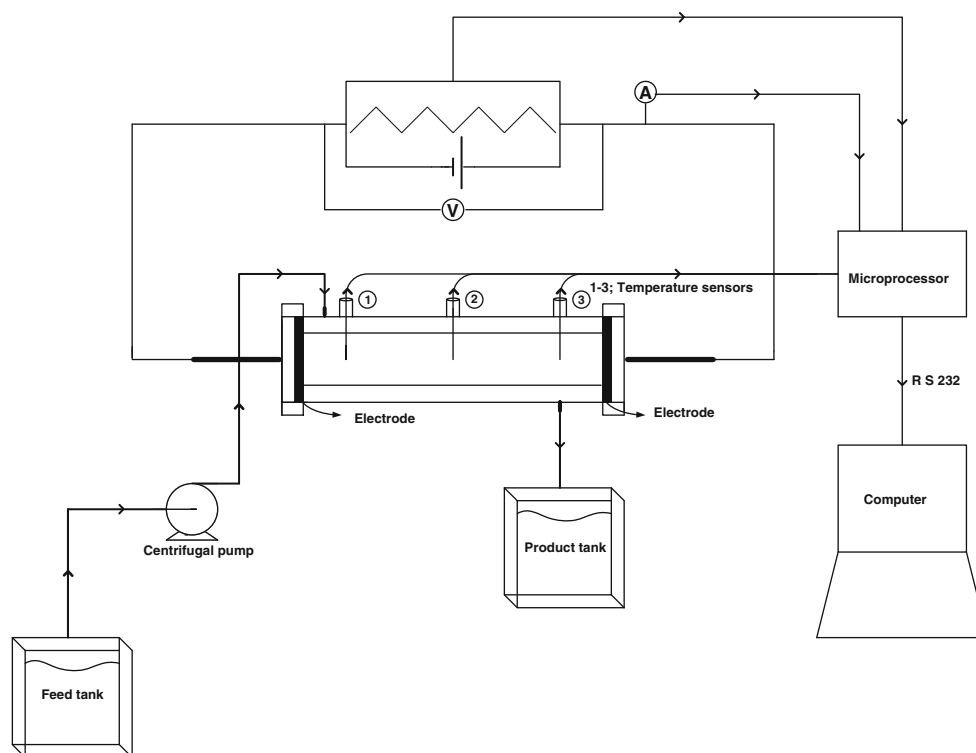


Fig. 4 Schematic diagram of continuous ohmic heating system [53]

systems include the flow system and cooling parts as well as the main parts of the ohmic heating system. They have several ohmic heater columns, each comprising insulating coverings (such as PTFE) and a single cantilever electrode. These columns are structured vertically or inclined to allow for an upward flow of product and are connected with insulated tubes [128]. The real-time measurement and the total power input to the sample at any given time are crucial to obtain efficient process control.

Ohmic heating has some advantages over conventional heating methods. Since the heating takes place as volumetric, the temperature increase is more uniform than conventional heating methods. It does not need convective and conductive heat transfer mechanisms in the heating chamber. It reduces the cold point possibility, thermal damage, and nutritional losses and increases the overall lethality in the mixture. It is a faster heating method than conventional methods. Since the degradation of proteins and fouling in the equipment surfaces during ohmic heating are less compared to conventional heating methods, the cleaning-up and maintenance costs are relatively lower [108, 128]. On the other hand, there are still problems arising in ohmic heating systems. The system needs proper electrical insulation, accurate process control system, and well-trained personnel. A disadvantage related to the type of food that can be processed occurs in the presence of nonconductive parts or some components such as fat globules [114]. If the temperature increase is highly rapid and uncontrollable, it creates the possibility of ‘runaway’ heating [9].

The most important parameter in ohmic heating of liquid food product is its electrical conductivity behavior. The determination of electrical conductivity changes and system performance coefficients during ohmic heating is important in the design of ohmic heaters. The effects of different types of electrodes on energy loss in ohmic heaters and the problems brought up by the reactions that occurred by using them must be further studied. In industrial-scale production, the voltage gradient, frequency, temperature range, concentration, and electrode type used must be taken as critical design parameters [60]. The variations in the operation conditions during ohmic treatment could result in divergence in the heating curves. The control of the voltage during heating is necessary to prevent the runaway heating [110].

Data on electrical properties of liquid foods are especially important in their ohmic processing as a whole product or fluid medium [34, 99]. The instantaneous values of current and voltage recorded during ohmic heating lead to the determination of electrical conductivities at various temperatures, provided the cell dimensions are known [73, 108]. Electrical conductivity of the samples can be

calculated from voltage and current data using the following equation [139, 140]:

$$\sigma = \frac{L}{AR} \quad (10)$$

where σ is the electrical conductivity (S/m), L is the length of the sample (m), A is the cross-sectional area of the sample (m²), and R is the resistance (ohm).

Electrical conductivity of food depends on both the system parameters (temperature, voltage gradient, frequency, etc.) and the properties of food (acidity, composition, concentration, etc.). As the temperature increases, the electrical conductivity value increases [26, 61, 63, 92]. Furthermore, concentration dependency of the electrical conductivity of the juices is explained by the increased drag for the movement of ions by increasing the concentration nonlinearly [58]. The electrical conductivity values of fruit juice concentrates (apple, sour cherry, and orange) are in the range of 0.1–1.6 S/m, having an increasing trend by decreasing the concentration (20–60% soluble solids). The acidity of the juices enhances their electrical conductivities. On the other hand, the electrical conductivities of the liquid solutions decreased as the sugar content increased. Sugar content and the nature of the other components may cause different electrical conductivities between the juice samples compared. Similarly, the electrical conductivity of fruit purees is strongly dependent on temperature, ionic concentration, and pulp content [58, 60].

