Chapter 17
Emerging Technologies for Targeted Food Processing

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17.1 Introduction

Taking advantage of the specific potentials and opportunities of new food processing technologies, including the understanding and control of the complex process-structure-function relationships, offers the possibility for a science-based development of tailor-made foods. In this chapter, we use high hydrostatic pressure (HP), pulsed electric fields (PEFs), ultrasound (US), and cold plasma (CP) to exemplify scalable and flexible food manufacturing techniques, discussing the state of the art regarding the research and application of these emerging technologies and demonstrating the potential of establishing new routes of process and product development by interfacing food science and food manufacturing.

Significant, science-based achievements have been made to better understand the basic principles underlying HP and PEF processing (Hendrickx and Knorr 2002; Raso and Heinz 2007).

The food and beverage industry offers manifold possibilities for the use of US. The basic phenomena, such as microstreaming and cavitation and the resulting hydrodynamic shear forces, make US an alternative technology for homogenization, dispersion, and emulsifying, as well as for the disintegration of tissue, to enhance mass transfer processes (Mason et al. 1996; Povey and Mason 1998).

A strong increase in plasma applications in medical device technology and therapeutic medicine is currently taking place, including applications such as plasma decontamination, and research is focusing on the interaction between

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plasma and biological cells and tissue as well as on plasma diagnostics with regard to the understanding and control of the complex behavior of CP (Daeschlein et al. 2010; Weltmann et al. 2009). Similar research work is being undertaken in the field of food science to explore the potential for CP application in the food industry (Mastwijk and Nierop Groot 2010) which will be discussed below.

Understanding the impact and potential of such technologies on food systems at the cellular level will enable the design of tailor-made foods and to establish process-structure-function relationships. Based on this knowledge, completely new process designs, the incorporation of HP, PEF, US, and CP in traditional processes, and the generation of improved equipment design will be possible. Consequently, the use of such nonthermal processes for maintenance or even improvement of product quality via processing to meet the PAN (consumer preference, acceptance, and needs) concept of the European Technology Platform Food for Life (http://etp.ciaa.eu), and thus the reverse food engineering approach, will be a major innovative approach within the food industry.

17.2 High Pressure Processing

High pressure processing (HPP) is one of the leading nonthermal food processing technologies and often regarded as one of the major technological innovations in food preservation in recent decades. In recent years HPP has emerged as a viable commercial alternative for food pasteurization for high-quality food.

The pressure levels used range from several tens of megapascals in common homogenizers or supercritical fluid extractors to several hundred megapascals in ultra-high-pressure homogenizers or HP pasteurization units. Besides the inactivation of microorganisms to enhance the shelf life of the treated food, which is by far the most common HPP application, there are numerous other interesting applications like food structure engineering or HP biotechnology (Aertsen et al. 2009; Diels and Michiels 2006; Knorr et al. 2006; Sharma and Yadav 2008).

17.2.1 Process Description: High-Pressure Processing on an Industrial Scale

On the industrial scale, HPP is commonly used for the inactivation of vegetative microorganisms in packed meat (30 %) and vegetable (34 %) products as well as fruit juices and smoothies (13 %), often accompanied by a simultaneous inactivation of enzymes

The applied pressure levels tend from 200 to 350 MPa for seafood, to increase the shucking yield, up to 600 MPa for meat products, to increase the shelf life. The installations that are in commercial use have vessel volumes between 35 and 687 L.

Typical industrial HP units consist of a horizontal HP vessel and an external pressure-generating device. The simplest practical system of an intensifier is a single-acting, hydraulically driven pump (Rovere 2002).

For HP treatment, the packaged food is deposed in a carrier and automatically loaded into the HP vessel, and the vessel plugs are closed. The pressure-transmitting medium, usually water, is pumped into the vessel from one or both sides. When the desired maximum pressure is reached, the pumping is stopped, and in ideal cases no further energy input is needed to hold the pressure during dwell time. In contrast to thermal processes where temperature gradients occur, all molecules in HP vessels are subjected to the same amount of pressure at exactly the same time due to the isostatic principle of pressure transmission (Heinz et al. 2009; Rastogi et al. 2007).

Accompanied by an increase in pressure the temperature rises as well due to the thermodynamic effect of the adiabatic heat of compression. This temperature increase could be calculated as a function of thermophysical properties of the compressible product for simple systems by a rearrengemant of the Maxwell equations (Perry 1984; Reineke et al. 2008). This quasi-adiabatic heating or cooling occurs instantly. Hence, pressure-induced temperature changes are predictable and homogeneous throughout the product, assuming it is homogeneous in its composition. This ideal adiabatic process does not occur in practical applications, but the extent of the temperature increase could be estimated at 3–9 °C per 100 MPa depending on the treated food or food composition (Ting et al. 2002).

17.2.2 Research State of the Art

The main thermodynamic driving force behind reactions under pressure is the specific reaction volume. Hence, reactions, accompanied by a decrease in its reaction volume, are favored under pressure. Consequently, HPP does not affect covalent bonds at pressure levels below 2 GPa or the structure of small molecules, contrary to macromolecules or the more complex systems that will be discussed in this chapter.

17.2.2.1 Impact of HP on Biological Cells

To ensure food safety, tremendous research was done on the inactivation of biological cells and its underlying inactivation mechanisms. In general HPP is described as a nonthermal technology, but with regard to the adiabatic heat of compression, thermal effects could not be fully ruled out. Hence, the complex inactivation mechanism of biological cells and viruses is almost always connected to the process temperature (Smelt et al. 2001). Primarily, HP affects the properties of biological membranes over a broad temperature range (Winter and Jeworrek 2009). Although this lethal effect could be further accelerated at higher treatment

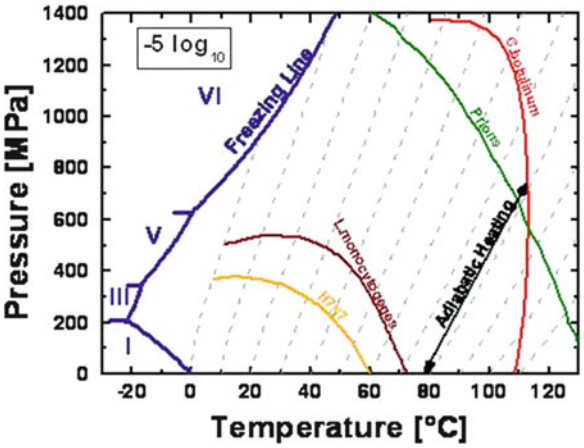

Fig. 17.1 Isorate lines for a 5 $\log_{10}$ reduction of microorganisms, prions, and viruses under various pressure and temperature conditions with adiabatic lines due to the compression (–) of water. H7N7, the surrogate for bird flu virus H5N1 (chicken meat slurry) (Isbarn et al. 2007), *Listeria monocytogenes* 75903 (in ham slurry), prions-PrP^{SC} (in raw meat), and *Clostridium botulinum* (in TRIS buffer pH 5.15) (Margosch et al. 2006). *Blue line*: freezing line between liquid water and different pressure-dependent ice modifications

temperatures, additional enzyme inactivation occurs (Ananta 2005; Ardia 2004) (Buckow and Heinz 2008).

