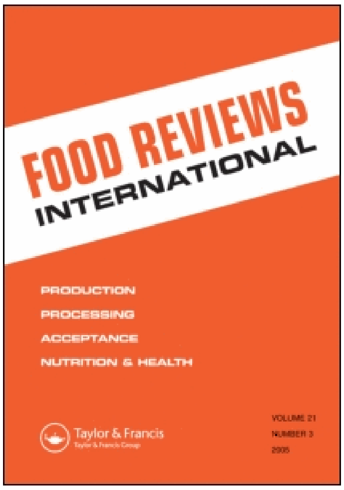

Food Reviews International
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597252

Review: Potential of High Hydrostatic Pressure and Pulsed Electric Fields for Energy Efficient and Environmentally Friendly Food Processing

S. Toepfl[a]; A. Mathys[a]; V. Heinz[b]; D. Knorr[a]
[a] Department of Food Biotechnology and Food Process Engineering, Berlin University of Technology, Berlin, Germany [b] German Institute of Food Technology (DIL e.V.), Quakenbrück, Germany

To cite this Article Toepfl, S. , Mathys, A. , Heinz, V. and Knorr, D.(2006) 'Review: Potential of High Hydrostatic Pressure and Pulsed Electric Fields for Energy Efficient and Environmentally Friendly Food Processing', Food Reviews International, 22: 4, 405 — 423

To link to this Article: DOI: 10.1080/87559120600865164
URL: http://dx.doi.org/10.1080/87559120600865164

Food Reviews International, 22:405–423, 2006

ISSN: 8755-9129 print / 1525-6103 online
DOI: 10.1080/87559120600865164

Review: Potential of High Hydrostatic Pressure and Pulsed Electric Fields for Energy Efficient and Environmentally Friendly Food Processing

S. TOEPFL[1], A. MATHYS[1], V. HEINZ[2] AND D. KNORR[1]

[1]Department of Food Biotechnology and Food Process Engineering, Berlin University of Technology, Berlin, Germany
[2]German Institute of Food Technology (DIL e.V.), Quakenbrück, Germany

The application of emerging, novel processing techniques such as high hydrostatic pressure or pulsed electric fields can be utilized to replace, enhance or modify conventional techniques of food production. In addition to quality improvements and consumer benefits by gentle microbial inactivation and improvement of mass transfer processes, their potential to improve energy efficiency and sustainability of food production will be discussed within this review.

Keywords Pulsed electric fields, High pressure, Energy efficiency, Sustainability, Non-thermal processing

Introduction

Consumer demand, regulative pressure to improve food processing towards better environmental performance, and the economic need to reduce waste or by-products stimulated the quest for novel food processing techniques. Furthermore, the concepts of "fresh," "natural," or "organic" foods also led to the development of environmentally sound and resource efficient food production systems.(1) In contrast to the environmental impact of agriculture and raw material production or food packaging, the energy requirements for unit operations in food processing, and the potential of novel processing techniques has not been a matter of intense public discussion since the oil crisis in 1974.(2) Applying novel, alternative processing techniques, requiring lower energy input or fewer resources than conventional techniques, as well as improving utilization of raw material or by-products are important issues for sound energy, water, and waste management in combination with life cycle assessment.(3) Energetic optimization and heat recovery in the food industry has been a focus in the past decades for conventional processes, but their replacement by novel techniques for food preservation or modification may still provide a potential to reduce energy consumption and costs of operation, as well as to improve sustainability of production. The application of pulsed electric fields for food processing was first reported in the 1960s.(4,5) Within the last decades it has received, similar as high hydrostatic pressure processing, considerable attention to improve or replace existing processes for food preservation, tissue disintegration, and

Address correspondence to S. Toepfl, Department of Food Biotechnology and Food Process Engineering, Berlin University of Technology, Koenigin-Luise-Str 22, Berlin D-14195, Germany. E-mail: stefan.toepfl@tu-berlin.de

food modification. The potential to improve sustainability of food processing, and/or to reduce energy requirements while maintaining or improving food quality and safety will be highlighted within this article.

Energy Usage in Food Processing

Energy consumption in the food industry consists of a mixture of energy types for different thermal processes such as pasteurization, drying, cooking, or frying and electrical energy for pumps, milling, conveyors, or light as well as cooling systems.[(6)] Unnecessary use of energy can be reduced to a minimum by introducing energy management, but food preservation by heat is dependent on temperature-time protocols, and drying at industrial scale requires a large amount of fossil fuel for water evaporation. According to the US Department of Energy (DOE) in 1994 (see Table 1), the food industry in the USA consumed 1.3×10^{18} J of energy, about 6% of the total energy use of all manufacturing industries. This made the food industry the third largest consumer after paper and primary metal industries. The most energy intensive food industries were wet corn milling (18.3×10^{16} J), cane (13.5×10^{16} J) and beet (6.8×10^{16} J) sugar production, and soybean oil milling (6.0×10^{16} J). Relating energy consumption to the value of shipped cane (81×10^6 J/$) and beet sugar ($28 \times 10^6$ J/$) require highest energy levels per unit of output.[(7)] By recirculation and recovery of heat, the energy consumption of food processing could be cut by 40 %. The food industry is highly diversified, with production sites that range from small plants to large industrial-scale units. It has been estimated that almost 15,000 establishments have been involved in food production in the US in 1994 with total expenditures for energy consumption of $\$5.6 \times 10^9$ US. Introducing new techniques, such as cold pasteurization by non-thermal methods or low-energy pre-treatments prior to drying, can provide good opportunities to continue improving energy efficiency of food processing.

The principal type of energy used is direct fuel use for thermal processing, whereas electricity is mainly used for refrigeration and generation of mechanical power for pumps,

Table 1
Primary energy consumption of energy in food industry and energy operating ratios[(75)]

Industry group	Total consumption (10^{16} J)	Consumption per value added (10^6 J/$)	Consumption per value shipped (10^6 J/$)
Total food industry	125,862	7,069	2,849
Meat packing plants	5,592	6,858	1,161
Canned fruits and vegetables	5,381	87,565	3,798
Frozen fruits and vegetables	4,431	10,339	4,642
Wet corn milling	18,252	54,227	23,316
Bread, cake, and related products	3,904	2,954	1,794
Cane sugar, except refining	11,711	167,851	72,268
Cane sugar refining	2,427	37,136	8,757
Beet sugar	6,752	79,653	28,169
Soybean oil mills	6,014	31,756	4,748
Malt beverages	5,381	5,486	3,165

compressors and conveying. The amount of electric energy used is highly dependent on the type of industry and product. For example, the milling industry as well as milk, frozen fruit and vegetable processing require large amounts for actuation and refrigeration.[7] Large variations of energy requirements for different production sites have been reported for milk processing, with a range of 0.25 to 2.65 GJ per 1,000 kg of milk observed, caused by inattention to energy losses and lack of concern as well as variations between plants.[8] Age of equipment installed, energy costs and type of fuel and heat transfer medium, as well as the extent to which the available plant capacity is used, have been identified as the most important operational factors.

As most of the studies concerning emerging technologies in food processing have been performed in lab-scale, the results obtained are difficult to scale-up and cannot be generalized. The broad variety of equipment used, and the large range of different processes, products, and recipes complicate comparison of energy use. Energy consumption data of single production sites are rarely available due to nondisclosure, and the same is true for single unit operations. For milk processing, Vickers and Shannon[9] reported the energy requirements of major individual processing steps. When introducing new techniques to replace or enhance conventional processes, their economic efficiency will have to be proven in terms of production costs, energy efficiency, and/or added value of the product. Within this article, the applicability of PEF and HP for different operations in food processing, and the potential to improve energy efficiency and sustainability of production will be discussed. In addition to energy requirements, food industry is producing a significant amount of organic waste and wastewater,[10] which could be processed by emerging technologies.

Application of Pulsed Electric Fields (PEF)

The exposure of biological cells to an external electrical field of sufficient field strength induces the formation of pores in the cell membrane. This phenomenon, termed electropermeabilization, can be utilized for many operations in food- and bioengineering as shown in Fig. 1. First reported in the 1960s for disintegration of plant or animal tissue,[4] research on the applicability of these gentle membrane permeabilization techniques in food processing has concentrated on microbial inactivation in different liquid food products[11,12,13,14] and engineering aspects.[15,11,16] In addition, the electropermeabilization of plant cells,[17,18,19,20] the effects of PEF on food matrices,[21] inactivation of enzymes,[22,23,24] and induction of stress reactions and secondary metabolites production[25,26] have been investigated.

