Nonthermal food processing/preservation technologies

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Chapter Outline

5.1 Introduction

In 2011, about one third of all the food produced worldwide was lost or wasted, corresponding to approximately to 1.3 billion ton of food waste per year (Tonini et al., 2018). In Europe a food waste was estimated of roughly 173 kg per capita, which represents about 170 Mt. of CO_2 and an economic loss of about 143 billion of euros per year. Nevertheless, food waste can be classified as unavoidable or avoidable. The avoidable fraction relates to food that is thrown out while still edible, representing not only a waste of food, but also a waste of resources such as energy, land-use demands, or other materials necessary to the production process (Quested and Johnson, 2009). The unavoidable portion represents the waste arising from food or drink preparation that is not, and has not been, edible under normal circumstances, such as bones, eggshells, fruit peels, among others (Quested and Johnson, 2009).

The food industry must deal with the food waste problem throughout the entire food chain, from the initial agricultural production till the final consumer purchase and consumption. Global sustainability, food security, and the protection of natural resources, environment, and human health can be achieved by the choice of the

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correct processing methodology on the different phases of the food chain (Saini et al., 2018).

A simple definition of food processing is related with the conversion of raw livestock and agricultural products (raw materials/ingredients) into a widely diverse range of products for human consumption. In other words, it consists in the transformation of raw or cooked ingredients by physical or chemical means, into other marketable food products that are more suitable or appealing to be consumed, always aiming to extend their shelf life or improve their quality (Compton et al., 2018). The main purpose of food processing is its preservation, but later it was discovered that organoleptic characteristics such as taste, appearance, flavor, color, aroma, texture and shape, or even nutritional value can be attractively improved by applying different processing methods. Today, these are effectively the main goals of the food industries; on one side they intend to extend foods shelf life by inhibiting microbiological and biochemical changes, and on the other side they yield improvements of the organoleptic characteristics preserving food's nutritional characteristics (Alexandre et al., 2013).

Consumers are increasingly aware of natural food benefits on human health, thus, the demand for high-quality food products, with fresh-like properties and high nutrient content, led to the necessary development of new food processing methods.

The traditional heat treatments are efficient in microbial inactivation, reducing product decay, and attaining safety targets. However, they have a significant impact on organoleptic quality, namely in texture, color, aroma, flavor, taste, and nutritive value, which are normally severely affected by temperature. Nonthermal and eco-friendly processing methodologies, such as high pressure processing (HPP), pulsed electric fields (PEF), and ultrasounds (US) have been studied by both industry and academia, in an attempt to meet the challenges of producing safe processed foods with a high-quality standard (Balasubramaniam et al., 2015). HPP and PEF are among the most commercial technologies being studied and some processed products can already be found on the market.

HPP is an increasingly implemented technology for food "cold" pasteurization that is also showing great promise for other food, pharmaceutical, and biotechnological applications. The use of high pressures involves the exposition of liquid or solid foods to pressures that can range from 100 to 1000 MPa, from a millisecond pulse to over 20 minutes. Depending on some factors such as food properties, initial food temperature, and applied pressure, the adiabatic temperature can increase 4°C–6°C for each pressure increase of 100 MPa. However, the products' temperature during holding time can be below 0°C or above 100°C depending on the requirements for the final intended product (Pereira et al., 2010; Alexandre et al., 2017a,b,c,d,e). Room or chilled temperatures could be especially useful for "cold" food pasteurization, assuring pathogenic and spoilage bacteria, yeasts, molds, viruses, and spores inactivation (Balasubramaniam et al., 2015). PEF technology involves the application of short duration pulses (from several nanoseconds to several milliseconds), of high electric-field strengths (from 100 V/cm to 80 kV/cm), and specific energy input in the range of 50–1000 kJ/kg (Fincan et al., 2002; Toepfl et al., 2007; Vorobiev et al., 2008; Koubaa et al., 2015). This technology is able to inactivate pathogenic microorganisms such as *Listeria monocytogenes*, *Escherichia coli*, and *Salmonella typhimurium*, without significant loss of the organoleptic and nutritional properties of food. US technology can be classified in two categories: high frequency or high intensity. The one usually applied in the food industry is the high-intensity US, also called power US, which operates at frequencies that range between 20 and 100 kHz. This technology is mainly used to improve processes that include oil extraction, microbial and enzyme inactivation, and starch–protein complex disintegration (Feng et al., 2011).

Nonthermal innovative food processing technologies have potential, through process intensification, to be environmentally sustainable by reducing energy and water consumption and at same time achieve food security and quality and extend shelf life of food products or expand the shelf-stable product spectrum. They play an important role for food industries contributing also to product innovation and providing more diversity of food industry products and more competitive and efficient processes (Knoerzer, 2016).

Food waste and byproducts generated during processing can be a great source of high added-value compounds, which, due to their different characteristics, can be applied as food additives and/or as nutraceuticals (Saini et al., 2018). Thus, the extraction of such interesting compounds can be another way to reduce food waste and promote food saving. Thus, the selection of an effective extraction process, depending on the previous food processing, can lead to the extraction and purification of bioactive compounds and should be seen as an ultimate goal in the industrial-scale processes. In agro-food waste management procedures, there are several extraction techniques commonly used, but the ideal should be not expensive, quantitative, fast, and nondestructive. Nevertheless, conventional extraction methods have many disadvantages, such as the health hazards of toxic organic solvents and the high volume needed, the long operation or reaction times, the high energy input, the low extraction selectivity, among others (Alexandre et al., 2017a,b,c,d,e). These limitations led to the need to develop other more environmentally friendly technologies. Therefore, green extraction methods such as HPP, PEF, and US have also been used as extraction assisting technologies to decrease food waste.

In this chapter, some of the main technological fundamentals of HPP, PEF, and US are reviewed. The impact of each technology on food composition and microorganisms, their applications and technological advantages and limitations, and their use as extraction methodology are discussed, too.

5.2 Quality indicators for processed food

Food processing aims to guarantee not only the preservation of organoleptic properties of fresh products but also food safety during food consumption.

Over the last 10 years, food quality was more intensively discussed by the public, governments, and the food industry. The increasingly complex and extended food supply chain significantly increases the risk of food presenting lower quality (Liu, 2018).

Food quality includes chemical, physical, and sensory characteristics of food products. These properties may be assessed by sensory inspection at purchase time or require quantification through instrumental measurements. For example, consumers through vision, touch, or smell can easily evaluate external attributes such as overall appearance, size, shape, aroma, color, state of maturation, and defects. But internal properties or hidden characteristics such as taste, flavor, texture, nutritive value, and wholesomeness cannot be assessed by consumer before purchase and some of that only can be evaluated through some specific instrumental measurements (Anonymous, 2002, Rico et al., 2007, Alexandre et al., 2012). Quality is also associated with food components (soluble solids content, starch content, carotenoids, sugar, ascorbic acid, total flavonoids, total phenolic, total tannins, total anthocyanins, antioxidant activity, among others) that have a positive and functional impact on human health. Fruits and vegetables are important sources of vitamins, fibers, minerals, and antioxidants that play an essential role in the human diet preventing numerous diseases (Abasi et al., 2018). In fruit, the external indicators of quality are the shape, size, skin color, and general appearance; nevertheless other internal characteristics are also important, such as soluble solids content, titratable acidity, ratio of soluble solids to titratable acidity, pH, starch and sugar content, carotenoids, ascorbic acid, total flavonoids, total phenolic, and antioxidant activity. For vegetables, nutritional composition, antioxidant activity, along with enzymatic activity and texture are the most important quality properties. Steak, roast, cubed, minced properties, color, fat, protein content, and marbling were important quality properties for meat products (Abasi et al., 2018). Fish is known to be an important supplier of micronutrients such as vitamins A and D, minerals such as calcium, phosphorus, magnesium, iron, zinc, selenium, fluorine and iodine, and essential fatty acids (Arino et al., 2005). However, one of the most important quality indicators common to all food products is food safety.