In addition to these variables, electrical field strength can be taken as an important process variable for electrical conductivity changes during ohmic heating of fruit pulps. The electrical conductivity of strawberry pulp increases with temperature and electric field strength [27, 66]. The electrical conductivity also changed significantly with heating temperature and the frequency [127]. The EC is higher at 10 kHz than at 1 kHz in all the juices, indicating that heating rate increases with increasing frequency.

Ohmic Heating Processing of Different Fruit Juices

Researches on a variety of liquid foods showed that ohmic heating did not cause further quality changes than conventional heating methods, and it could be used as an alternative heating method for pumpable fruit and vegetable products. To assess the possible electrical effect of ohmic heating on some quality properties, the matching of the thermal history during ohmic and conventional heating is essential.

Vikram et al. [137] studied thermal degradation kinetics of vitamin C and color in orange juice heated by conventional and electromagnetic methods including infrared, microwave, and ohmic heating. They reported that ohmic heating resulted in the highest retention of vitamin C.

In another study involving ohmic heating processing (10–40 V/cm) of pomegranate juice, it was revealed that there was no electrical effect rather than thermal effects during ohmic heating. On the other hand, ohmic heating resulted in fewer amounts of browning during heat treatment rather than conventionally heating [148].

The ohmic heating can also inactivate enzymes in fruit and vegetable products. The equal thermal histories of the samples (conventional and ohmically processed) are generally applied to determine whether there was an additional inactivation caused by the presence of an electric field, thus eliminating temperature as a variable. The presence of an electric field does not cause an enhanced inactivation to alkaline phosphatase, pectinase, and β -galactosidase, it causes significant reduction in the time needed for inactivation of lipoxygenase and polyphenoloxidase [25]. The critical deactivation temperature of polyphenoloxidase enzyme (PPO) in grape juice at higher voltage gradients is lower, probably because of the faster increase in electrical conductivity at higher voltage gradients causing higher deactivation in PPO [63].

Ohmic treatment can be successfully used as an alternative blanching method for vegetable purees, resulting in lower enzyme inactivation times and high retention of color attributes [56]. The peroxidase enzyme in the pea puree can be inactivated at lower critical inactivation times with less browning in the case of ohmic blanching at voltage gradients above 30 V/cm than water blanching. On the other hand, ohmic heating causes browning of pre-blanching spinach puree more than conventional water heating for the same temperature range (60–90 °C) and the same holding times [146].

The determination of changes in rheological properties of liquid foods during ohmic heating is important in the design of continuous ohmic heating units. Studies conducted on fruit juices show that ohmic heating does not result in different effects on change in rheological behavior of fruit juice, probably due to lower concentrations of degradable constituents by thermal treatments [19]. Since similar rheological constants are obtained with ohmic and conventional heating methods, there is no electrical effect of ohmic heating on rheological properties of fluid foods rather than thermal effects [148].

Complete inactivation of bacteria, yeast, and mold and reduced pectin esterase activity by 98% can be achieved during ohmic treatments [70]. It was reported that the retention of vitamin C in orange juice pasteurized by ohmic heating is high, and sensorial attributes between fresh and ohmic-heated orange juice are similar [70]. In addition to this, survival curves and calculated *D*-values for *Alicyclobacillus acidoterrestris* spores in orange and apple juices show significantly higher lethality with ohmic heating than conventional heating [11].

Ohmic heating could enhance the mass transfer at comparably low temperatures. The magnitude of frequency and wave form in addition to temperature and voltage gradient applied during ohmic heating affects the fruit juice yield. As the frequency applied decreases, the juice yield from apple increases [74]. On the other hand, the juice yield increases with the pretreatment temperature during ohmic heating, and ohmic heating requires less energy input for the extraction of juice [138, 139].

Research is needed on methods for identification, measurement, and testing of cold spots and overheated regions during ohmic heating of multiphase foods [120]. The fully commercialization of the ohmic heating technology depends in part on the development of adequate safety and quality assurance protocols in order to obtain an approved filing of the process with the FDA for all food materials possible [141].

Final Remarks

Studies related to processing fruits and fruit juices by PEF, MEF, and ohmic heating involve different food products and processing conditions. The basics of these technologies involve application of electric current through food materials, but due to the magnitude of electric field and/or system design, these technologies are considered as different food-processing methods. PEF processing can efficiently be applied to low-viscosity, high-acidity food products due to ions carrying electric fields through processing. Moreover, other key factors for the PEF processing are viscosity and particle size of the food products along with the ability to spore and enzyme inactivation.

MEF processing includes application of much lower electric current to food compared to PEF. In most of the cases, it has been successful for the extraction of some compounds from plant tissue. However, appropriate PEF-processing systems need to be developed to evaluate the potential of the technology.

Ohmic heating due to system design can be applied to different food products including particle containing ones for pasteurization and blanching, but more data are needed to evaluate its potential. In contrast to PEF processing, temperature increases during ohmic heating processing. This can have advantages as it provides microbial and enzyme inactivation; however, fouling and starch gelatinization as well as increase in conductivity during ohmic processing are the major problems in need to be solved. Moreover, the commercialization of these technologies is still not realized, because the data collected in bench scale should be checked with pilot plant scale. Studies related to novel technologies should involve achieving the microbial inactivation, determination of changes in the physical,

chemical, and sensory properties, shelf-life studies, mass transfer, structural and physicochemical changes, consumer acceptance as well as cost-benefit analyses at the same time determining whether these technologies can be used in the food industry. On the other hand, the development of adequate safety and quality assurance protocols is essential to obtain an approved filing of these processes with the legal requirements prior to the setting-up of the industrial systems. Further researches such as interaction of food matrices with electric field strength on molecular level, screening of both spoilage and pathogenic microorganisms, standardizing and quantifying PEF, MEF, and ohmic processing variables and their contribution to the mechanism of inactivation, and the effect of PEF, MEF, and ohmic processing on enzymes and inactivation mechanism are required in several areas regarding electrotechnologies [106].

