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Review

Applications of ultrasound in analysis, processing and quality control of food: A review

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ABSTRACT

Ultrasound is composed of sound waves with frequency beyond the limit of human hearing. By tuning frequency, ultrasound can be utilized in many industrial applications including food. Ultrasound techniques are relatively cheap, simple and energy saving, and thus became an emerging technology for probing and modifying food products. Low power (high frequency) ultrasound is used for monitoring the composition and physicochemical properties of food components and products during processing and storage, which is crucial for controlling the food properties and improving its quality. High power (low frequency) ultrasound, on the other hand, induces mechanical, physical and chemical/biochemical changes through cavitation, which supports many food processing operations such as extraction, freezing, drying, emulsification and inactivation of pathogenic bacteria on food contact surfaces. This review summarizes the major applications of low and high power ultrasound in food science and technology. The basic principles of low and high power ultrasound will be highlighted, and their methods and applications including important research results will be presented. These applications include meat products, vegetables and fruits, cereal products, aerated foods, honey, food gels, food proteins, food enzymes, microbial inactivation, freezing, drying and extraction.

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1. Introduction

Ultrasound is defined as sound waves having frequency that exceeds the hearing limit of the human ear (~20 kHz). Some animals utilize ultrasound for navigation (dolphins) or hunting (bats) using the information carried by back-scattering sound waves. Ultrasound is one of the emerging technologies that were developed to minimize processing, maximize quality and ensure the safety of food products. Ultrasound is applied to impart positive effects in food processing such as improvement in mass transfer, food preservation, assistance of thermal treatments and manipulation of texture and food analysis (Knorr et al., 2011).

Based on frequency range, the applications of ultrasound in food processing, analysis and quality control can be divided into low and high energy. Low energy (low power, low intensity) ultrasound has frequencies higher than 100 kHz at intensities below 1 W·cm^2, which can be utilized for non-invasive analysis and monitoring of various food materials during processing and storage to ensure high quality and safety. Low power ultrasound has been used to nondestructively support genetic improvement programs for livestock and for evaluating the composition of raw and fermented meat products, fish and poultry. It is also used for the quality control of fresh vegetables and fruits in both pre- and postharvest, cheese during processing, commercial cooking oils, bread and cereal products, bulk and emulsified fat based food products, food gels, aerated and frozen foods. Other applications include the detection of honey adulteration and assessment of the aggregation state, size and type of protein. Experimental research conducted to address issues and optimize these applications will be summarized in the low power ultrasound section of this review.

High energy (high power, high-intensity) ultrasound uses intensities higher than 1 W·cm^{-2} at frequencies between 20 and 500 kHz, which are disruptive and induce effects on the physical, mechanical or chemical/biochemical properties of foods. These effects are promising in food processing, preservation and safety. This emerging technology has been used as alternative to conventional food processing operations for controlling microstructure and modifying textural characteristics of fat products (sonocrystallization), emulsification, defoaming, modifying the functional properties of different food proteins, inactivation or acceleration of enzymatic activity to enhance shelf life and quality of food products, microbial inactivation, freezing, thawing, freeze drying and concentration, drying and facilitating the extraction of various food and bioactive components. The advantages of the technology are versatile and profitable to the food industry, yet more research efforts are still needed to design and develop efficient power ultrasonic systems that support large scale operations and that can be adapted to various processes (Gallego-Juárez, Rodriguez, Acosta, & Riera, 2010).

Recent advances in electronics helped to design ultrasound probes and instruments with high resolution and convenience, which diversified the applications of ultrasound in food science and technology as modifiers (high power ultrasound) or sensors (low power ultrasound) for enhancing food quality. Nevertheless, ultrasound cannot be simply generalized to meet the demands of different applications, and thus ultrasound equipments have to be custom designed to suit a specific application. An understanding of the physicochemical properties and functional properties of a specific food should guide in the selection of the appropriate ultrasound sensing or processing system in terms of probe design, geometry and characteristics (e.g., frequency), as well as operation conditions that provide optimum results for each individual application (Knorr et al., 2011). The following sections will detail the basics and applications of low and high power ultrasound in food analysis, quality control and processing.