Food safety is related with the guarantee that food will not cause harm to the consumer when it is prepared and eaten according to its intended use (Alexandre et al., 2013). Microbial counts of Gram-positive (such as *Bacillus cereus*, *Staphylococcus aureus*, *Methicillin-resistant S. aureus*, and *L. monocytogenes*) or Gram-negative (such as *Salmonella enteritidis*, *Pseudomonas aeruginosa*, and *E. coli*) food contaminant/pathogenic bacteria or even counts of total bacteria, coliform bacteria, or molds and yeasts are frequently considered food quality features that can be used as indicators of processed food safety (Alexandre et al., 2013). Some examples of unsafe food that commonly provoke food-borne diseases include uncooked foods of animal origin, fruits and vegetables contaminated with feces, raw shellfish and industrial pollution. Raw products often contain a great diversity of microbial flora that can be involved in food-borne outbreaks and may cause serious illnesses. The pathogens/commodities most frequently responsible in the 21st century for outbreak-related illnesses were norovirus/leafy vegetables, *Clostridium perfringens*/poultry, *Salmonella*/vine-stalk vegetables, and *C. perfringens*/beef (Fung et al., 2018). The symptoms of food contamination frequently include headache, muscle pain, nausea, fatigue, chills or fever, stomach or abdominal pain, vomiting, and diarrhea. Children and elderly are particularly vulnerable groups and food poisoning may be even a fatal illness for those due to some specific pathogenic bacteria (Alli, 2004; Behling et al., 2010; Waite et al., 2010; Alexandre et al., 2012). Other beneficial gut microbiota such as *Lactobacillus* and *Bifidobacterium* strains also can be used as quality markers, but in a different way since these microorganisms are beneficial and do not compromise the consumer's health.

5.3 Food contamination sources

There are many possible scenarios where food contamination may happen. Food products can become contaminated at any point from farm to table, as well as during production, processing, shipping, and distribution.

Food contamination can be classified as biological, chemical, physical, or of cross-contamination nature. Briefly, biological contamination is when food is contaminated with infectious bacteria (such as *Salmonella* spp. and *L. monocytogenes*) or toxin-producing organisms (such as *Clostridium botulinum*) and viruses (such as norovirus), which are a common cause of food poisoning and food spoilage. Chemical contamination happens when a food product is exposed to chemicals (such as food additives, heavy metals, dioxins, radionuclides, veterinary drug residues and pesticides residues, as well as contaminants from processing and packing or other environmental contaminants) that can lead to chemical food poisoning. Physical contamination occurs when foreign objects (such as metal filings, glass, jewelry, stones, or bone chips) contaminate foods and sometimes these objects can also be the vehicle for biological contamination (cross-contamination) if they harbor dangerous bacteria. Cross-contamination occurs when bacteria or pathogens are transported from one object to another that will contaminate food products (Mitchell et al., 2014).

Food contamination during food processing has been extensively reviewed by Nerín et al. (2016). Some of the most important contamination sources during processing are related with:

1. *external raw food contamination due to environmental contamination* (example of pesticides, fertilizers, toxic heavy metals, antibiotic residues, etc.);
2. *transport of raw materials to the factory where they will be processed* (caused by vehicle exhaust from petrol and diesel or cross contamination in the vehicle used for food transportation);
3. *food conditioning, which involves the storage of raw materials, preheating, disinfection, cleaning, and sterilization steps* (some common surfactants used to clean are quaternary ammonium compounds and nonionic surfactants);
4. *heating, which includes boiling, cooking, baking, frying, or combining with other ingredients at high temperature in an oven or in a reactor* (certain toxics compounds such as acrylamide, nitrosamines chloropropanols, furanes, or Polycyclic Aromatic Hydrocarbons (PAHs) can be formed in foods processing);

5. *food packaging* (different additives such as antioxidants, stabilizers, slipping agents, or plasticizers are commonly added to the package polymers to improve material properties that can end up transferred to food in a phenomenon called migration);
6. *transport, storage, and food distribution* (packaging material properties can be affected, low temperature and humidity) (Nerín et al., 2016).

It is extremely probable that biological, chemical, physical, or cross-contamination happen industrially. Today, the methods used by industry to assure product quality and safety are essentially thermal (such as blanching, pasteurization, and sterilization) or simply water washes with chemical sanitizer solutions (such as chlorine, hydrogen peroxide, and acid solutions). Although these methods guarantee the products' safety, many times they are inefficient to preserve fresh food quality such as the indicators of texture, color, nutritional quality; also, sometimes off-flavors can be formed, and they are expensive due to energy consumption and time-consuming methods. For all of these reasons it is extremely important to develop nonthermal preservation methods that can maintain or improve fresh food quality while assuring food safety for consumers at same time.

5.4 Nonthermal emerging processing technologies

In the last few decades, new nonthermal food processing methods have been faced with a challenge to accelerate the shift towards sustainable development and production. The identification of solutions that can enhance productivity and sustainability along the supply chain while helping the sector cope with climate change issues is urgent (Cavaliere et al., 2018). In fact, food waste gives rise to a heavy environmental burden. The Food and Agricultural Organization of the United Nations states that around 30% of global food production ends up as food waste and its effect on climate change is catastrophic since 95% of waste ends up at landfill sites, where it is converted into methane and other greenhouse gases (McCarthy et al., 2017). Researchers highlighted the negative externalities linked to food waste and showed that emergent nonthermal technologies are able to reduce food wastes through the food shelf-life extension, which is considered to be one of the most sustainability-driving food innovations contributing to sustainable development (Cavaliere et al., 2018). The transition towards these new methodologies of food production and consumption will depend on the sector's capacity to introduce innovative and emergent approaches and strategies at any level of the supply chain (Cavaliere et al., 2018). However, emergent technologies such as HPP, PEF, and US have been studied by both industry and academia, in an attempt to minimize the disadvantages of conventional thermal methods. Recently, these technologies have also been studied as extraction methods to recover bioactive compounds, which present important biologic activities, from food byproducts and residues, contributing to food waste valorization and also reducing its impact on environment (Alexandre et al., 2017a,b,c,d,e). HPP, PEF, and US, which will be discussed in this section, are among the most studied nonthermal alternative processing and extraction methods.