Conducting collaborative studies with newly developed high-capacity equipment is also required to inactivate most resistant enzymes and surrogate microorganisms. Because of equipment variations (continuous vs static), applied pulse wave forms (exponential, logarithmic, monopolar vs bipolar), and scaling variations (bench scale vs pilot scale), sometimes it is hard to compare the experimental results. Although it is very hard to solve equipment variations, it will be appropriate to create a multi-team database to more effectively compare results.

References

- Aguilar-Rosas SF, Ballinas-Casarrubias ML, Nevarez-Moorillon GV, Martin-Belloso O, Ortega-Rivas E (2007) Thermal and pulsed electric fields pasteurization of apple juice: effects on physicochemical properties and flavour compounds. *J Food Eng* 83(1):41–46
- Aguiló-Aguayo I, Soliva-Fortuny R, Martín-Belloso O (2007) Comparative study on color, viscosity and related enzymes of tomato juice treated by high-intensity pulsed electric fields or heat. *Euro Food Res Technol* 227(2):599–606
- Akin E, Evrendilek GA (2009) Effect of pulsed electric fields on physical, chemical and microbiological properties of formulated carrot juice. *Food Sci Technol Int* 15:275–282
- Alberts B, Johnson A, Lewis J, Raff M, Roberts K, Walter P (2002) *Molecular biology of the cell*, 4th edn. Garland Science, New York
- Altuntas J, Evrendilek GA, Sangun MK, Zhang QH (2009) Effect of pulsed electric fields on aroma compounds and sensory properties of apricot nectar. *International Conference on Bio & Food Electrotechnologies*, 22–23 October 2009, Compiègne
- Altuntas J, Evrendilek GA, Sangun MK, Zhang QH (2010) Effects of pulsed electric field processing on the quality and microbial inactivation of sour cherry juice. *Int J Food Sci Technol* 45(5):899–905
- Altuntas J, Evrendilek GA, Sangun MK, Zhang QH (2011) Processing of peach nectar by pulsed electric fields with respect to physical and chemical properties and microbial inactivation. *J Food Process Eng* 34(5):1506–1522
- Anderson DR (2008) Ohmic heating as an alternative food processing technology. Food Science Institute, College of Agriculture, Kansas State University Manhattan, Kansas, MSc thesis
- Anonymous (2000) Kinetics of microbial inactivation for alternative food processing technologies. US Food and Drug Administration, Center for Food Safety and 01 Apr 2009
- Barbosa-Canovas GV, Gongora-Nieto MM, Pothakamury UR, Swanson BG (1999) *Preservation of foods with pulsed electric field*. Academic Press, San Diego
- Baysal AH, Icier F (2010) Inactivation kinetics of *Alicyclobacillus acidoterrestris* spores in orange juice by ohmic heating: the effects of voltage gradient and temperature on the inactivation. *J Food Prot* 73(2):299–304
- Baysal T, Demirdöven A, Rayman A (2009) Elektrolizmoliz tekniğinin meyve ve sebze suyu verimi ve kalitesi üzerine etkileri, 6. Gıda Mühendisliği Kongresi, Kemer, Antalya. *Proceeding Book*, Turkey, pp 91–96
- Baysal T, İçier F, Yıldız H, Demirdöven A (2007) Nar ve vişne suyu üretiminde elektrolizmoliz uygulamasının verim ve kalite özellikleri ile durultma koşulları üzerine etkileri. *EBİLTEM Research Project 2007/Bil-027*
- Baysal T, Rayman A, Demirdöven A (2009) Yield and quality effects of electropulsation applications on carrot juice. *International Conference on Bio and Food Electrotechnologies* 22–23 October 2009, Compiègne
- Bazhal MI, Ngadi MO, Raghavan VGS (2003) Influence of pulsed electropulsation on the porous structure of apple tissue. *Biosys Eng* 86(1):51–57
- Bazhal M, Lebovka N, Vorobiev E (2003) Optimisation of pulsed electric field strength for electropulsation of vegetable tissues. *Biosys Eng* 86(3):339–345
- Bazhal M, Vorobiev E (2000) Electrical treatment of apple cossettes for intensifying juice pressing. *J Sci Food Agric* 80:1668–1674
- Bendicho S, Barbosa-Cánovas GV, Martín O (2002) Milk processing by high intensity pulsed electric fields. *Trends Food Sci Technol* 13:195–204
- Bozkurt H, Icier F (2009) Rheological characteristics of quince nectar during ohmic heating. *Int J Food Prop* 12(4):844–859
- Bozkurt H, Icier F (2010) Electrical conductivity changes of minced beef-fat blends during ohmic cooking. *J Food Eng* 96:86–92
- Bozkurt H, Icier F (2010) Ohmic cooking of ground beef. *J Food Eng* 96:481–490
- Bozkurt H, Icier F (2011) Ohmic thawing of frozen beef cuts. *J Food Process Eng*. doi:10.1111/j.1745-4530.2009.00569.x
- Castro AJ, Barbosa-Canovas GV, Swanson BG (1993) Microbial inactivation of foods by pulsed electric fields. *J Food Process Preserv* 17(1):47–73
- Castro AJ, Swanson BG, Barbosa-Cánovas GV, Zhang QH (2001) Pulsed electric field modification of milk alkaline phosphatase activity. In: Barbosa-Cánovas GV, Zhang QH (eds) *Electric fields in food processing*. Technomic, Lancaster, pp 65–82
- Castro I, Macedo B, Teixeira JA, Vicente AA (2004) The effect of electric field on important food-processing enzymes: comparison of inactivation kinetics under conventional and ohmic heating. *J Food Sci* 69(9):C696–C701
- Castro I, Teixeira JA, Salengke S, Sastry SK, Vicente AA (2003) The influence of field strength, sugar and solid content on electrical conductivity of strawberry products. *J Food Process Eng* 26(1):17–30