2. Low power ultrasound

Low power ultrasound (LPU) along with spectroscopy and nuclear magnetic resonance (NMR) are currently the most popular, practical and widely used nondestructive analytical methods. For many years, LPU has been successfully utilized for studying the physicochemical and structural properties of fluid foods (McClements, 1997). The changes in ultrasound properties enable to assess the properties of opaque fluids and to detect foreign bodies in foods through container walls (i.e., without contact), which allows to make measurements in the lab as well as on-line using a robust and reasonably cheap measurements apparatus (Coupland, 2004).

2.1. Basic principles of LPU for food analysis

Sound propagates through food materials as mechanical waves causing alternating compressions and decompressions (Blitz, 1963, 1971). These ultrasound waves have characteristic wavelength, velocity, frequency, pressure and period. The interaction of sound waves with matter alters both the velocity and attenuation of the sound waves via absorption and/or scattering mechanisms (McClements, 2005). The velocity of sound is the product of frequency and wavelength, thereby high frequency sound waves have short wavelength while low frequency waves have long wavelength. Ultrasonic velocity

(v) is determined by density (ρ) and elasticity (E) of the medium, according to the Newton–Laplace equation (Blitz, 1963):

$$\left(v = \sqrt{\frac{E}{\rho}}\right). \quad (1)$$

This equation implies that the ultrasound velocity of the solid form of a material is larger than that of its liquid form (e.g., solid and molten chocolate). For the analysis of food materials, ultrasound velocity is very sensitive to molecular organization and intermolecular interactions, which make ultrasound velocity measurements (UVM) suitable for determining composition, structure, physical state and various molecular process (Buckin, Kudryushov, & O'Driscoll, 2002; Buckin, O'Driscoll, & Smyth, 2003) such as phase transition and crystallization kinetics in bulk fats, emulsions and solid lipid nanoparticles (Awad, 2004; Awad, Hamada, & Sato, 2001; Awad & Sato, 2001, 2002a; Awad & Sato, 2002b; Awad et al., 2008; Maleky, Campos, & Marangoni, 2007; Martini, Awad, & Marangoni, 2006; Martini, Bertoli, Herrera, Neeson, & Marangoni, 2005a, 2005b; Martini, Herrera, & Marangoni, 2005; Povey, Awad, Huo, & Ding, 2007; Povey, Awad, Huo, & Ding, 2009; Singh, McClements, & Marangoni, 2004), and detection of foreign bodies and defects in processed and packaged food (Haeggstrom & Luukkala, 2001; Leemans & Destain, 2009; Zhao, Basir, & Mittal, 2009).

Other ultrasound parameters that correlate with many physicochemical properties of materials are attenuation coefficient and acoustic impedance. Attenuation is caused by the energy loss in compression and decompression in ultrasonic waves due to both absorption and scattering contributions (Buckin et al., 2002). The absorption contribution of attenuation is associated with homogeneous materials whereas the scattering only exists in heterogeneous ones. Attenuation is affected by viscosity, compressibility, wall material, and scattering and adsorption effects (Povey, 1997), which give information about the physicochemical properties of food materials such as molecular relaxation, microstructure, phase composition, bulk viscosity and rheology (Dukhin & Goetz, 2001, 2009; Dukhin, Goetz, & Travers, 2005; McClements, 1995), kinetics of fast chemical reactions and droplet sizing and stability in emulsions (Buckin et al., 2002). In addition, the attenuation coefficient for a given material is highly dependent on the way in which the material was manufactured (Umchid, 2008), which may be useful in quality control assurance of some products. Acoustic impedance is the product of density and sound velocity passing through the boundary of different materials, which affects the reflection coefficient. Materials with different densities will have different acoustic impedances, which results in reflections from the boundary between two materials with different acoustic impedances. Attenuation (A) and acoustic impedance (z) are expressed by the following relationships (McClements, 1995):

$$A = A_o e^{-ax} \quad (2)$$

$$R = \frac{A_T}{A_t} = \frac{z_1 - z_2}{z_1 + z_2} \quad (3)$$

where:

A_o is the initial (unattenuated) amplitude of the wave.
x is the distance traveled
R is the ratio of the amplitude of reflected wave (A_T) to the incident wave (A_t) reflection coefficient
z_1 and z_2 are the acoustic impedances of two materials.

2.2. Ultrasound measurement techniques

Pulse–echo and continuous wave ultrasound are two major techniques that are used in most ultrasound sensors. Another technique is called pitch and catch, which is a modification of the continuous wave technique. In these techniques, ultrasound is generated by transformation of electric current into ultrasound pulses of controlled frequency through transducers.