However, pressure treatments do not necessarily inactivate biological cells. At low pressure levels increased resistance of vegetative cells was observed. Ananta and Knorr (2003) reported a higher thermotolerance of lactic acid bacteria after HP treatments up to 200 MPa. As a result of this phenomenon, pressure-induced stress response was found to offer promising processing options, such as pretreatment of lactic acid bacteria before spray or freeze drying for the purpose of starter culture production (Ananta 2005).

Higher pressures between 300 and 800 MPa and ambient treatment temperatures are suitable for the inactivation of several vegetative microorganisms in food products (Ananta et al. 2005; Hendrickx and Knorr 2002). The special shape of isorate lines at these conditions are shown in Fig. 17.1. A synergistic effect between pressure and temperature on the inactivation of vegetative cells is typical but was also observed for bacterial spores (Ardia 2004; Margosch et al. 2006), viruses (Isbarn et al. 2007), and proteins (Heinz and Kortschack 2002; Smeller 2002). By increasing the process temperature, it is possible to decrease the applied pressure, but unwanted reactions (e.g., based on residual enzyme activity) that would lead to quality losses must also be taken into account.

According to Smelt et al. (2001), the HP induced effects resulting in vegetative cell death can be summarized as follows:

Proteins and enzymes: HP induces unfolding of globular proteins. It is assumed that the combined, complete, or partial inactivation of numerous enzymes and

metabolic pathways leads to an inability to proliferate and cell death, respectively (Bunthof 2002).

Membranes: besides the inactivation of enzymes, membrane damage is considered one of the key events related to microbial cell death. Membranes undergo phase transitions and solidify under pressure and perturbations are promoted (Schlueter 2004; Winter 1996). In addition, pressure leads to the detachment and inactivation of membrane proteins (Ulmer et al. 2002).

Ribosomes: the disintegration of ribosomes in their subunits is promoted by pressure and may be related to cell death (Niven et al. 1999).

pH: the maintenance of intracellular pH is crucial for the survival of cells. Some authors have related cell death predominantly to intracellular pH changes, which are related to inactivation of enzymes controlling acidity and membrane damage (Molina-Gutierrez et al. 2002).

Bacterial spores have a higher barotolerance than vegetative bacteria and survive pressures above 1,200 MPa at ambient temperatures (Ananta et al. 2001; Margosch et al. 2006). Early approaches to spore inactivation aimed at a pressure-induced germination at moderate pressure. However, combination processes with spore germination at pressures below 200 MPa and an additional moderate heat treatment could not guarantee sufficient inactivation since small populations of spores could not be germinated and remain in the dormant state (Heinz and Knorr 1996; Reineke et al. 2011).

Several papers indicate a synergism between pressure and temperature with regard to spore inactivation (Bull et al. 2009; Margosch et al. 2006; Mathys et al. 2009; Olivier et al. 2011; Rajan et al. 2006; Reineke et al. 2012). Consequently, the HP sterilization process is rapidly attracting industrial interest, especially due to the acceptance of pressure-assisted thermal processing (PATS) by the U.S. Food and Drug Administration in 2009, in which the adiabatic heat of compression is used to rapidly achieve 121.1 °C.

In contrast to the synergistic effect of pressure and temperature, several authors have stated that some spore strains are more resistant under certain pressure–temperature combinations (Margosch et al. 2006; Mathys et al. 2009; Wuytack et al. 1998), that their thermal resistance is nearly independent of the treatment pressure (proteolytic Typ B *Clostridium botulinum* TMW 2.357 for pressures below 1.2 GPa) (Margosch et al. 2006), or that their thermal/pressure resistance varies with the pH of the suspension medium or the food matrix being used, e.g., for *Bacillus coagulans* (Olivier et al. 2011; Vercammen et al. 2011).

The HP inactivation of bacterial spores is not yet fully understood and still of high relevance in today's HP sterilization research activities (Reineke et al. 2011a, b). A detailed discussion of HP-related spore inactivation mechanisms is given by Mathys (2008).

Furthermore, HPP below 0 °C enables a significant inactivation of vegetative microorganisms as well if the treated food is frozen under pressure. Here the dominant mechanism of microorganism inactivation is due to mechanical stress

during the freezing process. Luscher (2008) suggests two different mechanisms that occur during high freezing rates and the occurrence of different ice modifications. Internal disintegration occurs during freezing at high freezing rates, for example, during high-pressure shift freezing (HPSF), when water in the intracellular room freezes. The increase in volume of the water during crystallization initiates high internal pressure and eventually causes lethal membrane rupture. However, the freezing rate must be high enough to allow crystallization of the intracellular water since in general high freezing rates are linked to the formation of small ice crystals, which reduces the lethal effect of the freezing process.

The second supposed inactivation mechanism is external disintegration, which takes place during the solid–solid phase change from ice III to ice I. The density decrease of about 19 % during recrystallization causes high mechanical stress to the bacterial cells. The increasing volume of the ice crystals potentially breaks the cell walls of bacterial cells that are incorporated into the ice matrix.

17.2.2.2 Impact of HP on Enzymes

HP is regarded as a mild process by which the primary structure of proteins is not affected at pressure below 2 GPa. However, it could have an impact on hydrophobic interactions as well as on intermolecular covalent bonds, such as disulfide bonds, which stabilize the quaternary and tertiary structure. Generally pressure-induced changes in proteins and enzymes between 100 and 300 MPa at ambient temperature are reversible and could additionally lead to an unfolding of protein chains and a dissociation of oligomeric proteins (Buckow 2006; Tauscher 1995). A further pressure increase above 400 MPa could lead to an irreversible unfolding and, consequently, to an inactivation of the enzymes, for example.

Due to conformational changes, the unfolding of an enzyme can alter its functionality and result in a decreased or increased biological activity and could even change its substrate specificity (Buckow and Heinz 2008; Ludikhuyze et al. 2002). The pressure stability of enzymes can vary significantly, ranging from pressure-sensitive enzymes, such as phosphohexoseisomerase from bovine milk ($p < 400$ MPa) (Rademacher and Hinrichs 2006), to extreme pressure-resistant enzymes like peroxidase from horseradish ($p > 700$ MPa) (Smeller and Fidy 2002). However, a categorization of enzymes as a result of their pressure stability is not appropriate since there is a structural variability among enzymes catalyzing the same reaction (Buckow and Heinz 2008). Even isoforms of an enzyme from the same origin can vary in their physical stability between several hundred megapascals (Buckow et al. 2005; Rodrigoa et al. 2006).

Additionally, the pressure–temperature resistance of enzymes shows a significant dependency on matrix conditions like, for example, the pH value (Riahi and Ramaswamy 2004; Zipp and Kauzmann 1973).