5.4.1 High pressure processing technology

5.4.1.1 Technological fundamentals

The great and increasing interest of the food industry in HPP, as a "cold" pasteurization method, is mainly due to the low effect of this technology on functional and nutritional properties of food products and their capacity to inactivate/destroy microbial loads of foods (Barba et al., 2012; Barba et al., 2015,a,b). The high pressure effect is based on two fundamental physical principles: *Pascal's isostatic principle* and *Le Chatelier's principle. Pascal's isostatic principle* claims that pressure applied to a sample is transmitted uniformly and instantaneously by the entire food sample whether in direct contact or in a flexible container, regardless of its shape, volume, size, or geometry, unlike thermal treatment, which has slower heating points. Therefore, HPP technology is easier to implement industrially than thermal treatments (Neetoo et al., 2012; Misra et al., 2017). *Le Chatelier's principle* states that any change made in an equilibrium system (chemical reaction, phase transition or modifications of molecular configurations) accompanied by a volume decrease is favored by a high pressure increase, whereas reactions that involve a volume increase will be inhibited (Neetoo et al., 2012). Thus, the pressure has a huge influence on the biochemical reaction rates that occur in foods since most of these reactions are often involved in volume changes. Additionally, the enzymatic reactions may be affected by the pressure compromising the energy production (Welti-Chanes et al., 2005; Venugopal, 2006).

Food products are typically vacuum-packaged and placed inside a pressure basket, being after loaded into the pressure vessel and then HPP occurs in three distinct phases. The first one, *pressure boost*, happens during a short time and is related with the increase of pressure until that the desired treatment pressure is achieved; the second one, *pressure maintaining*, consists of pressure maintenance for the desired period; and the third one, *pressure relief*, is related with the pressure relief that happens from the target level to atmospheric pressure in a couple of seconds (Huang et al., 2013). High pressure can be generated by three different ways:

1. *by direct compression*, which requires dynamic pressure seals between piston and vessel surface;
2. *by indirect compression*, which requires static pressure seals; and
3. *by heating the pressure medium*, which is usually water combined with mineral or vegetable oil for lubrication with anticorrosive purposes (Ohlsson, 2002; Welti-Chanes et al., 2005).

In fact, the most common transmitting fluids are water, food grade glycol/water solutions, silicone oil, sodium benzoate solutions, ethanol solutions, and castor oil (Balasubramaniam et al., 2008). During HPP, food products are submitted to pressures that may range from 100 to 800 MPa in batch or semicontinuous processes, from a millisecond pulse to over 20 minutes, at temperatures that can be from below 0°C to above 100°C (Muntean et al., 2016). The processing temperature can be controlled by cooling jackets, heat exchangers, or by recirculation of the cooling/heating medium. The food temperature always increases through the adiabatic heating, around 3°C per 100 MPa at 25°C [but it can be significantly higher (8°C–9°C/100 MPa) for more compressible food ingredients such as fats], but if no heat is exchanged from the pressure vessel walls during the holding time (second phase), the temperature decreases to the original temperature on the decompression cycle (Guan et al., 2005; Pereira et al., 2010; Muntean et al., 2016). The packaging material of food products must be flexible since foods decrease in volume under pressure and regain volume during decompression (Lou et al., 2015) and currently, industrial HPP of solid foods can only be done in batch mode (Fig. 5.1) (Considine et al., 2008).

However, HPP and PEF are two of the most commercial technologies and some processed products can be even found on the market. Indeed, there is an increasingly high number of high pressure equipment operating worldwide (Fig. 5.2), the

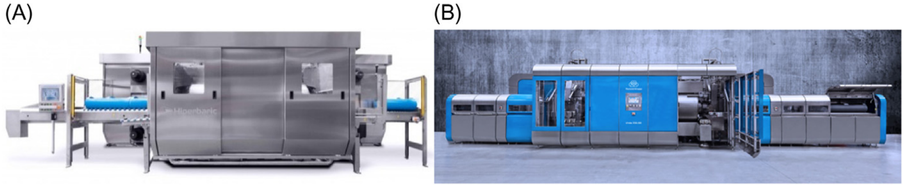

Figure 5.1 Industrial scale equipment of high pressure processing (in batch mode). Source: Courtesy Hiperbaric S.A (A) Model 135, www.hiperbaric.com and UHDE (B) Model 350–60, www.thyssenkrupp-industrial-solutions.com/en/high-pressure-processing.

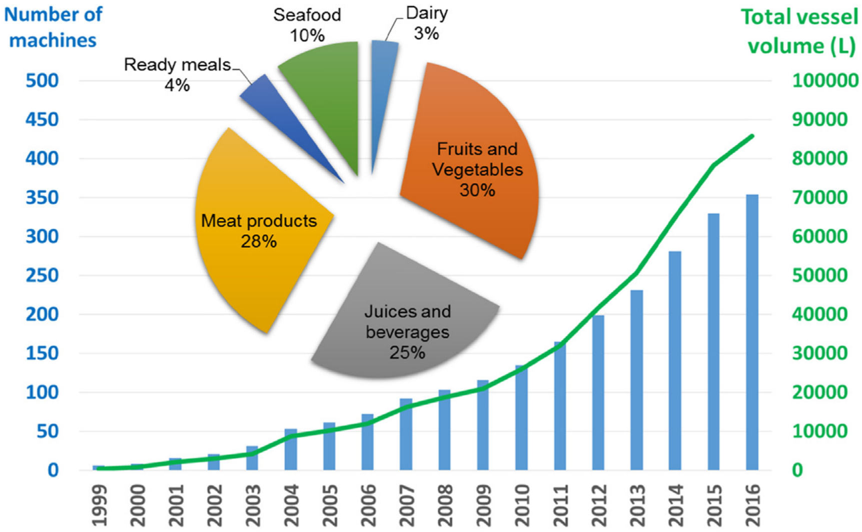

Figure 5.2 Evolution of the total number of high pressure industrial machines operating worldwide and global high pressure processing submarket share in 2015.
Source: Courtesy Hiperbaric S.A.

major suppliers being Avure Technologies (USA), Hiperbaric (Spain), and UHDE High Pressure (Germany) (Barba et al., 2016). Furthermore, Visiongain (2017) estimates that the HPP food equipment market will exceed 13 billion dollars in 2017 and predicts a strong revenue growth of HPP market through to 2027, primarily due to health-driven consumers.

5.4.1.2 Effect on food composition, microorganisms, and applications

The effect of HPP on molecules with a low molecular weight is minimal. Small molecules such as vitamins, alkaloids, saponins, flavonoids, peptides, fatty acids, and saccharides remain relatively undamaged compared with thermal processing since the covalent bonds have very low compressibility at high pressure. In this way the nutritional value and the quality of food is preserved during the HPP. High pressure only affects noncovalent bonds such as hydrogen, ionic, and hydrophobic bonds acting selectively. Therefore, only the native structure and functionality of macromolecules such as proteins, enzymes, lipids, polysaccharides, and nucleic acids may be disrupted by HPP (Jun et al., 2011; Huang et al., 2013; Jun, 2013). The primary structure of proteins is unaffected by pressure due to covalent bonds while the secondary, tertiary, or quaternary structure are changed, due to the disruption of ionic bonds, hydrogen bonds, and hydrophobic and electrostatic interactions responsible for the protein structure (Rendueles et al., 2011). Thus, some compounds are irreversibly changed during HPP such as the gelatinization of carbohydrates that can be achieved through pressure increases rather than through temperature increases and proteins can be denatured at high temperature (Muntean et al., 2016).