2.2.1. Pulse–echo technique

Pulse–echo system (Fig. 1) is composed of a sample cell, a transducer and an oscilloscope. A signal generator is used to produce unified electrical pulses, which are converted to ultrasound pulses after passing through the transducer. The generated ultrasound pulse propagates through the sample until it collides with the wall of the sample container then reflects back to the transducer, which converts the returned ultrasound pulses into electric signals again that is recorded on the oscilloscope. Each pulse is partially transmitted and partially reflected; therefore, the ultrasonic velocity and the attenuation coefficient can be calculated by analyzing the echoes received at the oscilloscope. The length of the sample cell (L) is equal to half the distance passed by the ultrasound pulse that can be calculated by referring to a material of known ultrasound velocity (e.g., distilled water). The ultrasound velocity (v) can be thus calculated by measuring the time delay (t) between successive echoes using the following equation:

$$v = 2L/t. \quad (4)$$

2.2.2. Continuous wave technique

This technique, also called "through transmission", utilizes two transducers located at both ends of a one way path (Fig. 2). The sample cell is equipped with two quartz X-cut transducers that are placed apart by a known distance (L). A pulse generator is used to generate electrical continuous pulses with specific frequency and wavelength. A function generator is connected to the pulse generator to adjust the electric pulse before measurements. Here, the ultrasound waves are also generated from electric pulses in the first transducer (transmitter). The returned pulses are received by the second transducer (receiver) after passing through the sample cell that is located in between the two transducers. An oscilloscope connected to both the sample cell and the function generator is to monitor both the original and final electrical pulses as a function of the ultrasonic velocity. The analytical data appearing on the oscilloscope is automatically transferred and stored in an attached computer. For accuracy, both of the ultrasonic signals and their equivalent temperature values are simultaneously recorded since the ultrasonic velocity through materials is temperature dependant. For controlled temperature measurements

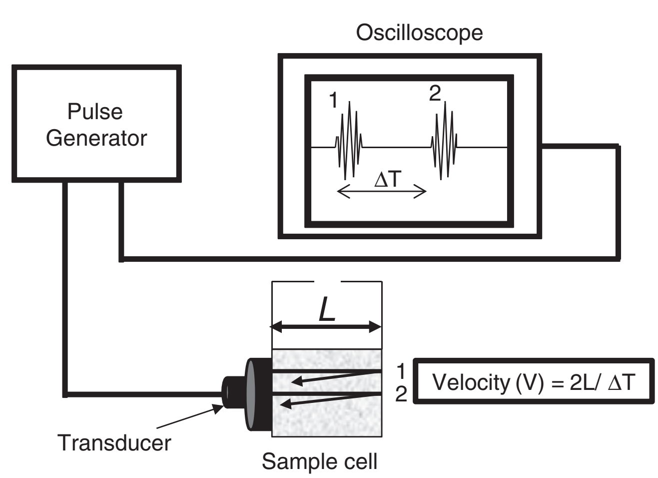

Fig. 1. Schematic diagram of ultrasonic velocity pulse–echo technique, and method of ultrasonic velocity (V) calculation. ΔT, time delay; and L, length of sample container (wave path).

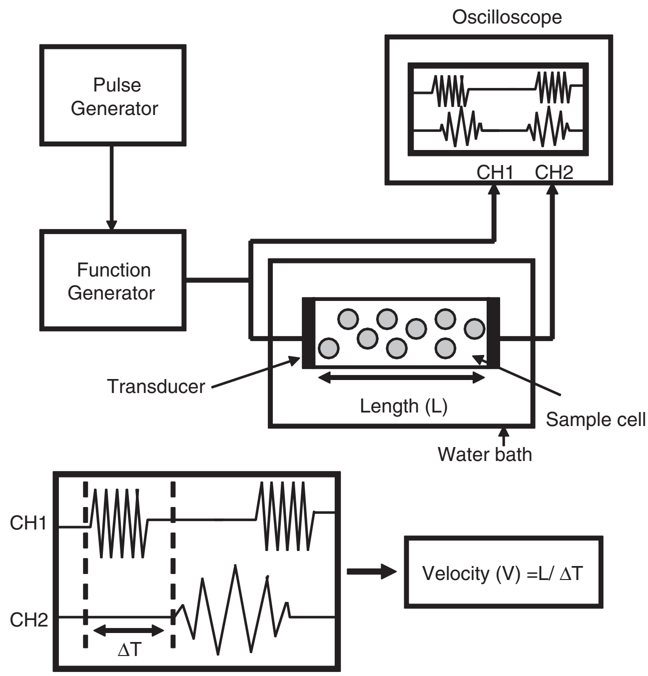

Fig. 2. Schematic diagram of ultrasonic velocity continuous wave technique, and method of ultrasonic velocity (V) calculation. ΔT, time delay; CH1, standard signal; and CH2, measured signal (Awad, 2004).