27. Castro I, Teixeira JA, Salengke S, Sastry SK, Vicente AA (2004) Ohmic heating of strawberry products: electrical conductivity measurements and ascorbic acid degradation kinetics. *Innov Food Sci Emerg Technol* 5:27–36
28. Charles-Rodríguez AV, Nevárez-Moorillón GV, Zhang QH, Ortega-Rivas E (2007) Comparison of thermal processing and pulsed electric fields treatment in pasteurization of apple juice. *Food Bioprod Process Eng* 85(2):93–97
29. Cho H-Y, Yousef AE, Sastry SK (1996) Growth kinetics of *Lactobacillus acidophilus* under ohmic heating. *Biotechnol Bioeng* 49:334–340
30. Cortes C, Esteve MJ, Frigola A (2008) Color of orange juice treated by High Intensity Pulsed Electric Fields during refrigerated storage and comparison with pasteurized juice. *Food Control* 19(2):151–158
31. Coster HG, Zimmermann U (1975) The mechanism of electric breakdown in the membranes of *Valonia utricularis*. *J Membr Biol* 22:73–90
32. Cserhalmi Zs, Vidacs I, Beczner J, Czukur B (2002) Inactivation of *Saccharomyces cerevisiae* and *Bacillus cereus* by pulsed electric fields technology. *Innov Food Sci Emerg Technol* 3:41–45
33. Cserhalmi ZS, Sass-Kiss A, Tóth-Markus M, Lechner N (2006) Study of pulsed electric field treated citrus juices. *Innov Food Sci Emerg Technol* 7(1–2):49–54
34. De Alwis AAP, Fryer PJ (1992) Operability of the ohmic heating process: electrical conductivity effects. *J Food Eng* 15:21–48
35. Demirdoven A, Baysal T (2009) Combined effects of electrical methods on orange juice production. International Conference on Bio and Food Electrotechnologies 22–23 October 2009, Compiègne
36. El-Hag AH, Jayaram SH, Griffiths MW (2006) Inactivation of naturally grown microorganisms in orange juice using pulsed electric fields. *IEEE Trans Plasma Sci* 34(4):1412–1415
37. Evrendilek GA, Zhang QH, Richter ER (1999) Inactivation of *Escherichia coli* O157:H7 and *Escherichia coli* 8739 in apple juice by pulsed electric fields. *J Food Prot* 62:793–796
38. Evrendilek GA (2009) Pulsed electric field processing of pomegranate juice. International Conference on Bio & Food Electrotechnologies, 22–23 October 2009, Compiègne
39. Evrendilek GA, Jin ZT, Ruhlman KT, Qiu X, Zhang QH, Richter ER (2000) Microbial safety and shelf life of apple juice and cider processed by bench and pilot scale PEF systems. *Innov Food Sci Emerg Technol* 1:77–86
40. Evrendilek GA, Tok FM, Soylu EM, Soylu S (2008) Inactivation of *Penicillium expansum* in sour cherry juice, peach and apricot nectars by pulsed electric fields. *Food Microbiol* 25:662–667
41. Evrendilek GA, Tok FM, Soylu EM, Soylu S (2009) Inactivation of *Botrytis cinerea* in sour cherry juice, peach and apricot nectars by pulsed electric fields. *Ita J Food Sci* 21:12
42. Fincan M, Dejmek P (2002) In situ visualization of the effect of a pulsed electric field on plant tissue. *J Food Eng* 55(3):223–230
43. Flaumenbaum BKI, Tancev SS, Girisin MA (1986) Osnovi Konsev, Rovaniya Piševih Productov, M. Agropromizdat, p 494
44. Flaumenbaum BL (1949) Electrical treatment of fruits and vegetables before juice extraction. *Trudy OTIKP* 3:15–20
45. Gachovska TK, Kumar S, Thippareddi H, Subbiah J, Williams F (2008) Ultraviolet and pulsed electric field treatments have additive effect on inactivation of *E. coli* in apple juice. *J Food Sci* 3(9):412–417
46. Garde-Cerdán T, Arias-Gil M, Marsellés-Fontanet AR, Ancín-Azpilicueta C, Martín-Belloso O (2007) Effects of thermal and non-thermal processing treatments on fatty acids and free amino acids of grape juice. *Food Control* 18(5):473–479
47. Giner J, Gimeno V, Espachs A, Elez P, Barbosa-Canovas GV, Martin O (2000) Inhibition of tomato (*Lycopersicon esculentum* Mill.) pectin methylesterase by pulsed electric fields. *Innov Food Sci Emerg Technol* 1:57–67
48. Girard B, Fukumoto LR (2000) Membrane processing of fruit juices and beverages: a review. *Crit Rev Food Sci Nutr* 40(2):91–157
49. Harrison SL, Barbosa-Canovas GV, Swanson BG (1997) *Saccharomyces cerevisiae* structural changes induced by pulsed electric field treatment. *Lebensm-Wiss u-Technol* 30:236–240
50. Hayes WA, Smith FG, Morris AEJ (1998) The production and quality of tomato concentrates. *Crit Rev Food Sci Nutr* 38(7):537–564
51. Heinz V, Toepfl S, Knorr D (2003) Impact of temperature on lethality and energy efficiency of apple juice pasteurization by pulsed electric fields treatment. *Innov Food Sci Emerg Technol* 4(2):167–175
52. Ho SY, Mittal GS, Cross JD (1997) Effects of high field electric pulses on the activity of selected enzymes. *J Food Eng* 31:69–84
53. Hodgins AM, Mittal GS, Griffiths MW (2002) Pasteurization of fresh orange juice using low-energy pulsed electrical field. *J Food Sci* 67(6):2294–2299
54. Hülsheger H, Potel J, Niemann EG (1981) Killing of bacteria with electric pulses of high field strength. *Radiat Environ Biophys* 20:53–65
55. Hülsheger H, Potel J, Niemann EG (1983) Electric field effects on bacteria and yeast cells. *Radiat Environ Biophys* 22:149–162
56. Icier F (2010) Ohmic blanching effects on drying of vegetable byproduct. *J Food Process Eng*. doi:10.1111/j.1745-4530.2008.00295.x
57. Icier F, Bozkurt H (2009) Ohmic heating of liquid whole egg: rheological behaviour and fluid dynamics. *Food Bioprocess Technol*. doi:10.1007/s11947-009-0229-4
58. Icier F, Ilicali C (2004) Electrical conductivity of apple and sourcherry juice concentrates during ohmic heating. *J Food Process Eng* 27(3):159–180
59. Icier F, Ilicali C (2005) The effects of concentration on electrical conductivity of orange juice concentrates during ohmic heating. *Euro Food Res Technol* 220(3–4):406–414
60. Icier F, Ilicali C (2005) Temperature dependent electrical conductivities of fruit purees during ohmic heating. *Food Res Int* 38(10):1135–1142
61. Icier F, Ilicali C (2005) The use of tylose as a food analog in ohmic heating studies. *J Food Eng* 69:67–77
62. Icier F, Yıldız H, Baysal T (2006) Peroxidase inactivation and colour changes during ohmic blanching of pea puree. *J Food Eng* 74:424–429
63. Icier F, Yıldız H, Baysal T (2008) Polyphenoloxidase deactivation kinetics during ohmic heating of grape juice. *J Food Eng* 85:410–417
64. Jia M, Zhang QH, Min DB (1999) Pulsed electric field processing effects on flavor compounds and microorganisms of orange juice. *Food Chem* 65:445–451
65. Jin ZT, Zhang QH (2007) Pulsed electric field inactivation of microorganisms and preservation of quality of cranberry juice. *J Food Process Preserv* 23(6):481–497
66. Kong Y-Q, Li D, Wang L-j, Bhandari B, Chan XD, Mao Z-H (2008) Ohmic heating behavior of certain selected liquid food materials. *Int J Food Eng* 4(3):1–13
67. Kulshrestha S, Sastry S (2003) Frequency and voltage effects on enhanced diffusion during moderate electric field (MEF) treatment. *Innov Food Sci Emerg Technol* 4(2):189–194
68. Lebovka NI, Shynkaryk M, Vorobiev E (2007) Moderate electric field treatment of sugarbeet tissues. *Biosys Eng* 96(1):47–56