The impact of high pressure in the microbiological food loads is similar to that previously discussed for chemical components of food. The microbial inactivation results in a multiplicity of injuries accumulated in different components of the cell including cell membranes, nucleoids, ribosomes, proteins, and enzymes (Considine et al., 2008; Daryaei et al., 2012). The cell membrane of the microorganisms is composed by a phospholipid bilayer with proteins and lipids, which are affected by high pressure. In fact, the proteins are essential to many functions of the bacterial cell and their denaturation by pressure will compromise the microorganism survival. Lipids also change their conformation and packing, altering the membrane fluidity. Thus, protein−lipid interactions are weakened and the membrane becomes less permeable reducing the transmembrane transport (Balasubramaniam et al., 2015). Below 300 MPa, most of these reactions can be reversible but above 300 MPa, irreversible cell damages can be achieved breaking the cell membrane integrity and the flow of internal substances, leading to bacterial death (Huang et al., 2014). HPP also changes ribosome configurations interfering with normal protein biosynthesis and inhibiting the protein repair system. Moreover, HPP also affects the normal DNA replication and gene transcription due to condensation of the genetic materials leading to degradation of the chromosomal DNA (Huang et al., 2014). Yeasts and molds are relatively sensitive to HPP being inactivated within a few minutes by 300−400 MPa at room temperature.

However, spore-forming microorganisms are highly resistant when in spore form, being required a combination of high pressure (exceeding 1000 MPa) and heat (above 80°C) to attain a significant log reduction of spores in food products. Viruses show a wide range of sensitivity in response to HPP (Muntean et al., 2016).

The efficacy of HPP is influenced by several factors such as the *treatment time* (time to achieve the desired pressure, holding time, and decompression time); *temperature* (initial temperature, processing temperature, and distribution temperature in the pressure vessel due to the adiabatic heating), *pressure* level used and the nature of pressure (batch or continuous), *food matrix characteristics* (such as pH, composition, and water activity), *packing material* and type of *microorganisms* present in food products (Venugopal, 2006; Alexandre et al., 2017a,b,c,d,e). The effect of high pressure on some of the most important food pathogens was reviewed by Alexandre et al. (2017a,b,c,d,e) and in general, the increase of the pressure's treatment time and/or the increase of the pressure level cause an increase of the microbial inactivation. For example, *E. coli* was analyzed in carrot, strawberry/blueberry, apricot, orange, and cherry juices as well as in raw milk cheese and dry fermented salami and microbial log reductions obtained by HPP were between 0.5 and 8.0 (Rodríguez et al., 2005; Van Opstal et al., 2005; Bayındırlı et al., 2006; Porto-Fett et al., 2010; Tadapaneni et al., 2014); *S. enteritidis* was analyzed in nuts and apricot, orange, and cherry juice showing log reductions between 1.0 and 7.3 log cycles due to HPP (Bayındırlı et al., 2006; Prakash, 2013); *S. typhimurium* was studied in strawberry/blueberry beverage and dry fermented salami presenting log reductions between 1.9 and 6.0 log cycles (Porto-Fett et al., 2010; Tadapaneni et al., 2014); *L. monocytogenes* was analyzed in strawberry/blueberry beverage, dry fermented pork sausage, dry fermented salami, and raw cow's milk cheese showing microbial reductions between 0.60 and 6.34 log cycles after HPP (Rodríguez et al., 2005; Jofré et al., 2009; Porto-Fett et al., 2010; Tadapaneni et al., 2014); and *S. aureus* was studied in dry fermented pork sausage, raw cheese, and apricot, orange, and cherry juice obtaining log reductions between 0.30 and 5.7 after HPP (Rodríguez et al., 2005; Bayındırlı et al., 2006; Jofré et al., 2009), depending on the food product and HPP conditions. The effect of HPP on fish meat quality was reviewed by Oliveira et al. (2017), while Hygreeva et al. (2016) reviewed the quality of processed meat products through HPP and Oey et al. (2008) reviewed the effect of HPP on color, texture, and flavor of fruit- and vegetable-based food products. In general, HPP had low impact on quality parameters of food products and some researchers, such as Fernandez et al. (2018), are optimizing the processing conditions to preserve quality attributes of a mixed fruit and vegetable smoothie, keeping in mind food quality and safety requirements.

HPP could be used for some commercial applications such as the pasteurization of meats and vegetables; pasteurization and sterilization of fruits, sauces, yogurts, and salad dressings; and decontamination of high risk and high value heat sensitive ingredients including flavorings and vitamins. In fact, there are already some HPP food products available on the market such as vegetables and fruit juices, salsas, dressings, meats, ready-to-eat meats and poultry, seafood, shellfish, and fish products (Muntean et al., 2016).

5.4.1.3 Advantages and limitations

As mentioned before, the major advantage of the HPP consists of the preservation of fresh food characteristics, namely sensorial and nutritional properties, extending shelf-life and improving food quality and safety, due to microbial and enzymatic inactivation (Rendueles et al., 2011). In other words, high pressure inactivates vegetative bacteria and spores (at higher temperatures) preserving nutrients, colors, and flavors. The impact of high pressure on food products is homogeneous, uniform, and instantaneous and there is no evidence of toxicity. Moreover, HPP reduces processing times and involves fewer energy requirements than thermal treatments; only a small amount of energy is necessary to achieve the desired processing pressure, and it is environmentally friendly with few effluents generated (it only needs water, which is usually recycled). HPP reduces or eliminates the need for chemical preservatives and their applicability to packaged foods may avoid microbial contaminations. Besides, food products have a positive consumer appeal (Alexandre et al., 2013; Muntean et al., 2016).

The biggest limitation for the industrial implementation of this technology is related with the high capital cost, that is, the equipment is still expensive and inevitably requires high investment. A set of HPP equipment costs between 0.5 and 2.5 million euros depending on the capacity and operating parameter range of the equipment (Galanakis, 2013; Huang et al., 2017). Intermittent operation and small workload (batch processing) are other limitations that increase the cost of production. Moreover, HPP allows inactivation of vegetative microorganisms but is insufficient to substantially destroy spores at room temperature (Balasubramaniam et al., 2015) and may have a reversible or irreversible and partial or complete unfolding effect on the enzyme structure being usually less efficient in enzymatic inactivation than heat treatments (Gong et al., 2015; Aghajanzadeh et al., 2018). Moreover, HPP products need transportation and storage under refrigeration; this process is not applicable to food products with low water content (foods should have 40% free water for antimicrobial effect) and there are limited packing options (the packaging material must be compressible to be suitable for HPP) (Muntean et al., 2016; Huang et al., 2017).

As extraction method, high pressure also is considered environmentally friendly since it complies with standards set by the EPA (2015), which include the reduction of synthetic and organic solvents used, and the reduction of operational time and energetic consumption, allowing higher yields and final extracts with a higher quality (Azmir et al., 2013).