such as crystallization and melting, a temperature-controlled water bath unit is used to adjust and control the temperature around the sample cell, which permits to perform different temperature-scanning programs set by the computer unit (Awad, 2004; Awad & Sato, 2001, 2002a; Awad & Sato, 2002b; Awad et al., 2001; Hodate et al., 1997). The ultrasonic velocity value can be calculated from the path length, which can be measured by measuring the length (L) of sample cell using distilled water, whose ultrasound velocity values (ν) are known at different temperatures. By calculating the average time delay (ΔT) between the original pulse and that propagates through the sample (Fig. 2), the cell length (L) can be obtained:

$$L = \nu/\Delta T. \tag{5}$$

Using the same equation, the ultrasonic velocity (ν) value of any sample can be calculated.

2.2.3. Pitch and catch techniques

This system includes two transducers; a first transmitting transducer generates a sound pulse while a second receiving transducer detects. In this technique, ultrasonic pulse generated at a certain frequency is sent through the sample and received either at the opposite site or after reflection from the wall of the container back to the source of ultrasound (Buckin et al., 2002). The resolution of this technique is limited by the path length of the pulse or by the size of the sample (Yang et al., 2008). The technique can provide accurately depth of the flaw in materials.

2.2.4. Process tomography

Ultrasonic imaging (ultrasonography) is a medical technology that has long been used as a diagnostic technique. It has many advantages over other diagnostic techniques (e.g., X-ray and NMR) such as safety, convenience, fast, real time, low cost, high contrast and high resolution (Wells, 1988). A low energy pulse of sound vibrating at frequencies between 3 and 30 MHz is transmitted into the body by transducer probe touching the investigated object surface. The pulse is attenuated as it travels through the investigated object being converted to heat and yet a small portion of the pulsed energy is scattered back to the probe. The same probe that transmits the pulse listens for scattered waves to produce echo signals that are processed to form images (Insana, 2006). This technique has found several applications in food technology, like the use of high contrast images to detect defects in food packaging seals using pulse–echo ultrasound with a 17.3 MHz transducer (Frazier, Qi, Ozguler, Morris, & O'Brien, 2000) and chicken breasts (Correia, Mittal, & Basir, 2008).

2.3. Applications of low power ultrasound (LPU)

2.3.1. Meat products

In the beef industry, LPU has been a fast, reproducible and reliable technology to enhance genetic improvement programs for livestock (Crews & Kemp, 2002; Stelzleni et al., 2002; Wilson, 1992). As same as for human pregnancy, sound waves of various frequencies (depending on depth of tissue penetration and resolution) produce vibration–reflection images of tissues such as muscle, fat, and internal organs in live animals, which can be used as a management tool in selection and replacement of breeding stock for the improvement of the genetics of the herd (DuPonte & Fergerstrom, 2006; Williams, 2002), research and management of beef cattle carcass (Paisley, Loehr, & Niemala, 2007; Williams, 2002) for estimating fat and muscle accretion and body composition (Faulkner, Parrett, Mckeith, & Berger, 1990), intramuscular fat (IMF) percentage (Chengcheng, Yufeng, & Kwabena, 2009; Ribeiro, Tedeschi, Stouffer, & Carstens, 2008), and carcass traits of Bali bulls (Sri Rachma & Harada, 2010). Real time ultrasound has become widely used for estimation of the body and carcass chemical composition of growing lambs (Ribeiro et al., 2008; Silva, Gomes, Dias-da-Silva, Gil, & Azevedo, 2005), sheep carcass (Silva et al., 2006) and degree of muscle development in lamb (Theriault, Pomar, & Castonguay, 2009).