69. Lee CH, Yoon SW (1999) Effect of ohmic heating on the structure and permeability of the cell membrane of *Saccharomyces cerevisiae*. IFT Annual Meeting, Chicago
70. Leizerman S, Shimoni E (2005) Effect of ultrahigh-temperature continuous ohmic heating treatment on fresh orange juice. *J Agric Food Chem* 53(9):3519–3524
71. Liang Z, Chang Z, Griffiths MW (2006) Inactivation of spoilage microorganisms in apple cider using a continuous flow pulsed electric field system. *Lebensm-Wiss u-Technol* 39:350–356
72. Liang Z, Mittal GS, Griffiths MW (2002) Inactivation of *Salmonella* Typhimurium in orange juice containing antimicrobial agents by pulsed electric field. *J Food Prot* 65(7):1081–1087
73. Lima M, Heskitt BF, Buriánek LL, Nokes SE, Sastry SK (1999) Ascorbic acid degradation kinetics during conventional and ohmic heating. *J Food Process Preserv* 23:421–434
74. Lima M, Sastry SK (1999) The effects of ohmic heating frequency on hot-air drying rate, desorption isotherms and juice yield. *J Food Eng* 41:115–119
75. Luo W, Zhang RB, Wang LM, Chen J, Guan JC (2010) Conformation changes of polyphenol oxidase and lipoygenase induced by PEF treatment. *J Appl Electrochem* 40(2):295–301
76. Marra F, Zell M, Lyng JG, Morgan DJ, Cronin DA (2009) Analysis of heat transfer during ohmic processing of a solid food. *J Food Eng* 91:56–63
77. Marsellés-Fontanet ÀR, Puig A, Olmos P, Mínguez-Sanz S, Martín-Belloso O (2009) Optimising the inactivation of grape juice spoilage organisms by pulse electric fields. *Int J Food Microbiol* 130(3):159–165
78. Marsellés-Fontanet AR, Martín-Belloso O (2007) Optimization and validation of PEF processing conditions to inactivate oxidative enzymes of grape juice. *J Food Prot* 83(3):452–462
79. Martín-Belloso O, Vega-Mercado H, Qin BL, Chang FJ, Barbosa-Cánovas GV, Swanson BG (1997) Inactivation of *Escherichia coli* suspended in liquid egg using pulsed electric fields. *J Food Process Preserv* 21:193–203
80. McDonald CJ, Lloyd SW, Vitale MA, Petersson K, Innings F (2000) Effects of pulsed electric fields on microorganisms in orange juice using electric field strengths of 30 and 50 kV/cm. *J Food Sci* 65:984–989
81. McLellan MR, Kime RL, Lind LR (1991) Electroporation and other treatment to improve apple juice yield. *J Sci Food Agric* 57:303–306
82. Min S, Zhang QH (2003) Effects of commercial-scale pulsed electric field processing on flavor and color of tomato juice. *J Food Sci* 68(5):1600–1606
83. Min S, Jin ZT, Zhang QH (2003) Commercial scale pulsed electric field processing of tomato juice. *J Agric Food Chem* 51(11):3338–3344
84. Min S, Min SK, Zhang QH (2003) Inactivation kinetics of tomato juice lipoygenase by pulsed electric fields. *J Food Sci* 68(6):1995–2001
85. Min S, Jin TZ, Min SK, Yeom H, Zhang QH (2006) Commercial-scale pulsed electric field processing of orange juice. *J Food Sci* 68(4):1265–1271
86. Min S, Jin ZT, Zhang QH (2007) Commercial scale pulsed electric field processing of tomato juice. *Food Bioprocess Technol* 1(4):364–373
87. Molinari P, Pilosof AMR, Jagus RJ (2004) Effect of growth phase and inoculum size on the inactivation of *S. cerevisiae* in fruit juices by pulsed electric fields. *Food Res Int* 37(8):793–798
88. Mosqueda-Melgar J, Raybaudi-Massilia RM, Martín-Belloso O (2007) Influence of treatment time and pulse frequency on *Salmonella* Enteritidis, *Escherichia coli* and *Listeria monocytogenes* populations inoculated in melon and watermelon juices treated by pulsed electric fields. *Int J Food Microbiol* 117:192–200