Interestingly, some enzymes show an enhanced thermostability under specific pressure–temperature conditions, which could be attributed to the often antagonistic effect of pressure and temperature (Heremans and Smeller 1998). Such

stabilization of enzymes could occur when the volume difference between the folded and unfolded states of the protein are positive, which might be caused by the promoted formation of noncovalent bonds under the applied pressure.

17.2.2.3 Impact of HP on Food Constituents

Due to their relatively simple three-dimensional structure, low molecular weight molecules like peptides, lipids, vitamins, and saccharides are rarely affected by isostatic HP because of the very low compressibility of covalent bonds at pressures below 2 GPa (Cheftel and Culioli 1997; Oey et al. 2006; Van den Broeck et al. 1998). Conversely, HP can change the native structure of macromolecules, such as starch, similar to thermal-induced structural changes.

In particular, the impact of HP on gelatinization of starch could influence the processing properties of starch-based food systems, whereas pressure-induced gelatinization differs in comparison to the thermal-induced one (Stute et al. 1996). HP-induced gelatinization is characterized by a limited swelling of the starch granules, which is accompanied by a retention of its structure and a loss of birefringence under polarized light (Buckow et al. 2007). The extent of starch gelatinization is dependent on the applied pressure, the dwell time, and the treatment temperature (Rumpold and Knorr 2005), whereas the type of starch has the highest impact on its gelatinization behavior under pressure. Starches with a B-type crystalline structure such as potato, which is generally found in roots, are more resistant to pressure than A- or C-type starches like, for example, wheat starch (Stute et al. 1996).

Furthermore, HP could significantly affect the three-dimensional structure of proteins. Depending on the applied pressure level, this could lead to a reversible or irreversible unfolding of the proteins, whereas the primary structure itself would not be affected. In this regard, examples and mechanisms were discussed in the previous section.

17.2.3 Process-Structure Function Interactions

As mentioned in Sect. 3.2.3, the gelatinization of starches under pressure is significantly different from that induced by heat, and hence they offer unique functional properties, like, for example, the formation of weak gels, which could be used as a fat replacement in dietary foods (Sharma et al. 2008; Zhang et al. 2008).

Gels with unique properties are also formed by proteins, such as ß-lactoglobulin (Dumay et al. 1998). For such a system, the pressure-induced gel matrix yields small particles in highly packed ß-lactoglobulin, unlike the gels after heating, which exhibit finely stranded aggregates. Furthermore, Zeece et al. (2008) reported that a HP treatment from 400 to 800 MPa at 20 °C considerably improved the digestibility of ß-lactoglobulin. Thus, pressure-induced protein gels open up the possibility of

generating new textures as they additionally retain their original flavor and color accompanied by a glossy appearance. Such gels can be applied for the manufacture of milk products to, for example, improve yogurt texture (Johnston et al. 1993) or increase cheese yield (López-Fandino et al. 1996).

A further possibility for the creation of a novel texture is to pressure treat mixtures of proteins and polysaccharides, which has been studied by Michel and Autio (2002).

17.2.4 Current Applications and Process Development

Actually, HP pasteurization of fresh products is the main application, with an annual production volume of more than 300,000 t/a (C. Tonelle, personal communication, NC Hiperbaric). Whereas most products are fresh-cut fruits and fruit purees (34 %), with the processing goal of an extended shelf life including reduced or no enzymatic browning, the pressure processing of meat. More than 30 % of the total vessel volume is used to process meat products like sliced ham, turkey or chicken cuts, and ready-to-eat-meals, primarily to inactivate *Listeria* and to increase the shelf life of the treated product.

17.2.5 Research Needs and Challenges

The continuous increase in HP research over the last several decades has already generated the bases for several commercially available HP-processed high-quality products. Besides "cold" pasteurization, isostatic HP can also be used to generate novel functional features, such as specific textures or health-promoting properties, to develop tailor-made foods. A very promising field for further research is the application of low and moderate HP to modulate microbial fermentations or enzymatic conversations. Under these conditions, biosyntheses pathways could be active, which could lead to the formation of product variants with novel functional properties (Aertsen et al. 2009). A better understanding of the pressure and temperature stability of proteins could enable the construction of HP-resistant enzymes. These findings may also be applicable to the behavior of nutrients, allergens, and food-spoiling viruses under defined matrix (Mathys and Knorr 2009) and treatment conditions.

A standardization of experimental protocols would increase the comparability of results, which could be used later on for modeling.

To successfully introduce HP thermal sterilization to the food industry, a pressure- and temperature-resistant indicator microorganism must be found and the microbial targets that lead to an inactivation of bacterial endospores understood.

It should also be noted that the physicochemical properties of food constituents such as water vary under high-pressure or high-temperature conditions, making

process development and the understanding of mechanisms challenging (Mathys and Knorr 2009) and promoting or inhibiting desired and undesired chemical reactions in processed food.

To reduce processing costs and to investigate the temperature distribution during HP treatment, especially under sterilization conditions, modeling and simulation of the behavior of HP-treated biomaterials plus the temperature distributions in the HP vessel present a challenge (Delgado et al. 2008).

17.3 Pulsed Electric Fields

17.3.1 Process Description

When exposed to high electric field pulses, cell membranes develop pores that may be permanent or temporary, depending on the intensity and treatment conditions (Angersbach et al. 2000; Zimmermann et al. 1976; Zimmermann et al. 1974). Pore formation increases membrane permeability, which results in the loss of cell content or the intrusion of surrounding media (Phoon et al. 2008; Vorobiev and Lebovka 2008). Low-intensity treatment has the potential to induce stress reactions in plant cells, resulting in the promotion of a defense mechanism by increased production of secondary metabolites (Dörnenburg and Knorr 1993; Galindo et al. 2009; Gomez Galindo, et al. 2008). An irreversible perforation of the cell membrane reduces its barrier effect permanently and causes cell death, which can be applied to plant and animal raw material disintegration (Angersbach and Knorr 1998; Puértolas et al. 2010; Toepfl and Heinz 2007) and to the nonthermal inactivation of microorganisms (Lelieveld et al. 2007; Toepfl et al. 2007).

Pulsed electric field (PEF) processing consists of the application of very short electric pulses (1–100 μs) at electric field intensities in the range of 0.1–1 kV/cm (reversible permeabilization for stress induction in plant cells), 0.5–3 kV/cm (irreversible permeabilization of plant and animal tissue), and 15–40 kV/cm for the irreversible permeabilization of microbial cells. Depending on cell size and shape, the aforementioned field intensities lead to the formation of a critical transmembrane potential that is regarded as the precondition for membrane breakdown (Tsong 1996).

Since the mechanism of electroporation is mainly based on a mechanical electrocompressive force affecting the cell membrane, PEF technology is considered a nonthermal cell disintegration or preservation process. It provides an alternative to mechanical, thermal, and enzymatic cell disintegration of plant and animal raw materials, providing a short-duration (milliseconds), low-energy treatment, and an alternative to the traditional thermal pasteurization of liquid food products (Barbosa-Cánovas et al. 1999; Raso and Heinz 2006).