LPU has also been used for studying the composition of fish and poultry. To estimate the moisture and protein content of cod fillets, McClements and co-workers investigated the relationship between ultrasonic properties of fish and their composition (Ghaedian, Coupland, Decker, & McClements, 1998; Ghaedian, Decker, & McClements, 1997). Using a frequency scanning pulse echo reflectometer (FSPER), they studied the temperature dependency of the sound velocity of fish analogs having various concentrations of solids-non-fat, water, and oil. They treated the fish composition as (solids-non-fat + water) and an oil phase, and developed an important relationship between the ultrasound velocity values at a constant temperature and the volume fractions of the two components, which gave excellent correlation between the values predicted and the actual measured values. The same method was later used to determine the composition of chicken analogs and the solid fat content of chicken fat (Chanamai & McClements, 1999) suggesting the advantages of LPU as a rapid and nondestructive method in food analysis. Ultrasonic velocity and temperature profiles were also used to study the composition of Atlantic mackerel (*Scomber scombrus*) tissues including fat content, solids and non-fat content (Sigfusson, Decker, & McClements, 2001). In contrast, there was no correlation between the attenuation coefficient and the fat content of mackerel tissue, which limited the use of attenuation coefficient for the composition analysis of mackerel tissue (Sigfusson et al., 2001). However, the authors indicated that this ultrasound parameter may be useful for monitoring structural deterioration of the mackerel tissue during post mortem, in agreement with the earlier work on Atlantic cod fillets (Ghaedian et al., 1997).

Similarly, ultrasound velocity measurements (UVM) have been used to determine the composition of raw meat mixtures (Benedito, Carcel, Rossello, & Mulet, 2001). Based on the behavior of ultrasound velocity at different temperatures for lean tissue and fats, they were able to accurately predict the ratios of fat, moisture and protein. Later, a pair of ultrasonic transducers (1 MHz, frequency) was used to determine the composition of fermented meat food products from sound velocity measurements (Simal, Benedito, Clemente, Femenia, & Rossello, 2003). Temperature–ultrasound velocity plots were also used to characterize and classify pig back fat from animals of different breeds and feeding regimes by comparing their melting behavior and solid/liquid fat content (Niñoles, Clemente, Ventanas, & Benedito, 2007). Recently, a methodology was proposed to assess cheese composition by UVM during the cooling process taking place in the container after the curdling process as a quality control tool to detect process anomalies in-line (Telis-Romero, Váquiro, Bon, & Benedito, 2011). Other workers also used contact or non-contact ultrasound to detect defects and internal objects in cheeses (Hæggström & Luukkala, 2001; Lee, Luan, & Daut, 1992; Leemans & Destain, 2009) and skinless poultry breast (Cho & Irudayaraj, 2003). Table 1 demonstrates the major applications, parameter and advantages of LPU in analysis and quality control of meat products.

2.3.2. Fruits and vegetables

Plant foods including fruits and vegetables are highly attenuating materials due to the scattering of sound from voids and pores, which complicates the interpretation of ultrasound data (McClements & Gunasekaran, 1997; Povey, 1998), and thereby unsuitable for evaluating their tissues (Mizrach, Galili, Rosenhouse & Teitel, 1991; Porteous, Muir, & Wastie, 1981; Sarkar & Wolfe, 1983). The application of ultrasound for the quality control of fresh vegetables and fruits in both pre- and postharvest applications was highlighted in a recent review (Mizrach, 2008). Mizrach explained the various physiological and physiochemical changes taking place during growth and maturation, and in the course of the harvest period, storage and shelf-life, and how linking the results of ultrasound measurements and other physiochemical measurements, such as firmness, mealiness, dry weight percentage (DW), oil contents, total soluble solids (TSS), and acidity enables the indirect assessment of the proper harvesting time, storage period or shelf-life (Mizrach, 2008). An early study has shown that the amplitude of the ultrasound wave transmitted through fruit peels increased when the color changed from green to yellow indicating a good correlation between the ripeness and the acoustic attenuation (Mizrach et al., 1991). In other work, the maturity and sugar content of plum fruits determined by measuring ultrasound attenuation in the fruit tissue correlated well with the firmness of plums (Mizrach, 2004) and that of tomato in other study (Mizrach, 2007). This proved the importance of using the attenuation parameter, which has also been used earlier for detecting defective potatoes (Cheng & Haugh, 1994). Ultrasound velocity measurements have also been used to determine the content of different sugar species in fruit juices and drinks (Contreras, Fairley, McClements & Povey, 1992). A non-contact ultrasonic system operating in either pulse–echo or through-transmission mode was used to measure the sugar content and viscosity of reconstituted orange juice (Kuo, Sheng, & Ting, 2008). This system gave a good linear correlation with sugar contents in solution denoted by Brix, and an exponential correlation with viscosity.