Even if application of PEF will require an additional input of electrical energy, the subsequent sections show selected examples of beneficial effects on total energy consumption of mass transfer processes such as extraction or pressing, as well as increased sustainability.

PEF Application on Plant or Animal Tissue

Improvement of extraction of intracellular compounds. Many operations in food and bioengineering, such as extraction, pressing or drying, include either enzymatic, thermal, or mechanical disruption of cellular material prior to recovery of intracellular compounds. These techniques may require a significant amount of mechanical or thermal energy, long holding times and storage tanks for an enzymatic maceration. Apart from the energy point of view, undesirable activities of endogenous or added enzymes and thermal degradation lead to significant losses of nutritionally and physiologically valuable substances. When

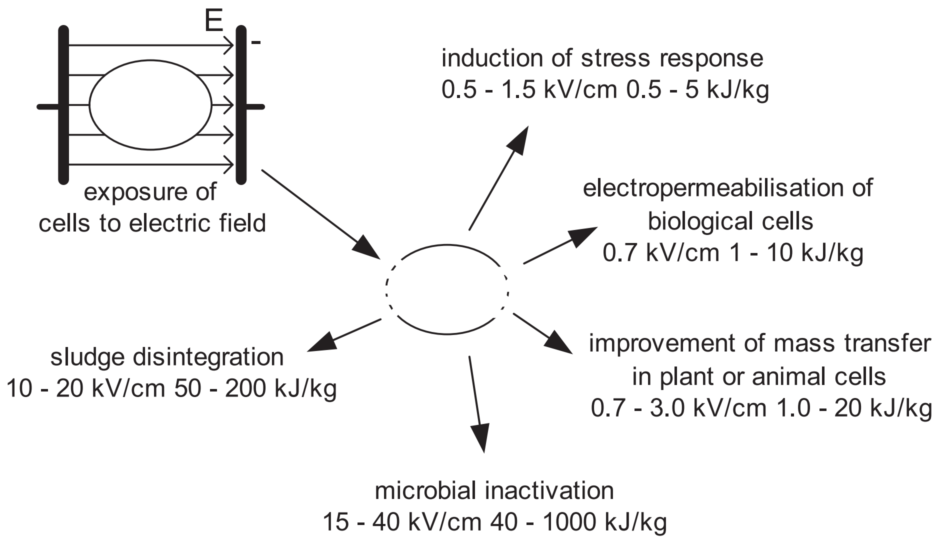

Figure 1. Electropermeabilisation of cells after exposure to electric field and applications in food and waste water processing with typical electric field strength and energy input requirements.

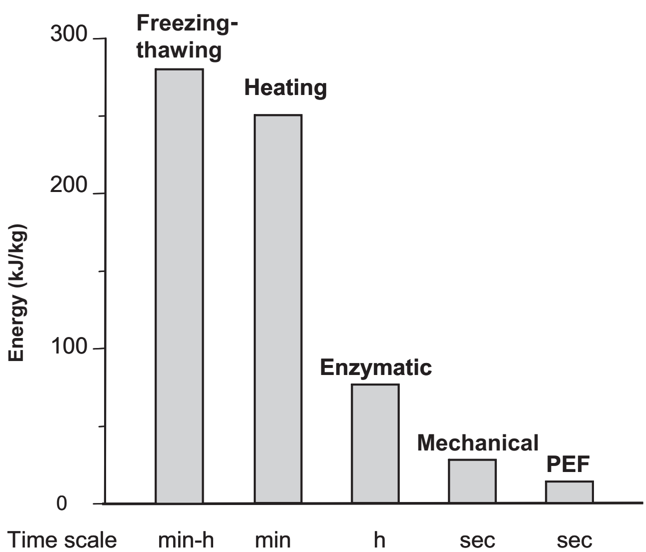

Figure 2. Energy required for cell disintegration of potato tissue with different techniques.

applying PEF to cellular tissues an increase in mass transfer coefficients could be observed.[27,28,29,30,31] An almost total permeabilisation of apple and potato tissue can be achieved with an electrical energy input in the range of 1–5 kJ per kg of product[32] in contrast to 20–40 kJ/kg for mechanical, 60–100 kJ/kg for enzymatic, and above 100 kJ/kg for thermal degradation of plant tissue (See Fig. 2). For an enzymatic or a thermal disintegration, heating of the raw material and considerable holding time at high temperature is required, heat transfer is slow, and heat recovery is poor as plate heat exchangers can hardly be applied for fruit mashes. A PEF treatment can be performed at ambient temperature and in a continuous operation, and in contrast to enzymatic maceration, no holding time and tank are required. It is noteworthy that the timescale required for a PEF treatment is in the range of seconds. An exemplary flow chart of such a process is shown in Fig. 3.

It has been shown that pressing of PEF-treated apple pieces at a pressure of 3 MPa resulted in an increased yield of 12%. At a pressure of 0.2–0.3 MPa, an increase of 40% was reported in contrast to untreated samples.[30] This clearly indicates that PEF treatment provides (in addition to lower energy requirements for disintegration) a possibility to reduce energy required for fruit juice pressing. For carrot juice, an increase of juice yield from 60.1 to 66.4% was found in comparison to an untreated sample, in the same way the dry matter of the pomace was increased from 13 to 15 %, resulting in less efforts for drying.[28] For grapes, a juice yield of 87%, similar to that after enzymatic maceration, and an increased content of soluble solids and pigments was reported after cell disintegration by PEF.[33] An increase in extractability of black tea and mint leafs by moderate electric

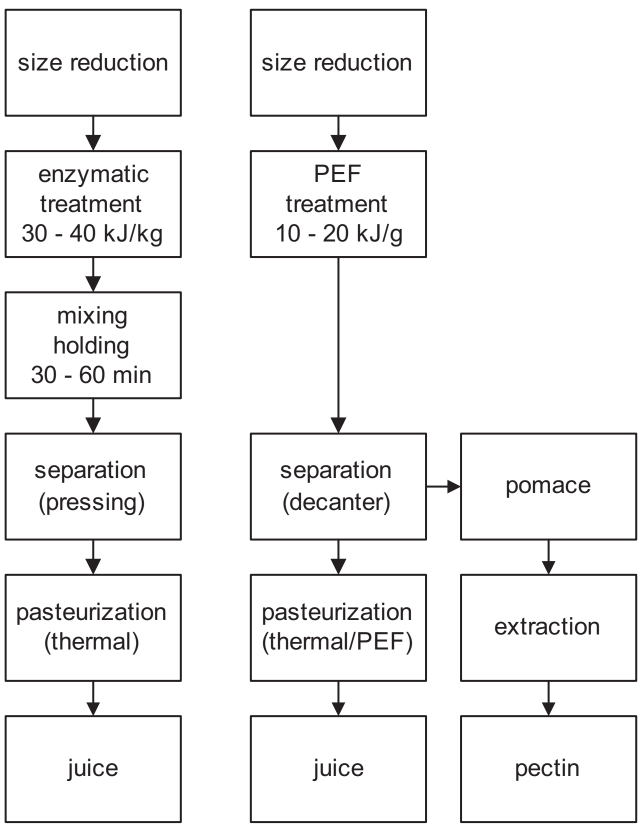

Figure 3. Flow chart for fruit juice processing with conventional or PEF pretreatment prior to liquid-solid separation and native pectin extraction from PEF-treated pomace. For PEF treatment an energy input of 10–20 kJ/kg will be required, preheating from 15 to 55°C prior to maceration require an energy input of 30–40 kJ/kg when assuming a heat recovery rate of 75%.

fields was shown by Sensoy and Sastry,[34] resulting in higher leaching of solutes. In the context of consumer demand for functional food with a composition close to the fresh product, an increased extractability of valuable components provides an enormous potential for product development.