17.3.2 Research State of the Art

Effective inactivation for most spoilage and pathogenic microorganisms has been demonstrated, and colony count reductions, depending on treatment intensity, product properties, and type of microorganism in the range of 4–6 log-cycles, are comparable to traditional thermal pasteurization. Bacterial spores and viruses are not affected by PEF treatment (Lelieveld et al. 2007). Reports on the effects of PEFs on enzymes are limited, and different experimental setups and processing parameters make them difficult to compare (Van Loey et al. 2002). Thermal effects were also found to contribute to enzyme inactivation during PEF treatment (Jaeger et al. 2009; Jaeger et al. 2010). The first large-scale industrial applications were carried out for the disintegration of plant raw materials such as sugar beet and fruit mashes (Bluhm and Sack 2009). Industrial equipment is available up to capacities of a single system of 5,000 L/h for PEF processing of liquids for nonthermal pasteurization with total treatment costs of around US$0.6/kg and 50 t/h for cell disintegration applications with related total treatment costs of around 0.5 euro/t (DIL 2011).

17.3.2.1 Impact on Biological Cells

Until now there has been no clear evidence on the underlying mechanisms at the cellular level, but two main effects have been described as being triggered by the electric field: the ionic punch-through effect (Coster 1965) and the dielectric breakdown of the membrane (Zimmermann et al. 1974). The factors affecting microbial inactivation during PEF treatment are process factors, such as electric field intensity, pulse width and shape, and treatment time and temperature, microbial factors such as type, shape, size, concentration, and growth stage of the microorganism, and media factors such as pH, antimicrobials and ionic compounds, electrical conductivity, and ionic strength of the medium.

Membrane damage and inactivation of microorganisms due to PEF, first considered as an all-or-nothing event in some studies (Russel et al. 2000; Simpson et al. 1999; Wuytack et al. 2003; Yaqub et al. 2004), revealed a required differentiated approach even if the critical parameters for the electrical breakdown of cell membranes were exceeded. Membrane damage and sublethal injury is repairable under certain conditions, and the extent to which cells repair their injuries was found to depend on treatment intensity, the microorganism, and treatment medium pH (Garcia et al. 2005).

17.3.2.2 Impact on Enzymes

The evaluation of the effect of PEFs on enzymes is complex, and available reports on the mechanisms are limited; the various experimental setups and processing

parameters make them difficult to compare (Schuten et al. 2004; Van Loey et al. 2001; Yang et al. 2004).

The observed effects of PEFs on enzymes by different research groups appear to depend, besides on the enzyme, on the characteristics of the PEF treatment system used and on the electric process parameters. PEF side effects, such as changes in pH at the electrode surface due to electrochemical reactions (Saulis et al. 2005) and the occurrence of temperature hot spots due to ohmic heating effects within a nonuniform electric field (Jaeger et al. 2009), may contribute to the observed overall enzyme inactivation during PEF processing. As the PEF effect on proteins, enzymes, and other food constituents remains small, possible applications could include the pasteurization of bioactive antimicrobial milk fractions, such as lactoperoxidase, lactoferrin, or immunoglobulins, as well as heat-sensitive vitamin solutions that are destroyed during thermal pasteurization.

Although enzymes do not contain membrane structures, which are the target of an inactivation based on electroporation, the possible impact of PEF side effects indicates that process modifications toward the inactivation of microorganisms and enzyme structures are also possible (Aguiló-Aguayo et al. 2010; Martín-Belloso and Elez-Martínez 2005). Improvements like treatment chamber design have offered the ability to selectively retain enzyme activities or to inactivate them via temperature effects caused by the electrodes and flow conditions in the treatment chamber.

A further discussion of PEF impact on proteins and enzymes is conducted in the following section.

17.3.2.3 Impact on Food Constituents

Few data are available regarding PEF effects on other food constituents, especially proteins (Barsotti et al. 2001). Perez and Pilosof (2004) reported a partial modification of the native structure of β-lactoglobulin when the concentrate is subjected to an electric field of 12.5 kV/cm. No effects of PEF treatment on the physicochemical properties of lactoferrin were found by Sui et al. (2010) for treatment intensities up to 35 kV/cm and a total specific energy input of 41 kJ/kg (treatment time 19 μs) with temperatures below 65 °C.

Fernandez-Diaz et al. (2000) studied the effects of PEFs on ovalbumin solutions (2 %; pH 7; 5 mS/cm) and dialyzed egg white (pH 9.2; 4–5 mS/cm) applying an electric field strength in the range of 27–33 kV/cm. Partial protein unfolding or enhanced SH ionization of ovalbumin was observed after PEF treatment and was found to increase with increases in the total specific energy input.

Recent investigations by Marco-Moles et al. (2009) focused on the PEF effect on proteins and lipids in liquid whole egg and the microstructure of these components studied by low-temperature scanning electron microscopy (Cryo-SEM). A partial denaturation and insolubilization of the protein was observed during conventional pasteurization and resulted in a thickening of the lipoprotein matrix as observed

by Cryo-SEM. The microstructure of PEF-treated samples showed some discontinuities in the lipoprotein matrix.

Due to the application of PEFs, changes in the conformational state of proteins might cause changes in enzyme structure and activity (Bendicho et al. 2003; Tsong 1990). In general, the mechanisms involved in the inactivation of enzymes by PEFs are not fully understood (Ohshima et al. 2006). Possible mechanisms have been proposed (Castro et al. 2001; Perez and Pilosof 2004). If the duration of the pulse is long enough, then the effects of PEFs on proteins could entail polarization of the protein molecule, dissociation of noncovalently linked protein subunits involved in quaternary structures, changes in the protein conformation so that hydrophobic amino acid or sulfhydryl groups are exposed, attraction of polarized structures by electrostatic forces, and hydrophobic interactions or noncovalent bonds forming aggregates.

17.3.3 Process-Structure-Function Interactions

The effect of PEFs on food constituents such as proteins and carbohydrates and the resulting changes in the functional properties have been discussed in the section "Impact on Food Constituents." The following section will focus on the PEF effects on structured foods.

PEFs affect cell membranes and thus can be expected to influence the texture of products in which the structure is largely dependent on the integrity of cells.

Fundamental research on the modification of the textural properties of plant and animal raw materials represents the basis for further possible applications. Lebovka et al. (2004) studied the impact of PEFs on apple, carrot, and potato tissue. Stress deformation and relaxation tests were performed to analyze the changes in tissue texture. PEF treatment, in combination with a mild heat pretreatment, leads to the complete elimination of the textural strength of tissue. It was shown that by proper selection of PEF treatment conditions, it was possible to obtain a controlled degree of tissue softening.

Suitable methods such as impedance measurement (Angersbach et al. 1999) and acoustic impulse response (Grimi et al. 2010) were developed and are in use as efficient tools to quantify structural modifications.

Various concepts for the application of PEFs to improve mass transfer processes and to affect plant food material properties have been developed (Ade-Omowaye et al. 2003; Knorr et al. 2001, Lebovka et al. 2007; Puértolas et al. 2010).