Another application of ultrasound velocity measurements is for the evaluation of oil composition, purity and quality. Sankarappa and coauthors measured the density and ultrasonic velocity at a frequency of 3 MHz in some refined and unrefined edible oils of coconut, castor, sunflower, safflower and groundnut (Sankarappa, Kumar, & Ahmad, 2005), which allowed to estimate various physical parameters (e.g., specific volume, molar sound velocity, adiabatic compressibility, molar compressibility and intermolecular free length). Recently, a pulse–echo technique was used to measure ultrasound velocity and attenuation in some Moroccan oils such as Argan oil, commercial cooking oil and olive oil. Data were processed to determine the acoustical characteristics of these oils (density, acoustical impedance, celerity, absorption losses coefficient, the dynamic viscosity and the compressibility modulus) (Aouzale, Chitnalah, & Jakjoud, 2010).

2.3.3. Cereal products

Bread is a major cereal product beside a variety of other food products such as biscuits, breakfast bars and other bakery products. The different stages of the bread-making process are mostly characterized by empirical or rheological techniques (Dobraszczyk & Morgenstern, 2003). A study to examine the extent of mixing on three different flour dough systems using ultrasound and conventional rheology technique showed strong correlations between ultrasound parameters (velocity and attenuation) and rheology, which indicated the possibility of using ultrasound for on-line dough quality control (Ross, Pyrak-Nolte, & Campanella, 2004). Other workers used ultrasound to characterize the fermentation phase during bread making (Elmehdi, Page, & Scanlon, 2003; Skaf, Nassar, Lefebvre, & Nongaillard, 2009). Skaf et al. (2009) developed a low frequency acoustic technique with two large sensors (through transmission) to overcome the continuous physical and chemical evolution of dough medium during fermentation, which allowed to evaluate the physical properties of dough and determine the critical time as well as the influence of several technological parameters in the process of dough development (Skaf et al., 2009). More recent work utilized a low cost and rapid through transmission ultrasound velocity technique to monitor changes in wheat flour dough consistency induced by proteins and gelatinization of the starch (García-Álvarez, Salazar, & Rosell, 2011). Porosity is an important physical–mechanical property that is directly linked to the quality of bakery products. For optimizing the bread texture and rheology, it is necessary that air bubbles are incorporated

Table 1
Applications of low power ultrasound in analysis and quality control of meat products.[a]

Meat product	Measurements	Parameter[b]	Advantage
Livestock, beef cattle carcass, sheep carcass, carcass traits of Bali bulls, growing lambs	Fat and muscle accretion and body composition, intramuscular fat (IMF) percentage, and carcass traits, degree of muscle development	Vibration–reflection images of tissues and internal organs in live animals	Enhance genetic improvement programs for livestock; quality control of meat
Pigs	Characterize and classify back fat from animals of different breeds and feeding regimes	V	Quality control; improve meat quality traits in breeding animals
Atlantic mackerel	Fat content (solids and non fat content)	V	Easy, rapid and non-destructive method
Atlantic cod fillets	Structural deterioration of tissue during post mortem	A	
Chicken	Composition of chicken analogs; solid fat content.	V	Nondestructive and rapid detection; alternative to x-ray methods.
Skinless poultry breast	Defects and internal objects	V	
Raw meat mixtures	Composition	V	Quality control
fermented meat	Quality determination	V	
Dairy products (cheese)	Composition, defects and internal objects, rheology	V	In line quality control

[a] The literature references for each food application are listed in the corresponding sections/subsections.
[b] V, ultrasonic velocity; A, attenuation coefficient.

during bread dough mixing and maintained until the dough is formed. However, air bubbles in bubbly media (like dough) have great effect on the sound velocity and attenuation, depending on wave frequency (Elmehdi et al., 2003; Leroy et al., 2008). A direct ultrasound measurement method at low frequency (to decrease attenuation) has been shown to be suitable, fast and nondestructive for evaluating the textural properties of bread products (Petrauskas, 2007).