Phytosterol concentration as well as oil yield during recovery of maize germ oil after a PEF treatment were investigated by Guderjan et al.[26] After a subsequent incubation time of 24 hours, allowing stress response of the "plant bioreactor," increases of up to 32% in phytosterol concentration and 88 % in oil yield were found. For olive oil, an increase of 7.4% in oil yield was found after a PEF treatment at a field strength of 1.3 kV/cm and 100 pulses, with an energy input as low as 2 kJ/kg of olives or 18 kg/kJ oil output. The energy requirements for soy oil extraction have been estimated at 70 kJ per kg of oil output.[35] These studies indicate that by an additional input of energy for a PEF treatment the recovery rate of plant oils can be increased, resulting in a reduction of specific energy consumption.

Sugar beet processing is one of the most energy consuming industries with a consumption of 626 MJ/t or 174 kWh/t beet for steam production.[36] It has been reported that the conventionally applied thermal extraction (70–120°C, 10–20 min.) became unnecessary after a PEF treatment with an energy input in the range of 3–10 MJ/t or 1–3 kWh/t while maintaining juice quality.[18] During conventional thermal degradation, the energy required to heat sugar beet to a temperature of 75°C was approximately 180 MJ/t or 50 kWh/t. A PEF energy input of approx. 30 kWh/t was required to achieve a juice yield of 78% when pressing at moderate pressure of 0.5 MPa.[37] These results indicate that during recovery of intracellular compounds by pressing or extraction the energy efficiency can be improved, as after a PEF treatment lower pressure or extraction temperatures can be utilized to achieve a similar product yield.

Improvement of drying processes. The electropermeabilisation of cell membranes leads to a drastic increase in mass transfer rates and can therefore be utilized to enhance drying of plant or animal tissue. Osmotic drying rates and diffusion coefficients in carrots were found to be increased with PEF treatment.[38] For apple slices, an increased osmotic drying rate, improved rehydration capacity and reduced rehydration times were reported.[39] The time required for fluidized-bed drying of potato cubes was reduced after a PEF treatment at an electric field strength of 1–2 kV/cm.[40] Ade-Omewaye et al.[41] investigated the relationship between a PEF treatment and drying rates of plant-based foods during osmotic dehydration and air drying. As a PEF treatment influences mass transport across the cell membrane, it can be utilized to significantly increase mass transfer rates by 10 to 30% when applying 5 to 20 pulses at a field strength of 1.0 kV/cm. For convective air drying at 60°C and an airflow of 1 m/s, a reduction of drying time of 20–30% was reported while maintaining drying parameters constant. The energy required for evaporation of water is dependent on temperature and pressure in the range of 2.5–2.7 MJ/kg, but total energy input required for conventional drying is in the range of 4–6 MJ per kg of removed water depending on thermal efficiency of the drying system. Heat and mass transfer within the product and losses on heating side, as well as to surroundings during drying, cause drying efficiencies in the range of 40–70%, depending on type of dryer. Taking into account the low energy input required for a PEF treatment of plant or animal tissue (2–20 kJ/kg), it is evident that there is a potential to reduce the total energy input for product drying. An increase in mass transfer rates, causing faster transport of water to product surface and therefore, reduction of drying time after PEF pretreatment could potentially lead to drastic saving of energy and better utilization of production capacities during convective air drying.

Potential to develop new processes and products and to increase sustainability. When replacing single unit operations during food processing, in addition to beneficial impact on energy efficiency, the techniques introduced may also have an impact on product constitution and/or product quality as well as waste or by-products. As stated previously, the conventional enzymatic maceration during fruit or vegetable juice production can be replaced by an electropermeabilization of the cellular tissue. Avoiding an enzymatic treatment will reduce undesired side effects of enzymes, and in addition, retain the native structure of pectins within the tissue. Providing a potential to extract pectin from the pomace after liquid-solid separation can help to additionally improve the utilization of resources and further cost-savings. It is noteworthy that tremendous amounts of pomace from fruit juice production or pulp of sugar processing are utilized for animal feeding. For drying, large amounts of thermal energy are required, especially since previous thermal cell disintegration as used during conventional sugar processing increases the water binding capacity. Utilizing the potential of by-products for recovery of valuable components will produce economical and ecological benefits.

Tissue softening and changes of textural properties of plant tissue have been reported after a PEF treatment,(20,42) and loss of turgor pressure was observed.(43) A reduction of cutting force for sugar beet tissue(36) has been demonstrated. The energy requirements and time-scale for disintegration of potato tissue by different cell disintegration techniques are shown in Fig. 3, indicating the potential of this gentle short-time permeabilisation technique.

Pasteurization of Liquid Food

Microbial Inactivation by PEF has been investigated extensively(5,12,44–49) within the last four decades. Even if the underlying mechanisms of action have not been fully elucidated up to now, key processing parameters have been identified and inactivation of a broad variety of vegetative cells has been shown. In general, yeasts have proven to be very sensitive against a PEF treatment.(14) Effective inactivation for most of the spoilage and pathogenic microorganisms has been identified, but it has to be emphasized that, in comparison to the treatment of plant or animal cells, the treatment intensity is much higher. The high electric field strength required (20–40 kV/cm), and the energy input in the range 100 to 1000 kJ/kg lead to investment costs estimated to be in the range of 2 to 3 million US $ for systems at industrial scale of 5 t/h. Since a treatment at this field strength will destroy the structure of solid food, a PEF treatment for preservation seems to be virtually impossible for solid food and is limited to liquid media. The potential to achieve sufficient reduction of microbes has been proven in a broad variety of food products, including fruit or vegetable juices,(23,50–55) model beer,(56) milk,(57,58) liquid egg,(59) and nutrient broth.(60) Differences in susceptibility of different microorganisms have been found and related to cell size distribution as well as to membrane constitution.(61,62)

The impact of pulse energy dissipation has to be taken into account, since the media temperature will increase. This energy might be removed by cooling or lead to a temperature increase of the medium, depending on the system. Data concerning the energy input required for microbial decontamination are not available from all research groups, as mainly electric field strength and pulse number are reported as treatment intensity parameters. Aronsson et al.(63) reported energy requirements of 160 and 384 kJ/kg for a 5 log-cycle inactivation of *Saccharomyces cerevisiae* and *Escherichia coli*. A study of temperature impact on treatment efficacy on *Escherichia coli* in apple juice has been performed by Heinz et al.(54) indicating the potential of a combined treatment of PEF and mild heat for gentle microbial inactivation. It was found that increasing treatment temperature from ambient to a range of 35 to 55°C can reduce the electric energy required for an inactivation of 6 log-cycles of *Escherichia coli* from far above 100 to 40 kJ/kg when operating at an initial treatment temperature of 55°C (see Fig. 4). An energy input of 40 kJ/kg will result in a temperature increase of 11°C in case of orange juice, showing that with a maximum temperature of 66°C the preservation process is still operating at lower maximum temperature and shorter residence times than during conventional heat preservation. An energy requirement of 357 kJ/kg for PEF and approximately 700 kJ/kg including cooling requirements was reported for pasteurisation of liquid egg at temperatures below 40°C.[(64)] For inactivation of *S. cerevisiae*, an energy requirement of 77 kJ/kg was reported to achieve an inactivation of 6 log cycles in dextrose agar, whereas, for *S. aureus*, 232 kJ/kg were required.[(65)] Qin *et al*.[(44)] reported an energy requirement of approximately 270 kJ/kg for a 4 log-cyle reduction of *S. cerevisiae* after a PEF treatment at 12 kV/cm and a temperature < 30°C. For treatment of apple juice and skim milk energy, requirements of 705 and 548 kJ/kg of pulse energy were reported to achieve a 2.7 and 2 log cycle inactivation, respectively, at a treatment temperature of 30°C.[(66)] To maintain treatment temperatures below 30°C, intermediate cooling between several treatment chambers was used causing a total energy requirement of above 1400 kJ/kg, indicating that energy efficient processing requires taking advantage of synergetic effects of mild heat.