5.4.1.4 High pressure processing as extraction method

As well as for HPP, extraction processes assisted by high pressure also occur in three distinct phases: pressure boost, pressure maintaining, and pressure relief. In the first one, the plant tissues and solvent are submitted to increasing pressures and the pressure differential generated between the interior and the exterior of the cell lead to cell deformation and wall damage. If the pressure applied is not enough to exceed the deformation limit of the membranes, the extraction solvent can permeate into the cell through some wall channels and the cells are quickly filled with solvent. Nevertheless, if the pressure applied is enough to exceed the deformation limit of the cell, the pressure will cause damage in the membrane structures and exterior wall, leading to the formation of cracks (Huang et al., 2013; Alexandre et al., 2017a,b,c,d,e). If in the first stage the pressure applied was not enough to exceed the deformation limit of the membranes, this may happen during the second stage and the solvent will permeate quickly into the cells, allowing the bioactive compounds' dissolution (Huang et al., 2013; Alexandre et al., 2017a,b,c,d,e). In the third stage the high pressure acts selectively, and may disrupt large molecule structure or even the cell structure (e.g., enzymes, proteins, and lipids) leaving small molecules (e.g., vitamins, pigments, fragrance ingredients, alkaloids, saponins, or flavonoids) unaffected, since only noncovalent bonds (such as hydrogen bonds, ionic bonds, and hydrophobic interactions) will be affected (Jun et al., 2011; Huang et al., 2013; Jun, 2013). In conclusion, high pressure can reduce the resistance to mass transfer during the extraction of important bioactive compounds from the solvent, mainly due to their effect in the tissues, cellular wall, membrane, and organelles (Shouqin et al., 2007; Huang et al., 2013).

The different parameters to take into consideration for HPP extraction are, in order of importance, extraction temperature, pressure level, solvent and its concentration, ratio of solvent to raw material, and holding pressure time (Chen et al., 2009). The most important parameter is the extraction temperature since the efficiency of thermosensitive compounds' extraction depends on it (Prasad et al., 2009). The solvent choice, and its concentration, are also closely related to the components to extract, and besides being nontoxic, it should be easy to remove from the final extract. The pressure holding time is the period of time needed to achieve the equilibrium between inside and outside of the cells, in terms of solvent and pressure (Xi et al., 2009).

High pressure has been used as an extraction method to recover several bioactive compounds from herbal materials and fruit residues. For example, total phenolic compounds and flavonoids have been extracted from Korean barberry and deodeok (Qadir et al., 2009; He et al., 2010; Lee et al., 2010; He et al., 2011) and from papaya seeds (Briones-Labarca et al., 2015) and citrus peels (Casquete et al., 2014; M'hiri et al., 2014; Casquete et al., 2015). Lycopene and carotenoids were extracted from tomato wastes (Jun, 2006; Xi, 2006; Strati et al., 2015), pectin from orange (Guo et al., 2012) and honey pomelo peels (Guo et al., 2014), mangiferin and lupeol from mango peels (Ruiz-Montanez et al., 2014), ginsenosides from ginseng (Shouquin et al., 2006; Shin et al., 2010; Lee et al., 2011), salidroside from rhodiola (Zhang et al., 2007; Bi et al., 2009), catechins and caffeine from green tea (Xi, 2009; Xi et al., 2010), deoxyschisandrin and y-schisandrin from Magnolia berry (Liu et al., 2009), and podophyllotoxin and 4'-demethylpodophyllotoxin from hance (Zhu et al., 2012). In general, high pressure extraction increases the extraction yields when compared with traditional thermal methods. The optimum conditions were extensively reviewed and discussed by Alexandre et al. (2017a,b,c,d,e) but will be mainly dependent on the target compound to be extracted and of course the plant material used for the extractions.

5.4.2 Ultrasounds

5.4.2.1 Technical fundamentals

Sounds can be defined as the continuous propagation of a mechanic compression or wave that cause particles vibration longitudinally propagated throughout a medium, according to the number of events/repetitions in a certain period of time (frequency). Sounds, according to the frequency range, can be categorized as infrasounds (frequencies up to 20 Hz), acoustic sounds (up to 20 kHz, audible to the human ear), and US (above 20 kHz and up to 10 MHz) (Leong, 2016). US are widely used in the medical field, namely in imagology (such as to visualize the fetus in utero, among other applications).

According to Tiwari (2015), US can be classified according to the intensity of the sonication as low-intensity sonication (<1 W/cm^2, used in several processes of quality and control and physical state of matter) or high-intensity sonication ($10-1000$ W/cm^2, usually used for extraction and food processing).

The use of US as a nonthermal alternative to the conventional thermal pasteurization procedures is raising quite a bit of interest (meeting consumer's demands for fresh, better tasting, healthier, and minimally processed products), not only for that purpose, but also as an assistant for other processes, such as freezing, cutting, drying, tempering, and sterilization (Chemat et al., 2011).

An US apparatus can simply consist of a water bath, or in more complex apparatus, with an US probe, as shown in Fig. 5.3, along with the propagation media (liquid/fluid food product or a solvent mixed to the interesting matrix). From an industrial point of view, US can be used in batch, semibatch, or continuous operation mode, allowing to obtain high yields (Tiwari, 2015). Nevertheless, as it is not an "in package" processing technology, such as HPP or PEF (in certain conditions),

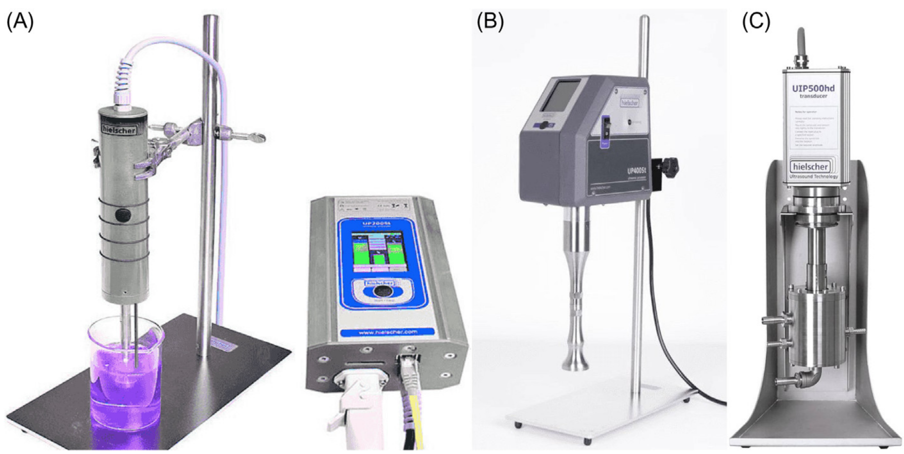

Figure 5.3 Hielscher system (with probe) with different potencies: (A) UP200St—200W, (B) UP400St—400W, and (C) UIP500hdT—500W, available for various applications. Source: Courtesy Hielscher Ultrasonics GmbH 2019 (www.hielscher.com).

it requires aseptic packaging to ensure that contaminants are not reintroduced in the processed product.