89. Mosqueda-Melgar J, Raybaudi-Massilia RM, Martín-Belloso O (2008) Combination of high-intensity pulsed electric fields with natural antimicrobials to inactivate pathogenic microorganisms and extend the shelf-life of melon and watermelon juices. *Food Microbiol* 25:479–491
90. Nguyen P, Mittal GS (2007) Inactivation of naturally occurring microorganisms in tomato juice using pulsed electric field (PEF) with and without antimicrobials. *Chem Eng Process* 46(4):360–365
91. Okilov Ş (1995) Klasik ve elektroplazmoliz yöntemleri ile elde edilen Golden Delicious elmalarının pres suyuna işlenmesi sırasında kimi özelliklerine etki eden faktörlerin araştırılması. YL Tezi Ege Üni Fen Bil Ens Gıda Müh Anabilim Dalı İzmir. 69s
92. Palaniappan S, Sastry SK (1991) Electrical conductivity of selected juices: influences of temperature, solids content, applied voltage, and particle size. *J Food Process Eng* 14:247–260
93. Peleg M (1995) A model of microbial survival after exposure to pulsed electric fields. *J Sci Food Agric* 67:93–99
94. Peleg M, Cole MB (1998) Reinterpretation of microbial survival curves. *Critical Rev Food Sci Nutr* 38:353–380
95. Piette G, Buteau ME, Halleux D, Chiu L, Raymond Y, Ramaswamy HS (2004) Ohmic cooking of processed meats and diet effects on product quality. *J Food Sci* 69:71–78
96. Pina Perez MC, Rodrigo Aliaga D, Ferrer Bernat C, Rodrigo Enguidanos M, Martinez Lopez A (2007) Inactivation of *Enterobacter sakazakii* by pulsed electric field in buffered peptone water and infant formula milk. *Int Dairy J* 17:1441–1449
97. Praporscic I, Lebovka NI, Ghnimi S, Vorobiev E (2006) Ohmically heated, enhanced expression of juice from apple and potato tissues. *Biosys Eng* 93(2):199–204
98. Prochownick L, Spaeth F (1890) Über die keimtötende Wirkung des galvanischen Stroms. *Deutsche Medizinische Wochenschrift* 26:564–565
99. Qihua T, Jindal VK, van Winden J (1993) Design and performance evaluation of an ohmic heating unit for liquid foods. *Comp Electron Agric* 9:243–253
100. Qin BL, Zhang Q, Barbosa-Cánovas GV, Swanson BG, Pedrow PD (1994) Inactivation of microorganisms by pulsed electric fields with different voltage wave-forms. *IEEE Trans Dielec Electric Insul* 1(6):1047–1057
101. Qin BL, Chang FJ, Barbosa-Cánovas GV, Swanson BG (1995) Nonthermal inactivation of *Saccharomyces cerevisiae* in apple juice using pulsed electric fields. *Lebensm Wiss u Technol* 28:564–568
102. Qui X, Sharma S, Tuhela L, Jia M, Zhang QH (1998) An integrated PEF pilot plant for continuous nonthermal pasteurization of fresh orange juice. *Trans ASAE* 41(4):1069–1074
103. Quitão-Teixeira LJ, Aguiló-Aguayo I, Ramos AM, Martín-Belloso O (2007) Inactivation of oxidative enzymes by high-intensity pulsed electric field for retention of color in carrot juice. *Food Bioprocess Technol* 1:364–373
104. Raso J, Calderon ML, Gongora M, Barbosa-Cánovas GV, Swanson BG (1998) Inactivation of mold ascospores and conidiospores suspended in fruit juices by pulsed electric fields. *Lebensm Wiss u Technol* 31:668–672
105. Raso J, Calderon ML, Gongora M, Barbosa-Cánovas GV, Swanson BG (1998) Inactivation of *Zygosaccharomyces bailii* in fruit juices by heat, high hydrostatic pressure and pulsed electric fields. *J Food Sci* 63:1042–1044
106. Ravishankar S, Zhang H, Kempkes ML (2008) Pulsed electric fields. *Food Sci Technol Int* 14:429–432
107. Reina LD, Jin ZT, Zhang QH, Yousef AE (1998) Inactivation of *Listeria monocytogenes* in milk by pulsed electric field. *J Food Prot* 61:1203–1206