Apart from the reduction of energy input, when operating at elevated temperatures the need to preheat the media to the initial treatment temperature provides a potential to

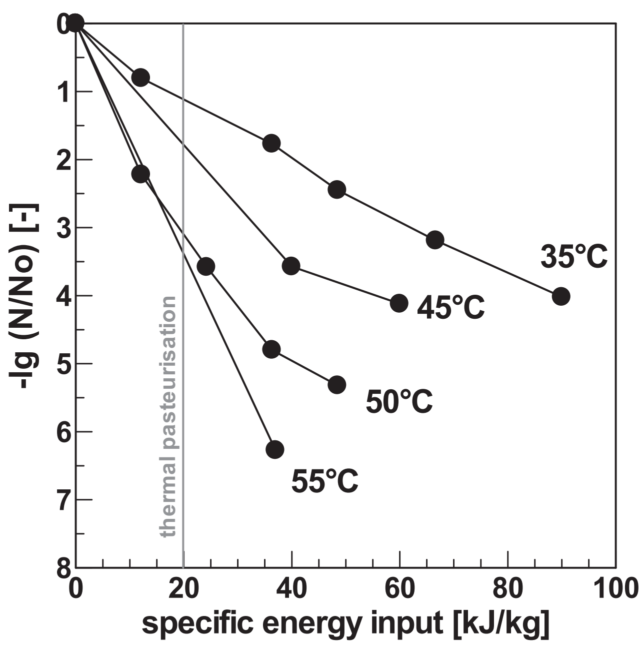

Figure 4. Electrical energy requirements for an inactivation of *Escherichia coli* in apple juice at an electric field strength of 36 kV/cm and different initial treatment temperatures in comparison to energy requirement for thermal pasteurization at 80°C and a heat recovery rate of 95%.

Reprinted from Innovative Food Science and Emerging Technologies, vol. 4, Heinz, et al., “Impact of temperature on lethality and energy . . .” pages 167–175, Copyright 2003, with permission from Elsevier.

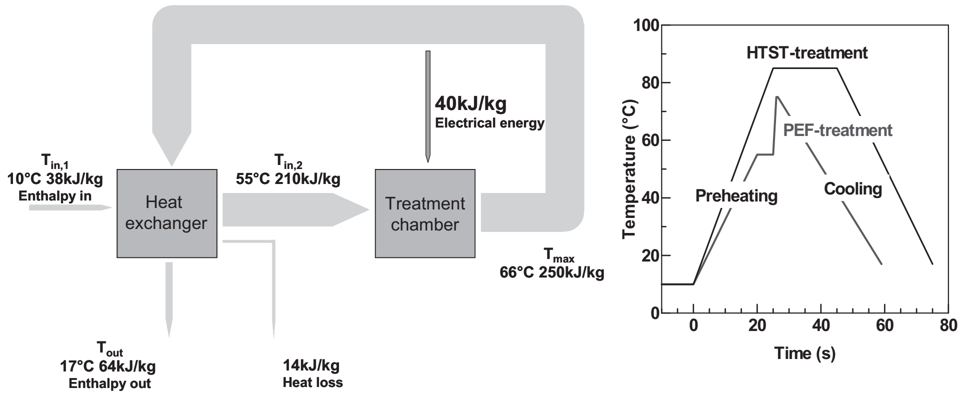

Figure 5. Enthalpy flow diagram and temperature time-profile of a PEF preservation (40 kJ/kg) of fruit juice with an initial treatment temperature of 55°C in comparison to a HTST-treatment (85°C, 20 s).[62] Adapted.

recover the electrical energy dissipated into the product in a heat exchanger (Fig. 5). When operating at ambient temperatures, there is no need for preheating and therefore, high cooling efforts are required. A combination of mild heat and pulsed electric field might also be helpful to achieve sufficient enzyme inactivation to avoid the necessity of refrigerated storage. It has to be stated that a PEF application for microbial decontamination of liquid food requires a higher input of energy than a thermal treatment, as heat recovery rates of thermal energy are in the range of 90–95%. Consequently, the input of electric energy should be minimized to a point where a high quality product is obtained with gentle processing parameters. When operating at elevated treatment temperatures and making use of synergetic heat effects, the PEF energy input might be reduced close to the amount of 20 kJ/kg required for conventional thermal pasteurization, assuming 95% of heat recovery.

Waste Water Treatment

Minimization of excess sludge production during waste water treatment has received considerable attention during recent years due to strengthened ecological and legislative measures. A disintegration of excess sludge and destruction of cells, organic matter consisting of a broad variety of different organisms, and subsequent release of intracellular material can be utilized to initiate biodegradation and autolysis of cells.[67] A PEF treatment can be utilized to induce cell lysis and release of intracellular content and consequently, relieving their biodegradation. On the other hand, metabolic activity may be driven towards maintenance and cell repair instead of biomass production after PEF induced cell damage. The underlying mechanisms of action are currently a focus of research activities. After a treatment at 15 kV/cm, a chemical oxygen demand (COD) release of up to 15% was reported after an energy input of 360 kJ/l. Volatile suspended solids and gas production during anaerobic degradation were found to be improved by 8 and 19% after a PEF energy input of 150 kJ/l in contrast to 445 kJ/l for a thermal treatment. Heat recovery from sludge is difficult; as viscosity is high and particles are present, only tubular heat exchangers can be used and will require large area. Biofouling and deposits on the surface cause short operation times. Taking into account a maximum heat recovery in the range of 50%, the energy requirement for thermal treatment could be reduced to 225 kJ/kg. The main advantages of PEF application, in contrast to conventional disintegration techniques as mechanical rupture, ozone application, thermal or ultrasound treatment, are short processing times and a direct electropermeabilisation of cell membranes. PEF-treated sludge showed a reduction of biological activity and an increase in organic matter in the water fraction.[(68)] The COD in the filtrate of the sludge was increased up to 25% after a treatment at 26 kV/cm with an energy input of 800 kJ/kg, and energy requirements were reduced to 250 kJ/kg when a temperature increase above 40°C was allowed. Release of organic material will improve sludge digestion and subsequent dewatering.

A total reduction up to 53% of volatile suspended solids and 45% of total suspended solids in the excess sludge can be achieved after a PEF treatment at 15 kV/cm, 35°C, and an energy input of 100 kJ/kg of sludge.[(69)] During these experiments, a flow of 5 l/h of sludge (3% dry substance) was subjected to electropermeabilisation and returned to the aerated reactor with a volume of 200 l, corresponding to a stress frequency of $0.47\ d^{-1}$ The sludge retention time was 14 days (Fig. 6). It has been shown that quality of the treated water was maintained and sludge quality was still acceptable in spite of drastic reduction of amount of excess sludge. In contrast to the relatively limited range of microorganisms inactived in food products, the biocenose within sludge is highly diverse; the impact of PEF on this broad variety of organisms has to be studied in detail. Further research work will be required for optimization of PEF treatment parameters and equipment design, but, as previously indicated, PEF application provides a potential to reduce the amount of excess sludge and can be utilized to improve anaerobic digestion. The average costs for sludge deposition in Germany are in the range of 50 (/t, or 40 US $/t,[(70)] whereas for incineration of mechanically-dewatered sludge, costs in the range of 230 to 580 US $ or 300 to 750) per ton of original dry matter have to be estimated.[(71)]

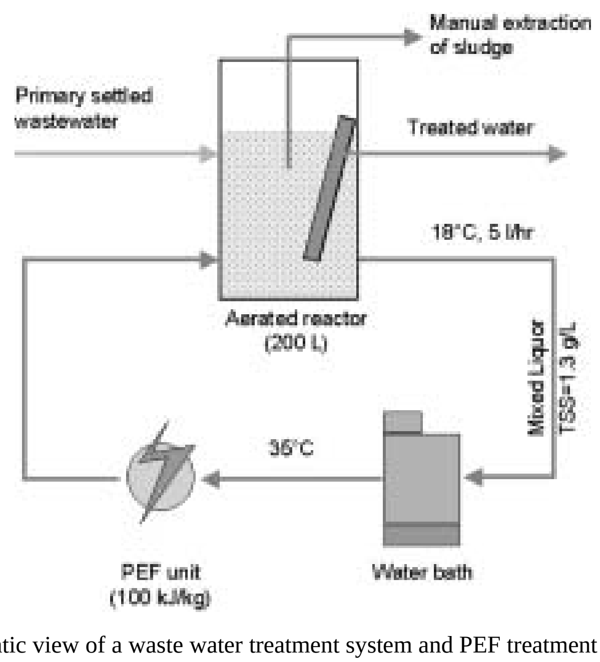

Figure 6. Schematic view of a waste water treatment system and PEF treatment of part of the reactor volume.[69]

Reprinted with permission from Shaker Verlag GmbH.