5.4.2.2 Effect on food composition, microorganisms, and applications

Piyasena et al. (2003) described the main factors that affect the resistance of microorganisms to ultrasonic treatment as (1) amplitude of the US waves, (2) treatment time, (3) food product properties (bulkier food products may not propagate the waves uniformly, especially nonhomogeneous foods), (4) food composition, and (5) operation temperature. The size, shape, and type of microorganism (Gram-negative vs Gram-positive) are also to be considered in inactivation studies by US, as Gram-positive bacteria are known to be more resistant than Gram-negative bacteria due to their thick peptidoglycan layer, while larger cells are more sensitive to US than the smaller ones, since the former have a larger contact area and "target points" to the US (Chemat et al., 2011).

Microbial inactivation by US is achieved by cavitation, which consists of the creation of bubbles by the ultrasonic waves on the cell membrane, causing local changes in pressure and temperature, leading to its breakdown/rupture, with consequent release of organelles and DNA damage by the production of free radicals (Ercan and Soysal, 2013). Similarly to other nonthermal processing technologies, US can only inactivate, generally, vegetative microorganisms, remaining the endospores, ascospores, and some enzymes not inactivated by US. Ultrasonic pasteurization is more common for liquid foods, such as juices, with application being the main review approach in this section. Gómez-López et al. (2010) sonicated raw orange juice at 20 kHz and 500 W for 8 minutes at 10°C and were able to reduce the total aerobic mesophile count in 1.38 log units, while yeast and molds counts were reduced about 0.56 log units, leading to a shelf-life extension up to 10 days under refrigeration (4°C), compared with the unprocessed juice (spoiled by the sixth day). The authors also reported a reduction on the ascorbic acid content and color degradation in sonicated juice. In another study, Yuan et al. (2009) reported a reduction of about 60% of *Alicyclobacillus acidoterrestris* (a heat-resistant bacterium that is prevalent in acidic fruit juices) in apple juice after US treatment at 24 kHz, 300 W, and 30 minutes, achieving higher inactivation rates (up to 80%) when the treatment time was increased to 60 minutes. The total sugar content, transmittance, and color value decreased with treatment intensity and time increase, while the titratable acidity increased with treatment intensity and time increase. Nevertheless, according to the authors, these alterations did not significantly change the appearance of the apple juice.

Regarding enzymatic inactivation, US, especially when combined with high temperatures, can inactivate several enzymes that compromise the organoleptic characteristics of food during storage. The mechanism for enzymatic inactivation by US starts with the cavitation phenomenon, which leads to the creation of bubbles that collapse as consequence of the increased pressure and temperature. Furthermore, the shock waves also create strong shear and streaming, which may cause changes in the secondary and tertiary structures of proteins, leading to the destabilization of hydrogen bonds and van der Waals interactions, leading to enzymatic inactivation. Free radicals (which form as a consequence of cavitation) may interact with proteins' amino acids (sonochemical reaction), which are related with the stability of the enzyme, substrate binding site, or catalytic function, thus compromising its activity (Raymond et al., 2011).

5.4.2.3 Advantages and limitations

According to Chemat et al (2011), the main advantages of using US in food processing are:

1. the effectiveness of mixing and micromixing products,
2. faster mass and energy transferences,
3. reduced temperature increments during processing,
4. selective components extraction,
5. reduced equipment size,
6. lower costs (when compared with other nonthermal processing technologies, such as HPP or PEF),
7. they are an easy to use technology,
8. they are considered environmentally friendly (due to the reduced energetic costs associated), among others.

Similarly to PEF, US can be operated in continuous operation mode, allowing higher yields from an industrial integration point of view. Nevertheless, some drawbacks are to be pinpointed, such as the fact that US are highly dependent on the sample matrix and on the presence of a disperse phase, which may reduce the effectiveness of the method by wave attenuation, with optimization necessary for each case (Alexandre et al., 2017a,b,c,d,e).

5.4.2.4 Ultrasounds as extraction technique

As aforementioned, the need for replacing hazardous organic solvents for extraction processes lead to the search for novel extraction techniques that reduce the volume of solvents, to meet consumers' demands for chemical-free food products, as well to improve the environmental sustainability of food related processes and waste management.

The success of ultrasounds as an extraction technique relies on four essential mechanisms, which are, according to Tiwari (2015):

1. the improved mass transference by acoustic streaming and turbulent mixing,
2. the damages in the solvent-matrix interfaces (matrix surface in contact with the solvent) caused by shock waves and micro jets,
3. the collisions of interparticles at high velocities, and
4. the disintegration of the matrix to maximize the surface contact area.

Ultrasounds, when in contact with a sample matrix, produce sound waves, which are then are able to generate a phenomenon called cavitation, which is characterized by the production, growth, and collapse of a bubble inside the cell (Adetunji et al., 2017). The bubble's growth bubbles are related with the expansion/compression cycles that affect the cellular structure by pulling/pushing the molecular content apart/together, respectively. The consequent disruption of the bubbles inside the cell wall lead to the damage of its structure, thus facilitating the mass transfer from the cellular particles into the solvent (Ebringerová and Hromádková, 2010).

At the final stages of the extraction, the compounds diffuse from the cell into the solvent. The factors that most affect ultrasound-assisted extractions are related to the sample matrix, due to properties such as its hardness, structure, composition, moisture content, and particle size. Also, the frequency, power, pressure, temperature, time of sonication, and the chosen solvent can significantly change the final extraction yields since all these factors can greatly affect the ultrasound intensity by sound waves attenuation (Alexandre et al., 2017a,b,c,d,e).

Several studies suggested the use of ultrasounds combined with green solvents as water, ethanol, and sunflower oil to enhance the extraction of antioxidant compounds (mainly phenolic compounds), anthocyanins, carotenoids, and polysaccharides, while decreasing the use of organic solvents (Alexandre et al., 2017a,b,c,d,e). The use of mildly nonpolar solvents, as ethanol and acetone, may allow to obtain higher extraction yields of lipid fractions from biomass, in attempts to replace the traditional hazardous solvents used for lipids extraction, such as *n*-hexane or others.

5.4.3 Pulse electric fields

5.4.3.1 Technological fundamentals

PEF is described as a nonthermal food pasteurization technique that relies on the application of short duration pulses (from several nanoseconds up to 1 ms) of moderate to high electric field strengths (up to 80 kV/cm) and low energy (up to 10 kJ/kg) to products placed between two electrodes in a chamber, at mild-high temperatures (Bobinaité et al., 2014) to inactivate both spoilage and pathogenic vegetative microorganisms, at room temperature (Sánchez-Vega et al., 2015), especially in acidic food products (Shahbaz et al., 2018). The PEF equipment can be described, in a simplistic way, as a pulse power supply and a treatment chamber. It can be operated discontinuously and continuously; the latter is more interesting for the food industry, as it allows to treat higher amounts of product at the same time.