108. Reznick D (1996) Ohmic heating of fluid foods. *J Food Technol* 50(5):250–251
109. Rivas A, Rodrigo D, Martínez A, Barbosa-Canovas GV, Rodrigo M (2006) Effect of PEF and heat pasteurization on the physical–chemical characteristics of blended orange and carrot juice. *Lebens-Wissen-Technol* 39:1163–1170
110. Roberts JS, Balaban MO, Zimmerman R, Luzuriaga D (1998) Design and testing of a prototype ohmic thawing unit. *Comput Electro Agric* 19:211–222
111. Rodrigo D, Martínez A, Harte F, Barbosa-Cánovas GV, Rodrigo M (2001) Study of inactivation of *Lactobacillus plantarum* in orange-carrot juice by means of pulsed electric fields: comparison of inactivation kinetics models. *J Food Prot* 64(2):259–263
112. Ross T (1996) Indices for performance evaluation of predictive models in food microbiology. *J Appl Microbiol* 81:501–508
113. Sale AJH, Hamilton WA (1967) Effects of high electric fields on microorganisms. I. Killing of bacteria and yeasts. *Biochim Biophys Acta* 148:781–788
114. Salengke S, Sastry SK (2007) Experimental investigation of ohmic heating of solid-liquid mixtures under worst-case heating scenarios. *J Food Eng* 83:324–336
115. Sampedro F, Rivas A, Rodrigo D, Martínez A, Rodrigo M (2007) Pulsed electric fields inactivation of *Lactobacillus plantarum* in an orange juice–milk based beverage: effect of process parameters. *J Food Eng* 80:931–938
116. San Martín MF, Sepulveda DR, Altunakar B, Gongora-Nieto MM, Swason BG, Barbosa-Canovas GV (2007) Evaluation of selected mathematical models to predict the inactivation of *Listeria innocua* by pulsed electric fields. *LWT-Food Sci Technol* 40:1271–1279
117. Sanchez-Moreno C, Plaza L, Elez-Martinez P, De Ancos B, Martín-Belloso O, Pilar Cano M (2005) Impact of high pressure and pulsed electric fields on bioactive compounds and antioxidant activity of orange juice in comparison with traditional thermal processing. *J Agric Food Chem* 53(11):4403–4409
118. Sanchez-Vega R, Mujica-Paz H, Marquez-Melendez R, Ngadi MO, Ortega-Rivas E (2009) Enzyme inactivation on apple juice treated by ultrapasteurization and pulsed electric fields technology. *J Food Process Preserv* 33(4):486–499
119. Sandik IV (1983) Konservnayai Ovoshchesushil'naya Promyshlennost'. No. 5
120. Sastry S (2008) Ohmic heating and moderate electric field processing. *Food Sci Tech Int* 14:419–422
121. Sastry SK (2008) Ohmic heating and moderate electric field processing. *Food Sci Technol Int* 14:419–422
122. Sastry SK, Li Q (1996) Modeling the ohmic heating of foods. *Food Technol* 50(5):246–248
123. Schilling S, Schmid S, Jager H, Ludwig M, Dietrich H, Toepfl S, Knorr D, Neidhart S, Schieber A, Carle R (2008) Comparative study of pulsed electric field and thermal processing of apple juice with particular consideration of juice quality and enzyme deactivation. *J Agric Food Chem* 56(12):4545–4554
124. Selma MV, Salmerón MC, Valero M, Fernández PS (2004) Control of *Lactobacillus plantarum* and *Escherichia coli* by pulsed electric fields in MRS Broth, nutrient broth and carrot-apple juice. *Food Microbiol* 21:519–525
125. Sharma SK, Zhang QH, Chism GW (1998) Development of a protein fortified fruit beverage and its quality when processed with pulsed electric field treatment. *J Food Qual* 21:459–473
126. Shcheglov YA, Rudkovskaya GV, Rozhko VS (1983) Use of electroporation in the manufacture of tomato paste. *Konservnaya i Ovoshchesushil'naya Promyshlennost'* 5:8–10
127. Singh SP, Tarsikka PS, Singh H (2008) Study on viscosity and electrical conductivity of fruit juices. *J Food Sci Technol* 45(4):371–372
128. Tempest P (1992) Experience with ohmic heating and aseptic packaging of particulate foods. technical report no. PT/FBD1368. APV Baker Ltd., Automation Process Division, Crawley
129. Toepfl S (2006) Pulsed electric fields (PEF) for permeabilization of cell membranes. In: Food and bioprocessing applications, process and equipment design and cost analysis. Von Der Fakultät III Prozesswissenschaften Der Technischen Universität Berlin, Ph.D. thesis
130. Toepfl S, Heinz V, Knorr D (2006) Applications of pulsed electric fields technology for the food industry. In: Raso J, Heinz V (eds) Pulsed electric fields technology for the food industry: fundamentals and applications. Springer, New York, pp 197–222
131. Toepfl S, Heinz V, Knorr D (2007) High intensity pulsed electric fields applied for food preservation. *Chem Eng Process* 46: 537–546
132. Torregrosa F, Esteve MJ, Frígola A, Cortés C (2006) Ascorbic acid stability during refrigerated storage of orange–carrot juice treated by high pulsed electric field and comparison with pasteurized juice. *J Food Eng* 73(4):339–345
133. Tsong TY (1990) On electroporation of cell membranes and some related phenomena. *Bioelectrochem Bioenerg* 24:271–295
134. Ulmer HM, Heinz V, Gaenzle MG, Knorr D, Vogel RF (2002) Effects of pulsed electric fields on inactivation and metabolic activity of *Lactobacillus plantarum* in model beer. *J Appl Microbiol* 93(2):326–335
135. Van Loey A, Verachtert B, Hendrickx M (2002) Effects of high electric field pulses on enzymes. *Trends Food Sci Technol* 12:94–102
136. Vega-Mercado H, Powers JR, Martín-Belloso O, Luedecke L, Barbosa-Cánovas GV, Swanson BG (2001) Change in susceptibility of proteins to proteolysis and the inactivation of an extracellular protease from *Pseudomonas fluorescens* M3/6 when exposed to pulsed electric fields. In: Barbosa-Cánovas GV, Zhang QH (eds) Pulsed electric fields in food processing: fundamental aspects and applications. Technomic Publishing Co. Inc, Lancaster
137. Vikram VB, Ramesh MN, Prapulla SG (2005) Thermal degradation kinetics of nutrients in orange juice heated by electromagnetic and conventional methods. *J Food Eng* 69(1):31–40
138. Wang WC, Sastry SK (1993) Salt diffusion into vegetable tissue as a pre-treatment for ohmic heating: determination of parameters and mathematical model verification. *J Food Eng* 20:311–323
139. Wang WC, Sastry SK (2002) Effects of moderate electrothermal treatments on juice yield from cellular tissue. *Innov Food Sci Emerg Technol* 3:371–377
140. Wu Y, Mittal GS, Griffiths MW (2005) Effects of pulsed electric field on the inactivation of microorganisms in grape juices with and without antimicrobials. *Biosyst Eng* 90(1):17
141. Ye X, Ruan R, Chen P, Doona C, Taub IA (2003) MRI temperature mapping and determination of liquid-particulate heat transfer coefficient in an ohmically heated food system. *J Food Sci* 68(4):1341–1346
142. Yeom HW, Zhang QH, Chism GW (2002) Inactivation of pectin methyl esterase in orange juice by pulsed electric fields. *J Food Sci* 67(6):2154–2159
143. Yeom HW, Streaker CB, Zhang QH, Min DB (2000) Effects of pulsed electric fields in the activity of microorganisms and pectin methyl esterase in orange juice. *J Food Sci* 65:1359–1363
144. Yıldız H (2004) Domates salçası üretiminde elektroplazmoliz uygulamasının salça kalitesi ve verimi üzerine etkilerinin araştırılması. EÜ Fen Bil Enst (Doktora Tezi; PhD thesis) Bornova. İzmir