Since PEF treatment of excess sludge reduction still needs to be optimized from technical and economic points of view, and results reported are in lab- or pilot-scale, the energy requirements can only be estimated at present. For a treatment of sludge with an energy input of 50 kJ/kg of liquid sludge with 5% dry substance, *a stress frequency of 0.4,* and a sludge retention time of 14 days will require an energy input of 5.6 MJ/kg or 1.55 MWh/t of original dry matter. Assuming a charge of 0.08 US $ per kWh, this results in energy costs of 124 US $/t, indicating that a PEF treatment can be utilized as an effective alternative to reduce the amount of excess sludge from civil or industrial waste water prior to incineration. Further research work should focus on determination of process parameter requirements and their optimization with regard to sludge reduction as well as energy efficiency.

Potential of High Hydrostatic Pressure

High hydrostatic pressure treatment has often been suggested for preservation of packaged food as an alternative to heat treatment. At pressures higher than 400 MPa, a significant inactivation of vegetative bacteria, yeast or virus is observed even at ambient temperatures within treatment times of several minutes. By increasing the pressure to 600 MPa (at present the technical limit of industrial scale equipment), most inactivation reactions are strongly accelerated. Under these conditions and in combination with temperatures higher than 80°C, even bacterial spores can be inactivated irreversibly. Reductions of proteinase K resistance and infectivity of prions after high pressure treatments between 700–1,000 MPa at moderate temperatures could be observed as well.[(72)]

Since hydrostatic pressure treatment is characterized by equilibrated mechanical forces in domains of similar compressibility, shear forces can be excluded as the major mechanism of microbial inactivation. Even though aqueous systems show a volume contraction of approx. 20% when pressurized to 800 MPa, the specific work of compression W_{compr}, which can be expressed as

$$W_{compr} = -\int V \cdot dp, \tag{1}$$

upon compression up to 800 MPa, is not higher than approximately 55 kJ/kg.

This value has been obtained upon integration of Eq. (1) for isothermal situations using the functional relation V = f(p) for pure water given by the National Institute of Standards and Technology (NIST) formulation.[73]

Only a few chemical reactions involving covalent bonds, such as cyclic additions, are affected by hydrostatic pressure, at least when the exposure to high pressure is limited to ambient temperatures. However, the impact of high pressure on molecular structure of food matrices still needs to be considered in a more sophisticated manner. Although atomic bonds are barely affected, alteration of proteins or lipids can be observed when exposed to high hydrostatic pressure. When such changes occur in membranes of biological cells, lethal damage can result.

Adiabatic Heat of Compression

Although it is widely accepted that high pressure processing is environmentally friendly and can retain the fresh-like characteristics of foods better than heat treatment, it has not yet been successfully introduced widely into food industry—often due to the high capital costs for the equipment. Changing the current processing concept could possibly open more effective options related to high pressure vessel design. Considering that all compressible materials change their temperature during compression,[74] an adiabatic heating will occur.

This temperature rise, caused by inner friction, occurs when fluids are compressed to extreme pressure under adiabatic conditions. A general expression for the temperature increase upon compression in adiabatic- isentropic- situations is given as

$$\frac{dT}{dp} = \frac{\beta \cdot T}{\rho \cdot c_p} \quad (2)$$

where β, ρ and c_p denote the thermal expansivity, the density and the specific heat capacity of the compressed fluid, respectively. The thermo-physical properties β, ρ and c_p are pressure-temperature dependent. When these parameters are known, the calculation of the thermal profile during the compression phase is possible. Different pressure transmitting media show different adiabatic heating curves, which can be obtained for simple fluid food systems by estimating physical properties of mixtures of pure substances. The use of water and sucrose solutions as a model system for orange juice has been shown by Ardia.[74] Some adiabatic heat of compression profiles are shown in Fig. 7, where n-hexane and sebacate are used as pressure transmitting media. The lack of thermodynamic data for real foods under high pressure conditions has limited the possibilities to study and calculate the temperature increase during compression. Mainly empirical measurements have been used to investigate the adiabatic heating in real food systems at present (see Table 2). The main ingredient in most foods is water and thus, the thermodynamic properties of water can be utilized to estimate the temperature increase upon compression of high moisture foods. The compression heating in fat-containing foods can be up to three times higher than for water.[74] In a situation where organic solvents or oils are used as pressure transmitting medium and for an aqueous food matrix, a difference in temperature increase between the food and the medium would occur, with the temperature increase in the food

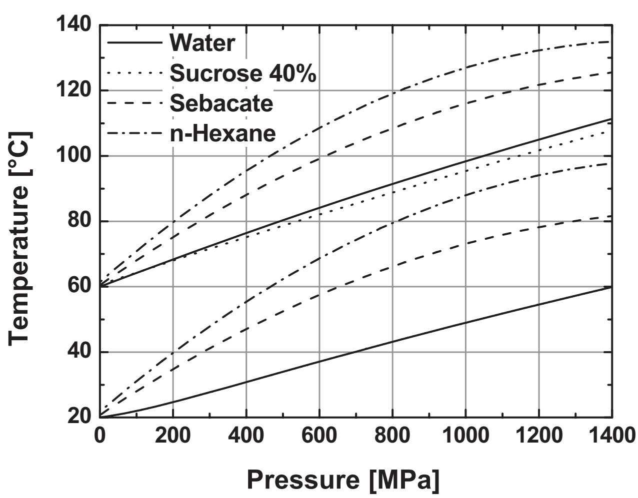

Figure 7. Adiabatic heat of compression of water, sucrose solution with 40% solid content, sebacate, and n-hexane.[75] Adapted.

Table 2
Adiabatic heat of compression in different food systems[74]

Substances at 25°C	Temperature increase per 100 MPa [°C]
Water	~3,0
Mashed potato	~3,0
Orange juice	~3,0
Tomato salsa	~3,0
2%-Fat milk	~3,0
Salmon	~3,2
Chicken fat	~4,5
Beef fat	~6,3
Olive oil	From 8,7 to <6,3[a]
Soy oil	From 9,1 to <6,2[a]

[a]Substances exhibited decreasing T as pressure increased.
Reprinted with permission.

being smaller. The transfer of heat from the pressure-transmitting medium into the product has to be taken into account and could be utilized to increase the temperature of the food system during and after the adiabatic heating.

Application of High Hydrostatic Pressure

As the pressure level in each volume element is the same in homogeneous food, the heat of compression is homogeneously distributed and can be utilized to improve microbial inactivation and to maximize process efficiency. Instantaneous adiabatic heating can help to reach the sterilizing end-temperature quickly and can result in a new approach to food sterilization with a significant improvement in food quality. Additional heat flow across the system must be taken into account as a transient temperature field, after which thermal equilibration will occur during pressure holding time between the warmest point in the center of the product and the metal high pressure vessel. It is noteworthy that after pressure release, the product will return to its initial temperature or even below, an aspect of high interest for processing of high quality foods. In contrast to liquid food, where the heat transfer can be improved by application of heat exchangers and heat recovery rates of above 90% are obtained, preservation of particulate food or packaged food requires long times for heat transfer or a large temperature gradient. Over-processing and fouling at the inner surface of the packaging may inhibit increasing the temperature gradient. Industrial scale systems for sterilization of cans therefore are limited to heat recovery rates in the range of 50%. The temperature-time profile for sterilization of a can with a diameter of 0.1 m is shown in Fig. 8. The autoclave is heated from 80 to 140°C, and after 130 minutes to reach an F-value of 2.4 min in the center of the can, the autoclave is cooled.