However, studies on the effect of electropermeabilization on protein-based structures of solid foods such as fish and meat are limited.

Improved water binding during cooking of meat was found to occur after PEF pretreatment due to enhanced microdiffusion of brine and water binding agents.

Hydrocolloids will influence protein swelling and water binding activity, and their microdiffusion into meat tissue can be enhanced by PEF pretreatment (Toepfl 2006).

The impact of a PEF treatment on the microstructure and texture of salmon was investigated by Gudmundsson and Hafsteinsson (2001). Fish muscle was found to be more susceptible to gaping due to PEF treatment in comparison to chicken meat, probably due to the lower content of connective tissue (0.6 % in comparison to 2 % for chicken meat).

An understanding of the impact and potential of PEF technology on food systems at the cellular level will allow for the design of tailor-made foods and to establish process-structure-function relationships.

17.3.4 Current Applications and Process Development

PEF technology is on the verge of industrial application with various pilot-scale units available worldwide (Lelieveld et al. 2007; Raso and Heinz 2006).

Application of PEF technology as a short-duration (milliseconds), continuous operation will improve the sustainability of food processing or reduce energy requirements while maintaining or improving food quality and safety. Even if PEF treatment requires an additional input of electrical energy, it has beneficial effects on the total energy consumption of mass transfer processes, such as extraction, pressing, and drying. Processing times are reduced, utilization of production capacities is improved, and water and raw material consumption is diminished (Toepfl et al. 2006).

Application of PEFs, in combination with mild heat, seems to be a promising technique for a gentle, multihurdle preservation process.

17.3.4.1 Low-Intensity PEF Treatment

Controlled reversible permeabilization offers the potential for sublethal stress induction on biological cells triggering a metabolic response (Bonnafous et al. 1999; Gomez Galindo et al. 2008) and an increased production of secondary metabolites such as phenols or phytosterols, leading to increased antimicrobial and antioxidative effects (Dörnenburg and Knorr 1995). It also offers the potential for the "infusion" of precursors or other desired constituents into cells as well as the recovery of metabolites from cells while maintaining their viability and productivity (Tryfona and Bustard 2008). The irreversible rupture of plant membranes offers various applications to replace or support conventional thermal as well as enzymatic processes for cell disintegration (Vorobiev and Lebovka 2008). Irreversible permeabilization allows for the significant improvement of mass transfer, especially for drying, expression, concentration, and extraction, resulting in higher product yields, shorter processing times, and, consequently, reduced energy consumption (Toepfl et al. 2006). Solid–liquid extraction, pressing, or drying of food matrixes is strongly dependent on diffusion and mass transfer through cells and tissue and is characterized by the disintegration of the material. To achieve a high

level of disintegration of solid tissue, thermal, mechanical, chemical, and enzymatic methods are commonly used. PEF technology could be applied as a new method for cell disintegration.

A comparison of juice yields obtained after PEF processing of apple and carrot mash is presented by Jaeger et al. (2012), with an emphasis on the integration of the technology into the whole juice winning process.

The extractability of intracellular pigments facilitated with PEF treatment has proven to be a very efficient process for the winning of these valuable components with beneficial antioxidant properties. PEF-induced cell permeabilization and the release of intracellular pigments (anthocyanins) from wine grapes were studied by Praporscic et al. (2007) and Puertolas et al. (2010). They showed a 30–40 % increase in total polyphenols and anthocyanin content in the juce obtained from Cabernet Sauvignon grapes.

PEF enhanced the permeability of potato tissue, which resulted in an improved mass transfer during dehydration, and therefore a shorter drying time was demonstrated by Lebovka et al. (2007). The process duration of the osmotic dehydration processes after PEF treatment of apples can be reduced by up to 40 % and the rehydration capacity could be increased substantially (Taiwo et al. 2002).

In the case of sugar beet processing, PEF treatment enables the sugar recovery process at lower extraction temperatures, which reduces the water binding properties of the treated couchettes, thereby doubling the dry matter content and significantly reducing energy costs for drying of the resulting pellets (Eshtiaghi and Knorr 2002; Lebovka et al. 2007).

17.3.4.2 High-Intensity PEF Treatment

Microbial inactivation of vegetative cells via PEF offers pasteurization with low energy input, selective inactivation of microorganisms depending on cell size or shape (Toepfl et al. 2007), and the retention of bioactive heat-sensitive food compounds while inactivating pathogenic microorganisms and increasing product shelf life and safety (Guerrero-Beltrán et al. 2010; Jaeger et al. 2009; Sui et al. 2010).

A number of studies have shown synergetic effects between PEF and heat treatment at nonlethal processing temperatures. The synergetic effect of temperature during PEF inactivation of microorganisms can be used to improve inactivation results or to reduce electrical energy costs (Craven et al. 2008; Riener et al. 2008). Energy savings derive from the lower PEF treatment intensity (treatment time and total specific energy input) required for a certain level of microbial inactivation at increased temperature and from the possibility to recover the electrical energy dissipated during PEF treatment in the form of thermal energy for preheating the incoming product. Another key aspect for the successful application of PEF pasteurization is its selective inactivation capability since the pore formation process and the required transmembrane potential depend on the size of the treated cell.

Larger cells like yeasts require a smaller intensity of the external electric field, and they are thus more sensitive to electropermeabilization. Hence, the inactivation of yeast in a product containing desirable probiotic bacteria can be realized without a loss of bacterial cell vitality.

The selectivity of PEF inactivation based on cell size and other factors that affect the electroporation mechanism are different from the susceptibility of microorganisms to thermal treatment. Thermotolerant microorganisms can be affected by PEFs, and inactivation of the more PEF-resistant species can be conducted by thermal effects; consequently, a combination of thermal and PEF treatment can improve inactivation effectiveness in addition to the synergistic temperature effect on PEF inactivation below thermal inactivation level.

17.3.5 Research Needs and Challenges

The application of PEFs to induce stress reactions in biological systems and a basic understanding of the underlying mechanisms at the cellular and metabolic levels will be the main focus of the research undertaken in the field of reversible permeabilization of plant cells. The first attempts at doing this, as described earlier, are already showing the potential for the modification and improvement of the production of valuable secondary metabolites.

The application of PEFs for the irreversible cell disintegration of plant and animal raw materials was limited by the availability of large-scale pulse modulators, but a forward-looking technical development was made in recent years to overcome production-scale limitations. To implement the cell disintegration processing step into existing processes, an integrative approach will be required that considers pre- and post-PEF processing unit operations, such as the mechanical disintegration of solid–liquid separation in the case of extraction of juice recovery in order to successfully translate the cell disintegration provided by PEF into improved process results such as higher juice yields.