145. Yıldız H, Baysal T (2007) Color and lycopene content of tomato puree affected by electropulsolysis. *Int J Food Prop* 10:489–495
146. Yıldız H, İcier F, Baysal T (2010) Changes in β -carotene, chlorophyll and color of spinach puree during ohmic heating. *J Food Process Eng*. doi:10.1111/j.1745-4530.2008.00303.x
147. Yıldız H, İcier F, Demirdoven A, Baysal T (2009) Optimization of electropulsolysis used in sour cherry processing. International Conference on Bio and Food Electrotechnologies 22–23 October 2009. Compiègne, France
148. Yıldız H, Bozkurt H, İcier F (2009) Ohmic and conventional heating of pomegranate juice: effects on rheology, colour and total phenolics. *Food Sci Technol Int*. doi:10.1177/1082013209350352
149. Zagorulko A (1953) Producing of diffusion juice by electropulsolysis. *Sakharnaya Promyshlennost* 10:23–25
150. Zell M, Lyng JG, Cronin DA, Morgan DJ (2009) Ohmic cooking of whole beef muscle-optimisation of meat preparation. *Meat Sci* 81(4):693–698
151. Zhang BG, Zhang M, Shi J, Xu Y (2010) Pulsed electric field processing effects on physicochemical properties, flavor compounds and microorganisms of longan juice. *J Food Process Preserv* 34:1121–1138
152. Zhang Q, Qin B-L, Barbosa-Canovas GV, Swanson BG (1994) Inactivation of *E. coli* for food pasteurization by high strength pulsed electric fields. *J Food Process Preserv* 19(2):103–118
153. Zhang Q, Chang F-J, Barbosa-Canovas GV, Swanson BG (1994) Inactivation of microorganisms in a semisolid model food using high voltage pulsed electric fields. *Lebensm-Wiss Technol* 27(6):538–543
154. Zhang Y, Hu XS, Chen F, Wu JF, Liao XJ, Wang ZF (2008) Stability and colour characteristics of PEF-treated cyanidin-3-glucoside during storage. *Food Chem* 106(2):669–676
155. Zhong K, Chen F, Wu J, Wang Z, Liao X, Hu X, Zhang Z (2005) Kinetics of inactivation of *Escherichia coli* in carrot juice by pulsed electric field. *J Food Process Eng* 28(6):595–609
156. Zhong T, Lima M (2003) The effect of ohmic heating on vacuum drying rate of sweet potato tissue. *Biores Technol* 87(3):215–220
157. Zimmermann U (1996) The effect of high intensity electric field pulses on eucaryotic cell membranes: fundamentals and applications. In: Zimmermann U, Neil GA (eds) *Electromanipulation of cells*. Boca Raton, CRC Press, pp 1–106
158. Zimmermann U, Pilwat G, Riemann F (1974) Dielectric breakdown of cell membranes. *Biophys J* 14(11):881–889