Alternatively, a combined application of high pressure and heat can be utilized to achieve a similar inactivation of spores of *Clostridium*. The temperature of the high pressure vessel will be maintained at 105°C. After 105 minutes, when a core temperature above 80°C is obtained, a pressure of 800 MPa will be applied for 10 minutes. Adiabatic heat of compression will cause a temperature increase to 110°C, after which decompression will cause a temperature drop to approximately 87°C and the can will be cooled. From the

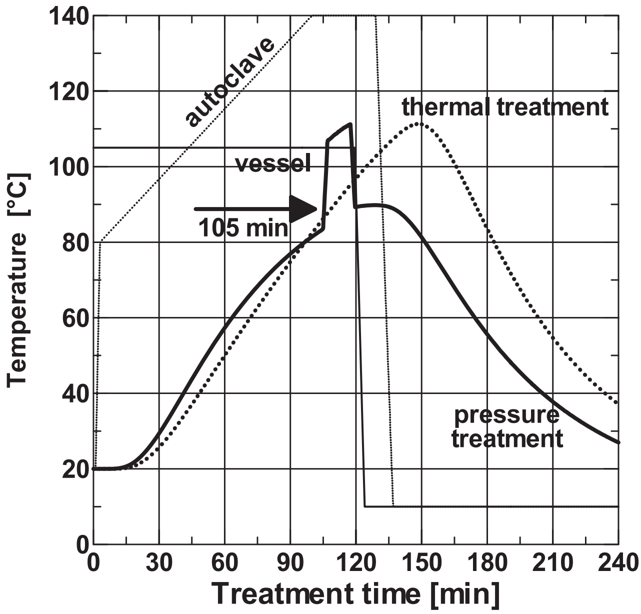

Figure 8. Core temperature of cylindrical sample with a diameter of 10 cm during a thermal and a combined thermal and high pressure sterilization (10 min., 800 MPa). Heat conductivity and density were 0.4 W/m^{2}K and 0.975 kg/l (Adapted from Heinz and Knorr, unpublished data).

temperature-time-profile, it is obvious that the thermal load of the product will be significantly reduced due to shorter residence times, in particular within the boundary regions of the can. The (transient) energy input of these processing techniques is compared in Fig. 9 at two different points of time. Ref 1 is defined as the time (105 min) when the core temperature of both techniques is equal. Ref 2 is defined as the moment when no additional energy will be transferred into the product anymore. For the high pressure process this corresponds to the end of compression, whereas for thermal processing, it occurs at the beginning of cooling. For the heating of both samples, both purely thermal processes, a heat recovery rate of 50% can be assumed, the same as for the rest of the thermal process. The specific energy input required for sterilization of cans can be reduced from 300 to 270 kJ/kg when applying a high pressure treatment. In case of high pressure processing, a compression energy recovery rate of 50% can be estimated when a two-vessel-system or a pressure storage is used. Making use of energy recovery, a specific energy input of 242 kJ/kg will be required for sterilization, corresponding to a reduction of 20%. It has to be noted that these calculations were based on the energy required for compression work.

On one hand, the discussed potential of high pressure technology for energy efficient use can be clearly described, whereas on the other hand, the high investment costs and cost intensive maintenance and service will make industrial application difficult. The advantages of high hydrostatic pressure are obvious, as high pressure application is a waste-free process since pre-sterilization of packaging by H_2O_2 or other agents will not be required; therefore, the ecological balance of preservation and filling of beverages will be improved. Pressure assisted sterilization processes are the focus of numerous research projects at present. Making use of adiabatic heat of compression, gentle temperature

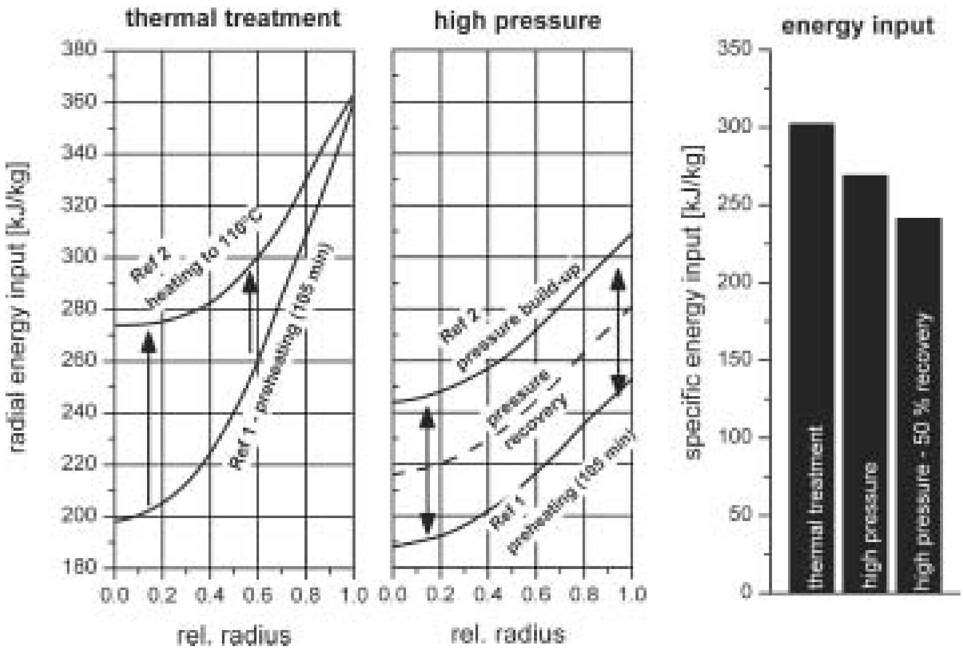

Figure 9. Comparison of radial specific energy input of a thermal and a combined thermal and high pressure sterilization for the process shown in Fig. 8 (Adapted from Heinz and Knorr, unpublished data).

profiles with lower energy inputs could be obtained in this field of application to produce superior quality products.

Conclusions

It has been shown that the application of emerging, nonthermal techniques provides a potential to reduce energy requirements for food processing and may contribute to improve energy efficiency in the food industry. Even if the techniques described are not widely applied in industrial scale at present, and evaluation of costs of investment and operation are based on results from lab-scale systems and assumptions, the selected examples indicate their potential to replace or enhance existing processes. Setting up energetic and cost balancing will be a key task for future research.

It is noteworthy that an application of pulsed electric fields to improve mass transfer rates requires very low energy input in contrast to conventional techniques; however, industrial exploitation has not yet taken place. The latest developments of impulse generation systems and high voltage components are promising and hopefully, will lead to a short term implementation of this mild and waste-free technique. In particular, improvement of sustainability and utilization of valuable components of by- and waste-products from food processing makes of PEF a promising application in the food industry. Further optimization of treatment chambers and processing parameters will help to reduce the costs of operation for pasteurization of liquid food by PEF to approach the low energy requirements for thermal pasteurization where heat recovery rates up to 95% can be reached. For heat sensitive products, or where application of plate heat exchangers is not suitable and lower heat recovery rates are obtained, the application of PEF for pasteurization may be economically sound. In addition, products where consumers and producers will accept extra costs in the range of 0.1–0.2 US $-cent for a high quality product with fresh-like character will also benefit from PEF processing.

At present, the high investment costs as well as cost-intensive maintenance and service of high pressure equipment inhibit a broad industrial exploitation, although numerous applications for high hydrostatic pressure food processing have been shown. Up to now, 82 installations are under operation worldwide, with a total production capacity 100,000 t per year (*Carole Tonello, NC Hyperbasic, personal communication*). In particular, high pressure pasteurisation units with a maximum pressure up to 600 MPa are utilized for treatment of highly valuable foods, or highly heat sensitive products that can not be preserved by other techniques. Apart from consumer benefit and reduction of energy costs, a key advantage of high pressure processing is its applicability to packaged foods, making obsolete efforts to prevent recontamination or an aseptic filling process.

Acknowledgments

The authors wish to acknowledge that part of this work has been supported by EC projects (FAIR CT96-1175, FAIR CT97-3044, W.I.R.E.S. EVK1-CT-2000-00050), the German Ministry for Education and Research (BMBF 0330089 and 0330090), the German Research Foundation (DFG Kn 260/6-1 and KN 260/11-3), and by the Research Association of the German Food Industry (FEI e.V.), the German Federation of Industrial Research Associations (AiF e.V.), and the German Ministry of Economics (Project. No. 10611 N).