For PEF-assisted pasteurization, the design and optimization of the PEF treatment chamber is the most challenging point with regard to different product properties, such as viscosity and electrical conductivity, and with regard to uniform treatment conditions in terms of electric field and temperature distribution. Many authors (Fiala et al. 2001; Gerlach et al. 2008; Jaeger et al. 2009; Lindgren et al. 2002; van den Bosch et al. 2002) have described the temperature distribution in a PEF treatment chamber and reported the occurrence of high local temperatures due to the inhomogeneous distribution of the electric field, limited flow velocity, and recirculation of the liquid. Numerical simulations using computational fluid dynamics have attracted increased interest for this purpose since experimental measurement of the related parameters is not possible in most cases due to the small dimensions of the treatment chamber as well as the interference of the measuring device with the product flow and electric field. Treatment homogeneity and the avoidance of overprocessing of the product, including the occurrence of

local high temperatures, are key aspects in guaranteeing predictable cell disintegration and microbial inactivation while maintaining heat-sensitive food constituents.

In PEF systems working at higher electric field intensities, electrochemical reactions can occur at the electrode surface (Morren et al. 2003). Related undesired effects, such as a partial electrolysis of the solution, the corrosion of the electrode material, and the introduction of small particles of electrode material into the liquid, can be limited or avoided by a suitable selection of electrode materials and by adaptation of the electrical pulse shape and duration (Roodenburg et al. 2005; Saulis et al. 2005). Its consideration is a crucial prerequisite in the study of inactivation kinetics in order to exclude other simultaneously occurring side effects.

Protective effects existing in real food systems may limit the process effectiveness of PEFs compared to inactivation studies conducted in model solutions, and the occurrence of sublethally injured cells must be taken into account with regard to food safety aspects (Jaeger et al. 2009). A comprehensive statement concerning the food safety aspects of PEF treatment can be found in Knorr et al. (2008). Furthermore, in addition to the complexity of treatment media, the consideration of microbial growth state, adaptation to the treatment media, and the existence of inhomogeneous microbial populations with less sensitive subpopulations seem to be the most challenging aspects when transferring inactivation results to real products and industrial implementation.

17.4 Ultrasound

17.4.1 Process Description

Ultrasound (US) is defined as the energy emitted by sound waves with frequencies from 18 kHz up to the gigahertz range. Longitudinal sound waves can be transmitted to gases, fluids, or foodstuffs, causing cyclic compressions and rarefactions of the respective material. High-intensity, low-frequency (16–100 kHz) US can lead to cavitation and the creation, growth, and violent collapse of gas bubbles (Patist and Bates 2008). The bubble collapse is accompanied by high pressure and temperature peaks (up to 100 MPa and 5,000 K) as well as intense local shear (Clark 2008). Such high-power US treatments have the potential to improve a large range of key processes in food production.

In contrast, low intensities and high frequencies in the megahertz range lead to US treatments with acoustic streaming as the main mechanism (Patist and Bates 2008). Such low-energy US is used for nondestructive testing as well as for the stimulation of living cells.

17.4.2 Research State of the Art

17.4.2.1 Impact on Biological Cells

A bactericidal effect of US was first reported in the 1920s (Harvey and Loomis 1929). US-induced cell damage is primarily explained by cavitation phenomena such as shear disruption (microstreaming), localized heating, and free radical formation (Hughes and Nyborg 1962). The cell walls and membranes of biological cells can be damaged by surface rubbing, leading to fracture and leakage (Kinsloe et al. 1954) and separation of the cytoplasmic membrane (Alliger 1975).

US has an additive or even synergistic effect when combined with other lethal effects such as elevated temperatures (thermosonication – TS), pressure (manosonication – MS), or both (manothermosonication – MTS) (Knorr et al. 2004), which has been explained by the weakening of the cell wall, making it more susceptible to the effects of cavitation (Patist and Bates 2008). US pasteurization carried out at lowered temperatures could preserve the physicochemical properties of color and flavor (Patist and Bates 2008). However, the specific energy requirement of such combined treatments must be considered as the most important limitation for the application of US in food preservation processes today (Zenker et al. 2003).

Low-intensity US can improve fermentation processes due to increased mass transfer through cell walls and membranes and its influence on boundary layers (Sinisterra 1992). Increased fermentation rates could be observed because of the US-assisted removal of CO_2, which otherwise can inhibit fermentations (Matsuura et al. 1994).

17.4.2.2 Impact on Enzymes

Research on the inactivation of enzymes for food preservation revealed increased effects for TS, MS, and MTS compared to US alone. Nevertheless, the sensitivity can be very different from one enzyme to another. Among others, positive results have been reported for tomato pectic enzymes as well as for α-chymotrypsin and porcine lipase, whereas phospholipase A_2 was nearly insensitive to MTS and the sensitivity of trypsin was found to be temperature dependent (Vercet et al. 2001; Vercet et al. 2002).

Positive effects on enzyme activity can be achieved by the application of low-energy US. Substrates can be made available in large amounts, and the transport of substrate to immobilized enzymes is increased by microstreaming (Mason et al. 1996).

17.4.2.3 Impact on Food Constituents

Intense pressures, temperatures, and shear forces induced by US and cavitation can lead to the denaturation of proteins and the alteration of their structure and functional properties. Cavitation-induced tissue disruption results in the migration of proteins, minerals, and other components, and periodic oscillations lead to the softening of cell membranes (Jayasooriya et al. 2004), which is of importance for US-induced meat tenderization (Jayasooriya et al. 2007; Lyng et al. 1998; McClements 1995), where US is reported to release myofibrillar proteins and improve physical properties, such as water binding capacity, tenderness, and cohesiveness, and sensory properties (Jayasooriya et al. 2004; Roberts 1992).

On the other hand, US-induced cavitation may promote undesired changes depending on the treated product. In water-filled cavities, one of the primary reactions is the degradation of water molecules into H and OH radicals. Radical formation is fundamental for the explanation of US-induced oxidation reactions, adversely affecting fats, oils, vitamins, and color pigments (Roberts 1993). Critical results were obtained in the case of rabbiteye blueberries, with reduced product quality following US treatment (Stojanovic and Silva 2006). In contrast, a US treatment of blackberry juice resulted in only minor color changes and retention of 94 % of the anthocyanins, which led to a positive rating of the application of US for the preservation of fruit juices (Tiwari et al. 2009).

17.4.3 Process-Structure-Function Interactions

The impact of US on protein structures and their functional properties has already been discussed. In addition to meat tenderization, US can be applied to achieve certain textural characteristics of tailor-made foods. US-treated soy proteins showed significant textural changes in model food systems (Jambrak et al. 2009), such as changes in conductivity, increased solubility, and increased specific surface area, which is of importance for food texture and functionality.

In extrusion processes ultrasonic excitation can lead to a reduction in drag resistance, improved flow characteristics, and the formation of edible coatings due to a denaturation of proteins (Knorr et al. 2004; Mousavi et al. 2007).

Effects on viscosity are additionally observed for US treatments of macromolecular solutions due to degradation caused by hydrodynamic forces. Sonolytic degradation of aqueous carboxymethylcellulose polymers showed that the rate of degradation increased with increasing initial dynamic viscosity, higher molecular mass, and increased polymer concentration (Grönroos et al. 2008).