The most commonly used continuous units are formed by a pump that inlets the product into the treatment chamber, wherein the electrodes discharge the current on the food product, which is then pulled out (Fig. 5.4). The treated product is then aseptically packed to avoid recontamination. The industrial application of PEF is often coupled with preheating systems ensuring higher microbial inactivation rates when compared with the conventional pasteurization processes (and to nonthermal PEF). These methodologies allow to reduce the impact of thermal processing on the organoleptic attributes of the food products. After the PEF treatment chamber, a cooling system is often used to quickly cool the processed product, as a result of the temperature increase due to the high conductivity of the product itself or the

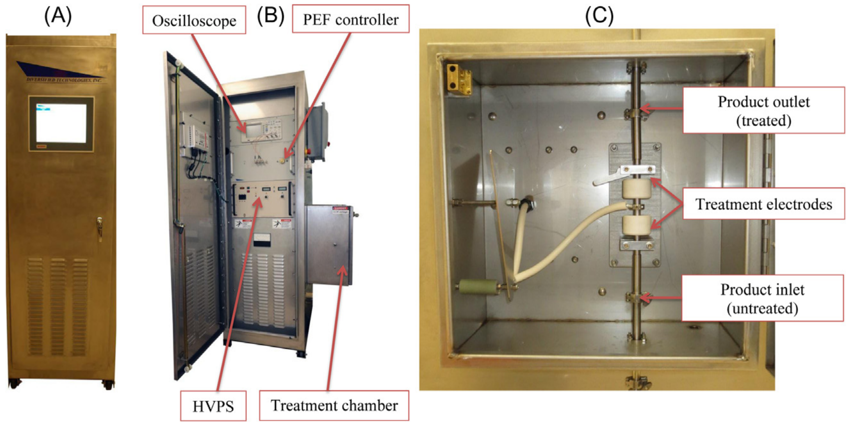

Figure 5.4 Laboratorial/pilot scale pulsed electric field (PEF) equipment, showing the control panel (A), the oscilloscope, the PEF controller and the high voltage power supply (HVPS) (B), and the treatment chamber (C).
Source: Courtesy Diversified Technologies (http://www.divtecs.com/).

high inlet temperatures (Loeffler, 2010). As no heat is applied (even though the temperature increases during the treatment are widely dependent on the product conductivity), the resulting food products present fresh-like attributes, thus answering the consumers' demands for minimally processed food products (Li et al., 2016).

The first experiments concerning the application of PEF on food products were carried out in the 1950s, although it wasn't until 1995 that the first continuously operated equipment was launched, resulting from a consortium between food processors, universities, and equipment manufacturers in Europe and the United States. Nevertheless, it was only in 2006 that the first PEF system was installed for operation in the juice industry, in the United States (Sitzmann et al., 2016).

5.4.3.2 Effect on food composition, microorganisms, and applications

The efficacy of the application of strong electric fields for food safety is related to the formation of pores on microorganism's membranes (a phenomenon called electroporation), which leads to the loss of cellular integrity and viability. The feasibility of PEF on microbial inactivation is well reported in the literature, namely in acidic fruit juices, milk, and liquid eggs. According to Barba et al. (2015,a,b), several factors affect the effectiveness of PEF as a microbial inactivation strategy, namely the field strength, treatment temperature and time, pulse width, pulse frequency, pulse shape (monopolar, bipolar, square, exponential, etc.), electrode distance (treatment gap of the chamber), polarity, and applied energy. This emergent nonthermal technology can be used to improve the quality and safety of dairy products, such as milk, whey, infant formulas, liquid eggs, and fruit juices, to enhance their shelf-stability.

Sharma et al. (2014) studied the effect of PEF treatment (23−28 kV, 17−101 μs, 4.2 mL/s) in whole milk and reported that, due to the product specific constitution, no significant microbial load reductions were found in milk treated at low temperatures (4°C), even when using higher electric strengths and treatment times. Nevertheless, considerable microbial load reductions were found when the milk was preheated before the PEF treatment, as the PEF was more effective after higher preheating temperatures. The same authors also reported that the matrix composition had a major role on the microbial inactivation after PEF, as more pronounced microbial load reductions were found in skimmed milk than in whole milk. This could be associated with whole milk's richness in fat and proteins, which confer a protective effect against bacterial membrane electroporation during PEF treatments. A known protection mechanism is the thick peptidoglycan layer present in Gram-positive bacteria, which are known to be more resistant to electric field pulses than Gram-negative, since that specific layer helps to protect bacteria from electroporation.

In another study, the effect of PEF treatment on raw milk for cheese production was accessed, with the outcomes revealing that treated milk (20 and 30 kV/cm, 2 μs, 120 pulses, 20°C) presented higher curd firmness than thermally pasteurized milk (63°C, 30 minutes), with this parameter decreasing with higher treatment intensities. The same study reported that the rennet coagulation time was lower after PEF treatment, which increased as the intensity also increased (Yu et al., 2009). These results led to the formation of an improved, stronger gel, probably due to the partial protein denaturation that occurs at higher intensity treatments, as stated by Yu et al. (2009). Denaturation is known to be due to protein molecule polarization, dissociation of noncovalent bonds from the quaternary structure of the protein, exposure of entrapped hydrophobic amino acids, and/or sulfhydryl groups exposure as a result of protein conformational changes. During PEF treatment, the milk proteins can change their total charge leading to the establishment/modification of ionic interaction between proteins. Milk functional aspects such as coagulation, emulsification capacity, and foaming can be changed after PEF treatment due to the modification of protein network (Floury et al., 2006; Perez et al., 2004).

The most popular application of PEF in the food industry is in acidic fruit juices treatment, namely on strawberry, apple, orange, and pear juices (among others), since their low pH acts as a hurdle that hinders endospore germination and outgrowth, thus expanding the juice shelf-life, which is difficult in low acidic food products. Timmermans et al. (2014) studied the inactivation of *Salmonella panama*, *E. coli*, *L. monocytogenes*, and *Saccharomyces cerevisiae* inoculated in fruit juices with different pH values, namely apple (3.5), orange (3.7), and watermelon juices (5.3), using a continuous-flow PEF system (frequencies of 120−964 Hz, 2 μs monopolar pulses, 20 kV/cm at a flow of 14 mL/min). The results showed that, for the same treatment conditions, *S. cerevisiae* was more sensible than the other microorganisms under study, proving that bacteria need more energy expense to be inactivated than yeasts. At temperatures above 35°C, a combined effect of temperature and electric field pulses on the microbial inactivation was observed.

When it comes to the quality parameters, the use of nonthermal approaches to preserve fruit juices can be very promising regarding the preservation of thermolabile compounds, such as vitamin C, which are lost during thermal pasteurization procedures. Nonetheless, general physicochemical parameters (such as pH, Brix degree, conductivity, and hydroxyethyl furfural) are not affected by PEF processing. Otherwise, viscosity is known to increase in PEF treated juices, as well as color degradation (Koubaa et al., 2017).

Concerning the application of nonthermal PEF for microbial inactivation in alcoholic beverages, such as beer and wine, Puértolas et al. (2009) reported a 3 log units reduction (after a treatment at 22−31 kV/cm, 1 Hz, up to 100 pulses, at 24°C) of *Dekkera anomala*, *Dekkera bruxellensis*, *Saccharomyces bayanus*, *Lactobacillus plantarum*, and *Lactobacillus hilgardii*. These microorganisms are responsible for off-flavors production by using the residual sugars of wine to produce D-lactic and acetic acids, thus changing the organoleptic characteristics of wine. As sulfur dioxide (SO_2) is a chemical recognized as harmful and usually used for microbial inhibition in wines, those authors also stated that nonthermal PEF could be an interesting technology for the production of additive-free wines.