References

1. Mattson, B.; Sonesson, U. Introduction. In. *Environmentally-friendly food processing*; Mattson, B., Sonesson, U., Eds.; CRC Press: Boca Raton, 2003; 1–2.
2. Pimentel, D.; Pimentel, M. The future of american agriculture. In *Sustainable Food Systems*; Knorr, D. Ed.; AVI: Westport, 1983, 3–27.
3. Andersson, K.; Ohlsson, T. Including environmental aspects in production development: a case study of tomato ketchup. LWT **1999**, *32* (3), 134–141.
4. Doevenspeck, H. Influencing cells and cell walls by electrostatic impulses. Fleischwirtschaft **1961**, *13* (12), 968–987.
5. Sale, A.J.; Hamilton, W.A. Effect of high electric fields on micro-organisms. I. Killing of bacteria and yeast. II. Mechanism of action of the lethal effect. Biochimica Biophysica Acta **1967**, *148*, 781–800.
6. Dalsgaard, H.; Abbotts, A.W. Improving energy efficiency. In *Environmentally-friendly food processing*; Mattson, B., Sonesson, U.; Eds; CRC Press: Boca Raton, 2003, 116–129.
7. DOE, US Department of Energy. *Manufacturing consumption of energy 1994*; Energy Information Administration: USDOE, Washington DC, 1997.
8. Miller, E.J. Energy management in milk processing. In energy in food processing; Singh, R.P., Eds.; Elsevier: Amsterdam, The Netherlands, 1986, 137–154.
9. Vickers, V.T.; Shannon, D.V. Energy use in the dairy industry. New Zealand Energy Research and Development Committee: Auckland, 1977, 54.
10. Orkos, M.; Rao, N.; Drecher, S.; Rode, M.; Kozak, J. *Energy usage in the food industry*; American Council for an energy-efficient economy (ACEEE): Washington, DC, 1998, 86.
11. Zhang, Q.; Barbosa-Canovas, G.V.; Swanson, B.G. Engineering aspects of pulsed electric field pasteurization. J. Food Engin. **1995**, *25*, 261–281.

12. Grahl, T.; Märkl, H. Killing of microorganisms by pulsed electric fields. Appl Microbiol. Biotechnol. **1996**, *45*, 148–157.
13. Wouters, P.C.; Smelt, J.P.P.M. Inactivation of microorganisms with pulsed electric fields: Potential for food preservation. Food Biotechnol. **1997**, *11*, 193–229.
14. Barbosa-Cánovas, G.V.; Góngora-Nieto, M.M.; Pothakamury, U.R.; Swanson, B.G. *Preservation of foods with pulsed electric fields*; Academic Press: San Diego, 1999.
15. Peleg, M. A model of microbial survival after exposure to pulsed electic fields. J. Sci. Food Agricult. **1995**, *67*, 93–99.
16. Heinz, V.; Alvarez, I.; Angersbach, A.; Knorr, D. Preservation of liquid foods by high intensity pulsed electric fields-basic concepts for process design. Trends Food Sci. Techno. **2002**, *12*, 103–111.
17. Brodelius, P.E.; Funk, C.; Shilito, R.D. Permeabilization of Cultivated Plant Cells by Electroporation for Release of Intracellularly Stored Secondary Products. Plant Cell Reports **1988**, *7*, 186–188.
18. Eshtiaghi, M.N.; Knorr, D. **1999**, Process for treatment of sugar beet. European Patent No. EP 99923708. Filed June 9, 1999; approved March 3, 2001.
19. Fincan, M. Pulsed Electric Field Treatment of Plant Tissue. Ph.D.-Thesis. Department of Food Engineering. Lund University, **2003**, Lund, Sweden.
20. Lebovka, N.I.; Praporscic, I.; Vorobiev, E. Effect of moderate thermal and pulsed electric field treatments on textural properties of carrots, potatoes and apples. Inno. Food Sci. Emerging Technol. **2004**, *5* (1), 9–16.
21. Aibara, S.; Esaki, K.; Effects of high-voltage electric field treatment on bread starch. Biosci. Biotech. Biochem. **1998**, *62*, 2194–2198.
22. Ho, S.Y.; Mittal, G.S.; Cross, J.D. Effects of high field electric pulses on the activity of selected enzymes. J. Food Engin. **1997**, *31*, 69–84.
23. Hodgins, A.M.; Mittal, G.S.; Griffiths, M.W. Pasteurization of Fresh Orange Juice Using Low-Energy Pulsed Electrical Field. J. Food Sci. **2002**, *67* (6), 2294–2299.
24. Bendicho, S.; Barbosa-Cánovas, G.V.; Martín, O. Reduction of Protease Activity in Simulated Milk Ultrafiltrate by Continuous Flow High Intensity Pulsed Electric Field Treatments. J. Food Sci. **2003**, *68* (3), 952–957.
25. Dörnenburg, H.; Knorr, D. Cellular permeabilization of cultured plant cell tissues by high electric field pulses or ultra high pressure for recovery of secondary metabolites. Food Biotechnol. **1993**, *7*, 35–38.
26. Guderjan, M.; Toepfl, S.; Angersbach, A.; Knorr, D. Impact of pulsed electric field treatment on the recovery and quality of plant oils. J. Food Engin. **2005**, *67* (3), 281–287.
27. Flaumenbaum, B.L. Anwendung der Elektroplasmolyse bei der Herstellung von Fruchtsäften. Flüssiges Obst. **1968**, *35*, 19–22.
28. Knorr, D.; Geulen, M.; Grahl, T.; Sitzmann, W. Food application of high electric field pulses. Trends Food Sci. Techno. **1994**, *5*, 71–75.
29. Knorr, D.; Angersbach, A. Impact of high-intensity electric field pulses on plant membrane permeabilization. Trends Food Sci. Techno. **1998**, *9*, 185–191.
30. Bazhal, M.; Vorobiev, E. Electrical Treatment of apple cossettes for intensifying juice pressing. Journal of the Science of Food and Agriculture **2000**, *80*, 1668–1674.
31. Fincan, M.; DeVito, F.; Dejmek, P. Pulsed electric field treatment for solid-liquid extraction of red beetroot pigment. J. Food Engin. **2004**, *64*, 381–388.
32. Angersbach, A.; Heinz, V.; Knorr, D. Elektrische leitfähigkeit als maß des zellaufschlussgrades von zellularen materialien durch verarbeitungsprozesse. LVT **1997**, *42*, 195–200.
33. Eshtiaghi, M.N.; Knorr, D. Anwendung elektrischer Hochspannungsimpulse zum Zellaufschluss bei der Saftgewinnung am Beispiel von Weintrauben. LVT **2000**, *45*, 23–27.
34. Sensoy, I.; Sastry, S.K. Extraction Using Moderate Electric Fields. J. Food Sci. **2004**, *69* (1), 7–13.
35. Singh, R.P. Energy accounting in food processing operations. In Energy in food processing; Singh, R.P. Ed.; Elsevier: Amsterdam, 1986.