In crystallization processes cavitation can lead to crystal fracture, leading to overall smaller crystal size and improved crystal size distribution (Zheng and Sun 2006). This fracturing also affects fat globules or solid particles in liquids, leading to homogenization effects (Jafari et al. 2007; Villamiel and de Jong 2000).

When US is applied to plant-based tissues, cavitation damage, distortion of cells, and alteration of tissue structure appear, influencing the internal mass transfer characteristics of the product (Fernandes et al. 2009; Jambrak et al. 2007).

17.4.4 Current Applications and Process Development

In addition to US application to assist in food preservation processes using the synergistic effects of US, heat, and pressure on microorganisms and enzymes, US process development has covered a large range of food manufacturing where the structure and properties of the raw material are of importance.

Ultrasonic pulverization techniques are applied for the destruction of residual cell wall material and vegetable purees achieving significant modifications of textural and rheological properties, as by releasing pectin from cell walls, which contributes to the formation of continuous matrices (Bates et al. 2006; Mawson and Knoerzer 2007). In the case of the preparation of biomaterials for further processing by fermentation or enzyme digestion, US-assisted pulverization of cell matrices is used to facilitate the release of substrates or nutrients (Matsuura et al. 1994; Mawson and Knoerzer 2007; Wu et al. 2000).

Thermal processes can be improved by enhanced heat transfer, microstreaming at boundary layers, reduced fouling due to cavitation phenomena, and a faster formation of gas bubbles in evaporation processes. The positive effect on heat and mass transfer processes is used for the assistance of drying processes (García-Pérez et al. 2006; Schössler et al. 2012; Simal et al. 1998).

During extraction processes, cavitation can improve penetration with the solvent and disrupt cell walls when high intensities are applied (Li et al. 2004).

Cavitation, shear forces, and an influence on boundary layers provide the opportunity to improve emulsification and homogenization (Jafari et al. 2007; Villamiel and de Jong 2000).

A change in the US parameters can lead to the opposite effect, and emulsions can be split into their components (Pangu and Feke 2004). An acoustic radiation force holds particles in position in a stationary field, leading to coalescence (Masudo and Okada 2006).

US during freezing processes can promote ice nucleation and enhance heat and mass transfer processes (Zheng and Sun 2006). Crystal size distribution can be controlled, leading to reduced cell destruction, and cavitation effects can minimize fouling in surface freezers (Acton and Morris 1992).

US filtration systems are used as an add-on to existing vibratory screens, while the combination of US and membrane filtration is still in the early phase of development (Patist and Bates 2008).

Airborne US is used for the defoaming of carbonated beverages and fermentation systems (Gallego-Juárez 1998).

At lower treatment intensities US can be applied to the detection of foreign bodies in packaged and nonpackaged food (Knorr et al. 2004; Leemans and Destain

2009) and for nondestructive testing. Low-intensity US has been used to monitor the gelation process in milk and tofu (Dwyer et al. 2005; Ting et al. 2009) and to measure the mechanical properties of cheese products (Benedito et al. 2000).

17.4.5 Research Needs and Challenges

The presented overview of US research in the food industry underlines the versatility of US processes. One of the most important challenges for the industrial application of US is the definition of optimized parameters for all processes and products. Detailed knowledge about quality aspects, together with a thorough analysis of energy requirements, is the basis for the successful scale-up from laboratory tests to industrial scale.

17.5 Plasma Treatment

17.5.1 Process Description

Plasmas can be described as quasineutral particle systems in the form of gaseous or fluidlike mixtures of free electrons and ions, frequently also containing neutral particles (atoms, molecules), with a large mean kinetic energy of the electrons or all of the plasma components and a substantial influence of the charge carriers and their electromagnetic interactions on the system properties (Rutscher 2008).

According to Fridman et al. (2005), all varieties of plasma–chemical systems are traditionally divided into two major categories: thermal and nonthermal plasmas, both with specific advantages and disadvantages. Thermal plasmas [usually arcs or radiofrequency (RF) inductively coupled plasma discharges] are associated with Joule heating and thermal ionization and enable the delivery of high power (up to over 50 MW per unit) at high operating pressures. Besides other limitations, very high gas temperatures limit thermal plasmas' applicability to food systems.

In nonthermal plasmas, the electron temperature is much higher than the bulk gas temperature. While the electron temperature can reach several tens of thousands of degrees Kelvin, the gas temperature remains at temperature levels below 40 °C (Mastwijk and Nierop Groot 2010). Nonthermal plasmas may be produced by a variety of electrical discharges at different pressure levels. Working pressures below atmospheric conditions are mainly suitable for dried food materials or packaging materials since a vacuum will support liquid-to-gaseous phase changes in high-moisture food products. The most suitable systems for food processing are atmospheric-pressure plasma devices since mild conditions at low temperatures can be realized. Atmospheric-pressure plasma devices like corona discharges, dielectric

barrier discharges (DBD), and plasma jets used for microbial inactivation were described in detail by Ehlbeck et al. (2011).

17.5.2 Research State of the Art

Recent research activities in food-related application of plasma have focused mainly on the inactivation of microbes, but little is known about the effect of plasma on food matrices. Since emitted reactive species react with bacteria, they may also affect food components such as water, lipids, proteins, and carbohydrates (Deng et al. 2007; Keener 2008).

17.5.2.1 Impact on Biological Cells

An overview of microbial inactivation in model systems using nonthermal plasma published during the last 3 years is given by Wan et al. (2009).

Although several reviews focus on the inactivation mechanisms of plasma (Boudam et al. 2006; Gaunt et al. 2006; Moisan et al. 2001; Moreau et al. 2008), they are not yet fully understood. In particular, the inactivation mechanisms of different plasma sources are difficult to compare because the effects depend on, for example, the plasma source, process parameters, and generated reactive species within the plasma due to the application of different process gases. Additionally, the inactivation mechanisms also depend on the type and the differentiation state of bacteria (e.g., spores, Gram-negative or Gram-positive bacteria, biofilm). Moisan et al. (2001) stated that three basic mechanisms are involved in plasma inactivation at low pressures: (1) UV irradiation of genetic material, (2) intrinsic photodesorption, and (3) etching. Although three-phase survivor curves were also reported in atmospheric-pressure plasma studies (Laroussi 2002), the explanation of the inactivation mechanism cannot be transferred to these studies. Most of the researches claim that UV plays a minor role in the inactivation of microorganisms at atmospheric pressure and the inactivation process is controlled by chemically reactive species. However, it was shown that in some cases UV photons can play a role in the inactivation process of microorganisms at atmospheric pressure (Boudam et al. 2006). Moreau et al. (2008) compared plasma inactivation effects to the effects of micro pulses. Similar to the effects of micro pulses, the cell membrane of microorganisms is perforated following plasma treatment. Besides the perforation of the cell membrane, the inactivation effect of plasma is induced by the bombardment of the cell membrane by radicals (OH17 or NO17). These radicals are absorbed onto the bacteria surface, and volatile components are formed and eliminated from the cells (etching). Xiong et al. (2011) evaluated the penetration depth of plasma in a biofilm. For a treatment with a plasma jet at atmospheric pressure a penetration depth of 15 μm was obtained and related to O and OH.