Puértolas et al. (2009) also reported that, after a PEF treatment (35 kV/cm, 2296 μs, 2122 kJ/L, 14.7°C), *Bacillus subtilis* populations inoculated in beer were reduced in 8.4 log units, while a treatment performed at 45 kV/cm, 804 μs, 1169 kJ/L at 4°C reduced the population of *L. plantarum* in about 7.0 log units, as well of the pathogenic *Salmonella choleraesuis* in about 5.7 log units, when compared with thermal pasteurization.

Pasteurized liquid eggs are quite popular and useful, not only for the food industry, but also for hotels, restaurants, and cafes (HoReCa channel services) that have to ensure the quality and safety of their egg-based products. The conventional thermal pasteurization procedure of whole egg products (61.1°C for 3.5 minutes) is reported to be the minimal temperature/time binomial to ensure the inactivation of pathogenic microorganisms (Puértolas et al., 2009), as lowering the processing temperature can result in nonpasteurized whole eggs, while higher temperatures result in overheating, leading to egg coagulation and the formation of films (Li-Chan et al., 1995). The possibility of applying PEF on liquid eggs as a nonthermal alternative (despite its high conductivity) is gaining particular interest. Puértolas et al. (2009) reported 3 log units' reduction of *B. cereus* reduction in liquid whole egg after a PEF treatment of 40 kV/cm, 2.5 μs pulse width, 155 pulses for 360 μs, at 20°C, while a 1.3 log reduction was found for *E. coli* O157:H7 after exposure to electric fields of 15 kV/cm, up to 500 pulses at 1 Hz, at 0°C (Amiali et al., 2004). *Salmonella* sp., one of the most prevalent pathogenic bacteria in eggs and responsible for food poisoning outbreaks (such as gastroenteritis), was reduced by about 3 log units after a PEF treatment of 40 kV/cm, 300 Hz, 5 pulses for 15 μs, below 35°C (Monfort et al., 2010), showing the potential of this technology to pasteurize liquid whole eggs, without compromising its quality attributes.

5.4.3.3 Advantages and limitations

As previously discussed, the use of PEF as a nonthermal food processing technique has advantages over the conventional thermal processes, since it avoids the destruction of food products' thermolabile compounds, such as proteins, vitamins, and enzymes, providing safe and shelf-stable food products with natural-like sensorial attributes (Vega-Mercado et al., 2007).

Nonetheless, some drawbacks to PEF processing should be pointed out, for example, the temperature rise during the pulse application, as a result of the product conductivity (higher conductivities result in higher temperature rise during processing), thus decreasing the effect of nonthermal processing, leading to loss of sensorial attributes, similarly to the conventional thermal processes (Toepfl et al., 2006).

The transition between laboratorial/pilot scales to industrial units is still a hard task, due to the multiplicity of variables influencing the feasibility of PEF nonthermal pasteurization, such as the product flow, electrodes distance, capillary diameter, and product viscosity and conductivity (Shahbaz et al., 2018).

Industrial PEF units also require aseptic filling at the end of the processing line, which is expensive and can introduce contamination into the processed food products if it is not properly carried out and maintained (Toepfl et al., 2006).

5.4.3.4 Pulse electric fields as extraction method

Electric fields are also being widely explored as an alternative to the conventional extraction methods, to obtain interesting bioactive compounds, that are, most of the time, degraded by high temperature. The extraction of selective molecules by PEF can be applied by diffusion in solvent (solvent extraction) or by application of pressing procedures (expression) (Vorobiev and Lebovka, 2016). The feasibility of PEF as an extraction technique relies on cell membranes' electroporation that allows the solvents to penetrate the cells and solubilize the interest compounds (according to their polarity) (Saldaña et al., 2017; Yan et al., 2017). The electroporation phenomenon occurs when the cells are exposed to an electric field and the consequence charge accumulation on cell membranes leads to an increase of the transmembrane potential and the consequential formation of pores. The cell membrane permeability can increase drastically and probably result in cell breakdown, which is often a key processing step in food and bioengineering operations. The extent of electroporation is dependent on several parameters, such as treatment time, type of pulse waveform, number of pulses, the plant material components, and electric-field intensity. The duration and number of pulses should be limited to avoid significant temperature elevations that are usually lower than 3°C−5°C (Donsì et al., 2010).

Additionally, PEF can also enhance osmotic dehydration, allowing to obtain higher extraction yields of value-added compounds.

The main advantages of PEF as an emergent extraction methodology compared with the conventional thermal extraction procedures are:

1. the improved extraction yields,
2. enhanced mass transfer rates,

3. short extraction times,
4. milder extraction parameters (lower extraction temperatures and lower volume of solvents),
5. lower degradation of thermolabile compounds (proteins, vitamins, flavors, aromas, etc.),
6. lower environmental impact (reduction of the energy costs), and
7. easier extract purification (reduced grinding) (Barba et al., 2015,a,b).

Several studies report the possibility of using PEF as an improvement for fruit maceration to electroporate the vegetal cells to extract higher amounts of high added-value compounds such as carbohydrates, polyphenols, tannins, carotenoids, etc., using green-solvents such as water and ethanol. For example, Brianceau et al. (2015) reported an increase of phenolic compounds extraction from fermented grape pomace using PEF assisted extraction, obtaining higher yields when compared with control samples. Additionally, the authors demonstrated the selective nature of PEF for extracting anthocyanins (with higher ratios of anthocyanins:flavan-3-ols after PEF assisted extraction), using ethanol as solvent. During PEF extraction the cell network acts as a barrier for the passage of some undesirable compounds, whereas the cell wall remains intact, acting as a "filter" for a selective extraction process, allowing to obtain final extracts with high purity and high extraction yields.

The electric pulse intensity (among other factors, such as temperature, number of pulses, etc.) ultimately determine the efficiency of the extraction process, as observed by Parniakov et al. (2016), who combined aqueous extraction at several pH values and temperatures to PEF and high voltage electric discharges in mango peels. The authors obtained final extracts rich in proteins, carbohydrates, and antioxidant compounds (especially phenolic compounds). The combination of PEF to high voltage electric discharges may be an interesting approach to increase the extraction yields, yet it triggers the production of contaminants (as a result of electrolysis of the extracted compounds, free reactive radicals, etc.), which are inconvenient on value-added extracts (Parniakov et al., 2015).

5.5 Final remarks

Nonthermal emerging processing technologies have a great potential to produce safe food products of high quality. These processing methodologies can minimize the adverse effect of heat verified on conventional methods and there is an increased interest in their application to meet the increasing consumer demand for nutritious foods, in terms of bioactive compound retention and sensorial characteristics and at the same time ensuring food safety standards. These technologies are efficient, rapid, and reliable as an alternative for improving the food quality. Besides, they also have the potential to develop new food products having distinctive functionality. The possible combination of different technologies could be also improve food products quality and, at this time, could be a good starting point for interested researchers to develop their knowledge in this field.

HPP and PEF have already been implemented at industrial scales and some products are even available on the market. However, extensive work remains unchartered to simplify the processes. Thus, an active and strict collaboration between scientists and engineers from different disciplines such as electronic, mechanical, information technology, food technology, among others, is urgently required to reduce the cost of equipment, establish possible processing modes (batch, continuous, semicontinuous), as well as increase efficiency of labor and utilities.

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