36. Kraus, W. The 2002 beet campaign — VDZ Zweigverein Süd. Zuckerindustrie **2003**, *128* (5), 344–354.
37. Bouzrara, H.; Vorobiev, E. Beet Juice Extraction by pressing and pulsed electric fields. Int. Sugar J. **2000**, *102* (1216), 194–200.
38. Rastogi, N.K.; Eshtiaghi, M.N.; Knorr, D. Accelerated mass transfer during osmotic dehydration of high intensity electrical field pulse pretreated carrots. J. Food Sci. **1999**, *64* (6), 1020–1023.
39. Taiwo, K.A.; Angersbach, A.; Knorr, D. Influence of high intensity electric field pulses and osmotic dehydration on the rehydration characteristics of apple slices at different temperatures. J. Food Engin. **2002**, *52*, 185–192.
40. Angersbach, A.; Knorr, D. Anwendung elektrischer Hochspannungsimpulse als Vorbehandlungsverfahren zur Beeinflussung der Trocknungscharakteristika und Rehydrationseigenschaften von Kartoffelwürfels. Nahrung **1997**, *41*, 194–200.
41. Ade-Omowaye, B.I.O.; Angersbach, A.; Taiwo, K.A.; Knorr D. Use of pulsed electric field treatment to improve dehydration characteristics of plant based foods. Trends Food. Sci. Techno. **2001**, *12*, 285–295.
42. Bazhal, M.; Lebovka, N.I.; Vorobiev, E. "Optimisation of pulsed electric field strength for electroplasmolysis of vegetable tissues." Biosys. Engin. **2003**, *86* (3), 339–345.
43. Angersbach, A.; Heinz, V.; Knorr, D. Effects of pulsed electric fields on cell membranes in real food systems. Inno. Food Sci. Emerging Technol. **2000**, *1*, 135–149.
44. Qin, B.-L.; Zhang, Q.; Barbosa-Cánovas, G.V.; Swanson, B.G.; Pedrow, P.D. Inactivation of microorganisms by pulsed electric fields of different voltage waveforms. IEEE Transactions on Dielectrics and Electrical Insulation **1994**, *1* (6), 1047–1057.
45. Zhang, Q.; Qin, B.L.; Barbosa-Cánovas, G.V.; Swanson, B.G. Inactivation of *Escherichia coli* for food pasteurization by high-strength pulsed electric fields. J. Food Proc. Preservation **1995**, *19*, 103–118.
46. Gaskova, D.; Sigler, K.; Janderova, B.; Plasek, J. Effect of high-voltage electric pulses on yeast cells: factors influencing the killing efficiency. Bioelectrochem. Bioenerg. **1996**, *39*, 195–202.
47. Jeyamkondan, S.; Jayas, D.S.; Holley, R.A. Pulsed electric field processing of foods: a review. Journal of Food Protection **1999**, *62* (9), 1088–1096.
48. Ho, S.; Mittal, G.S. High voltage pulsed electrical field for liquid food pasteurization. Food Rev. Int. **2000**, *16* (4), 395–434.
49. Cserhalmi, Z.; Vidacs, I.; Beczner, J.; Czukor, B. Inactivation of *Saccharomyces cerevisiae* and *Bacillus cereus* by pulsed electric field technology. Inno. Food Sci. Emerging Technol. **2002**, *3* (1), 41–45.
50. Zhang, Q.; Monsalve-González, A.; Qin, B.L.; Barbosa-Cánovas, G.V.; Swanson, B.G. Inactivation of *Saccharomyces cerevisiae* in apple juice by square-wave and exponential-decay pulsed electric fields. J. Food Proc. Engin. **1994**, *17*, 469–478.
51. Qui, X.; Sharma, S.; Tuhela, L.; Jia, M.; Zhang, Q.H. An integrated PEF pilot plant for continuous nonthermal pasteurization of fresh orange juice. Transactions ASAE **1998**, *41*, (4), 1069–1074.
52. Evrendilek, G.A.; Jin, Z.T.; Ruhlman, K.T.; Qiu, X.; Zhang, Q.H.; Richter, E.R. Microbial safety and shelf-life of apple juice and cider processed by bench and pilot scale PEF systems. Inno. Food Sci. Emerging Technol. **2000**, *1*, 77–86.
53. McDonald, C.J.; Lloyd, S.W.; Vitale, M.A.; Petersson, K.; Innings, F. Effect of pulsed electric fields on microorganisms in orange juice using electric field strengths of 30 and 50 kV/cm. J. Food Sci. **2000**, *65* (6), 984–989.
54. Heinz, V.; Toepfl, S.; Knorr, D. Impact of temperature on lethality and energy efficiency of apple juice pasteurization by pulsed electric fields treatment. Inno. Food Sci. Emerging Technol. **2003**, *4* (2), 167–175.
55. Molinari, P.; Pilosof, A.M.R.; Jagus, R.J. Effect of growth phase and inoculum size on the inactivation of *S. cerevisiae* in fruit juices by pulsed electric fields. Food Res. Int. **2004**, *37* (8), 793–798.

56. Ulmer, H.M.; Heinz, V.; Gaenzle, M.G.; Knorr, D.; Vogel, R.F. Effects of pulsed electric fields on inactivation and metabolic activity of *Lactobacillus plantarum* in model beer. Journal of Applied Microbiology **2002**, *93* (2), 326–335.
57. Reina, L.D.; Jin, Z.T.; Zhang, Q.H.; Yousef, A.E. Inactivation of *Listeria monocytogenes* in milk by pulsed electric field. Journal of Food Protection **1998**, *61*, 1203–1206.
58. Bendicho, S.; Barbosa-Cánovas, G.V.; Martin, O. Milk processing by high intensity pulsed electric fields. Trends Food Sci. Techno. **2002**, *13*, 195–204.
59. Martín-Belloso, O.; Vega-Mercado, H.; Qin, B.L.; Chang, F.J.; Barbosa-Cánovas, G.V.; Swanson, B.G. Inactivation of *Escherichia coli* suspended in liquid egg using pulsed electric fields. J. Food Proc. Preservation **1997**, *21*, 193–203.
60. Selma, M.V.; Salmerón, M.C.; Valero, M.; Fernández, P.S. Control of *Lactobacillus plantarum* and *Escherichia coli* by pulsed electric fields in MRS Broth, nutrient broth and carrot-apple juice. Food Microbiology **2004**, *21*, 519–525.
61. Lado, B.H.; Yousef, A.E. Selection and Identification of a *Listeria monocytogenes* target strain for pulsed electric field process optimization. Applied and Environmental Microbiology **2003**, *69*, 2223–2229.
62. Toepfl, S.; Heinz, V.; Knorr, D. Optimization of pulsed electric field treatment for liquid food pasteurization. European Pulsed Power Symposium 2004, Hamburg, Germany, Shaker Verlag: Aachen, Germany.
63. Aronsson, K.; Rönner, U.; Borch, E. Inactivation of Escherichia coli, Listeria innocua and Saccharomyces cerevisiae in relation to membrane permeabilization and subsequent leakage of intracellular compounds due to pulsed electric field processing. Int. J. Food Micro. **2005**, *99*, 19–32.
64. Góngora-Nieto, M.M.; Pedrow, P.D.; Swanson, B.G.; Barbosa-Cánovas, G.V. Energy analysis of liquid whole egg pasteurized by pulsed electric fields. J. Food Engin. **2003**, *57*, 209–216.
65. Zhang, Q.H.; Chang, F.J.; Barbosa-Cánovas, G.V. Inactivation of microorganisms in semisolid foods using high voltage pulsed electric fields. LWT **1994**, *27* (6), 538–543.
66. Evrendilek, G.A.; Zhang, Q.H. Effect of pulse polarity and pulse delaying time on pulsed electric fields-induces pasteurization of *E. coli* O157:H7. J. Food Engin. **2005**, *68*, 271–276.
67. Kopplow, O.; Barjenbruch, M.; Heinz, V. Sludge pre-treatment with pulsed electric fields. Water Sci. Technol. **2004**, *49* (10), 123–129.
68. Loeffler, M.; Schmidt, W.; Schuhmann, R.; Röttering, A.; Neumann, J.; Dreesen, C. Treatment of sewage sludge with pulsed electric fields. International Conference on Pulsed Power Applications, Gelsenkirchen, Germany, March 27–29, 2001.
69. Koners, U.; Toepfl, S.; Heinz, V.; Camacho, P.; Ginestet, P.; Knorr, D. *Application of pulsed electric field treatment for sludge reduction on waste water treatment plants*, 2nd European Pulsed Power Symposium, Hamburg, Germany, 2004, Shaker Verlag: Aachen, Germany.
70. Anonymous. Umfrage zur Klärschlamm-Entsorgung in Baden-Württemberg. Dienstleistungsgesellschaft des Gemeindetags Baden-Würtemberg: Herzebock-Clarholz, 2003.
71. Halbach, U.; Eichhorn, U.; Hallbach, M.; Behlke, A. Abwasserentsorgung in Brandenburg. U. u. R. d. L. B. Ministerium für Landwirtschaft. Potsdam, Ministerium für Landwirtschaft, Umweltschutz und Raumordnung des Landes Brandenburg: **2003**, 61.
72. Fernandez Garcia, A.; Heindl, P.; Voigt, H.; Büttner, M.; Wienhold, D.; Butz, P.; Stärke, J.; Tauscher, B.; Pfaff, E. Reduced proteinase K resistance and infectivity of prions after pressure treatment at 60°C. Journal of General Virology **2004**, *85*, 261–264.
73. National Institute of Standards and Technology (NIST). NIST Standard Reference Database 10; Steam Properties Database Version 2.21. Available at http://www.nist.gov/srd/nist10.htm.
74. Ting, E.; Balasubramaniam, V.M.; Raghubeer, E.; Determining thermal effects in high pressure processing. Journal of Food Technolgy **2002**, *56* (2), 31–35.
75. Ardia. *Process Considerations on the Application of High Pressure Treatment at Elevated Temperature Levels for Food Preservation*; Department of Food Biotechnology and Food Process Engineering, Berlin University of Technology, Berlin, 2004; 94.
76. U.S. Department of Energy. Manufacturing Consumption of Energy 1994, DOE/EIA-0512(94), USDOE: Washington, DC, 1997.