17.5.2.2 Impact on Enzymes

To date, information regarding the impact of plasma on enzymes has been given in only a small number of papers. Dudak et al. (2007) found a decrease in enzyme activity following RF glow discharge plasma treatment, with the highest decrease in activity within the first 10 min of treatment, including a fragmentation of proteins. A fragmentation of proteins was also found by Deng et al. (2007) after DBD treatment. In this process, atomic oxygen has been shown to play a dominant role in destruction and degradation reactions. Oxygen plasma generated by RF discharge led to a reduction in C-H and N-H bonds in casein protein and to a modification of the secondary protein structure (Hayashi et al. 2009).

17.5.2.3 Impact on Food Constituents

Although much work has already been performed on the effects of nonthermal plasma on microorganisms, information on plasma interactions with food components is scarce. This is mainly due to the fact that the application of plasma was for a long time limited to heat- and vacuum-resistant materials.

A time- and dose-dependent degradation has been observed for flavonoids, known for their high antioxidant activity protecting cells against the damaging effects of reactive oxygen species. The degradation rate strongly depended on the polyphenolic substitution pattern. While glycosidic flavonoids showed a rather inert behavior throughout plasma treatment, aglycosid derivates were quickly degraded (Grzegorzewski et al. 2010).

However, organoleptic analysis of plasma-treated nut samples likewise showed no relation between treatment and perceptual sensory character (Basaran et al. 2008). On a molecular level, SEM analysis of varius cabbage and lettuce species revealed that under certain conditions, plasma treatment may lead to changes in plant surface hydrophobic wax layers (Grzegorzewski et al. 2010). On the other hand, Ragni et al. (2010) observed no negative effects of plasma treatment on egg quality.

17.5.3 Process-Structure-Function Interactions

The complex process-structure-function interactions are not yet fully understood. Depending on the plasma source, process parameters, and process gases, the reactive species vary within the plasma, which makes reaction mechanisms difficult to compare.

Plasma treatment in air or using oxygen as feed gas led to a strong surface oxidation, resulting in the formation of carbonyl and carboxyl functions, as was demonstrated for several polymers (Morent et al. 2008). The modification of starch

in a glow discharge argon plasma was manifested in a loss of OH groups, probably due to the crosslinking of α-D-glucose units (Zou et al. 2004).

17.5.4 Current Applications and Process Development

Plasma technologies in food processing are not yet established, but investigations using complex food raw materials have been performed. Some studies focus on the plasma-related decontamination of bacteria at the surface of several fruit and vegetable samples without evaluating the obtained product quality (Niemira and Sites 2008). For example, Critzer et al. (2007) showed the capability of a one atmosphere uniform glow discharge plasma to inactivate *E. coli* on mangos and *E. coli* O157:H7, *Salmonella*, and *L. monocytogenes* on apples, cantaloupe, and lettuce, respectively. Perni et al. (2008a, b) used a cold atmospheric plasma pen to inactivate *Saccharomyces cerevisiae, Pantoea agglomerans,* and *Gluconacetobacter liquefaciens* inoculated on pericaps of mango and melon or cut melon and mango pieces inoculated with *E. coli, S. cerevisiae, G. liquefaciens*, and *L. monocytogenes*.. A decontamination of the fruit pericaps was detected, whereas the efficiency on cut fruit surfaces was reduced.

17.5.5 Research Needs and Challenges

Approaches to studying the effects of plasmas in industrial plasma engineering often regard plasma as a black box with inputs and outputs. In addition, studies are focusing on plasma application to foods the desired output of a plasma-related process is mainly achieved by adjusting inputs until the desired result is obtained. In such approaches, no serious attempt is made to understand the plasma-physical, plasma-chemical, or plasma-biological processes occurring in this black box. Future research needs to involve more interdisciplinary studies to allow a better understanding of the complex interactions during plasma processing and, thus, the design of beneficial and controlled plasma applications for food processing, which might encompass microbial inactivation as well as the modification of functional food properties. Further, plasma processing must be considered as a surface treatment, and the impact of potential toxicological effects resulting from chemical reactions based on plasma-air-food surface interactions must be viewed in relation to the surface volume ratio of the particular product.

17.6 Conclusion

High HP treatment offers the promise to produce microbiologically safe, high-quality, tailor-made foods under gentle processing conditions. Process improvement can only be achieved by understanding and applying the different temperature, time, and pressure dependencies of desired and undesired reactions. Detailed studies regarding the inactivation kinetics and mechanisms of pathogens should be performed in the respective food matrix and must result in constant process parameters or, if that is not possible, in optimally controlled process parameters. Controlled and reproducible studies on the pressure effect of high pressure on nutrient biopolymers, toxins, and allergens are also needed.

The interactions between products and PEF processes and possible undesired changes during PEF treatment remain uncertain and require further investigation. For example, high-value products – such as enzyme or vitamin solutions or protein fractions isolated from milk, all of which are heat sensitive – are potential products for nonthermal pasteurization by PEFs. A combination of techniques that deliver effective preservation without the excessive use of any single conventional process parameter such as time or temperature will allow for the selective retention or inactivation of food constituents. The combination of PEFs with other stress factors like mild heat, antimicrobial compounds, pH, or organic acids, as well as their combination with other thermal or nonthermal decontamination techniques, will determine further development. The impact of PEFs on the structure of food matrices and on mass transfer within food matrices and the subsequent understanding of PEF-related process-structure relationships will allow the development of unique tailor-made foods.

US-assisted processing offers advantages for a large variety of food production processes. The unique characteristics of sound waves provide opportunities to treat products with specifically adapted parameters. For instance, US with a low maximum pressure amplitude will cause microstreaming in fluids, gently manipulating mass transfer, whereas high-pressure amplitudes cause cavitation associated with high pressure and temperature peaks, permitting changes in the cell structure as well as homogenization of disperse systems. However, the large range of attainable effects is one of the most important obstacles to the transfer of laboratory-scale results to the industrial scale. Equipment and parameters must be directly adapted to all products and objectives. Furthermore, undesired changes in product structure and quality must be known and minimized. A better understanding of the basic mechanisms of US treatments depending on the product and process parameters is necessary to allow general conclusions to be drawn and the design of new processes and applications to be simplified.

CP treatment at atmospheric pressures offers various opportunities in food processing, e.g., surface decontamination, modification of surface properties, and enhancement of mass transfer with respect to foods and food-related materials. Attempts to limit heat transfer to sensitive materials such as food products resulted in the development of new atmospheric plasma jets and will allow efficient in-line

integration in production lines; however, further research is required in light of the lack of data regarding plasma-matrix interactions and to ensure the development of safe and tailor-made processes for food application. Further investigations focusing on, for example, the spatial composition of plasma, physicochemical reaction kinetics, and penetration depths, should be supported by validated mathematical models and simulation approaches.

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