Crispness is an important sensory characteristic of biscuits and other cereal products. Povey and Harden (1981) performed measurements on biscuits using pulse–echo technique, and found a good correlation between ultrasound velocity and sensory crispness (Povey, 1989; Povey & Harden, 1981). The same group at Leeds University later developed an acoustic envelope detector to assess the crispness based on the force/displacement behavior of food materials and their acoustic nature (Chen, Karlsson, & Povey, 2005). In general, the acoustic ranking of biscuits from instrumental assessment was in very good agreement with that from sensory panel tests. Recently, a low frequency acoustic method was developed to estimate the structural and mechanical properties of cereal products such as wafer sheets, crisp bread, crackers and ring-shaped rolls from the magnitude of the amplitude of a penetrated acoustic signal (Juodeikiene & Basinskiene, 2004). Good correlations were found between penetrated acoustic signals and the structural and mechanical properties (density, surface porosity, mechanical strength) of porous food products, measured by a traditional method.

Many food products are made with batter such as pancakes, cupcakes, waffles, doughnut, tempura, etc. Ultrasound techniques are used to monitor the physical properties of batters (density, viscosity and rheology) and cakes (volume, symmetry, volume index, height and density). Fox et al. (2004) described the design and application of a low cost ultrasound system, to monitor specific quality of batters as it is mixed (Fox, Smith, & Sahi, 2004). Changes in compressibility in batters were monitored by measuring the acoustic impedance of the batter (Salazar, Turó, Chávez, & GarcIa, 2004). In other ultrasound measurements, significant correlations were obtained between the acoustic impedance and the batter consistency (Gómez, Oliete, García-Álvarez, Ronda, & Salazar, 2008). Table 2 summarizes the major applications, parameter and advantages of LPU in analysis and quality control of food resources from plant origin. Other food applications (see below) of low power ultrasound are summarized in Table 3.

2.3.4. Fat and emulsion products

Fats and their emulsions are important food materials that are used in many products. The solid fat content (SFC) of food products containing significant amounts of fats (e.g., chocolate, butter, margarine, shortening and creams) determines many of the sensory attributes such as texture and mouthfeel (Martini et al., 2006). Thus, SFC determination is an essential analytical procedure to ensure the product quality during processing (Martini et al., 2005b). SFC is traditionally measured by pulsed field nuclear magnetic resonance technique (p-NMR) (Awad, 2004; Gribnau, 1992; Madison & Hill, 1978; Petersson, 1986; Van Putte & Van Den Enden, 1974; Wright, Narine, & Marangoni, 2000). A major disadvantage of using NMR is the difficulty of performing online measurements. Low intensity ultrasound is a powerful analytical technique for the characterization of edible fats and oils and assessing the physical and chemical properties such as crystallization and melting temperatures, SFC, hardness, oil content and oil composition (Awad, 2004; Awad & Sato, 2001, 2002a; Awad & Sato, 2002b; McClements & Povey, 1987; McClements & Povey, 1988; McClements & Povey, 1992; Saggin & Coupland, 2002; Singh & Dwivedi, 1995; Wokke & van der Wal, 1991). It has been shown that the ultrasound velocity was not only a function of the solids' content but also sensitive to changes in polymorphism/microstructure (Singh et al., 2004). Ultrasound was also used to monitor the crystallization of fats and determine SFC online (Martini et al., 2005a). Ultrasonic signal attenuation was dependant on SFC and microstructure (crystal size). A combined system of ultrasonic spectroscopy and a low-resolution pulsed nuclear magnetic resonance spectrometer was used to monitor crystallization. Specific relationships were found between ultrasonic parameters [integrated response, time of flight, and full width half maximum] and SFC. total fat (TF), which is an indirect measurement of the ultrasonic velocity, was highly correlated to SFC in a linear fashion (Martini et al., 2005b). The same group has recently used on-line ultrasonic spectroscopy and NMR-MOUSE (NMR mobile universal surface explorer) techniques and found a good correlation with off-line p-NMR measurements. Ultrasonic measurements accurately described the SFC variation, and the two techniques can be used as on-line methodologies to determine SFC during the crystallization of fats (Martini et al., 2005).

Ultrasonic characterization of fluid properties is mainly based on the physical measurement of the ultrasonic wave attenuation coefficient and/or phase velocity as functions of frequency (Challis, Povey, Mather, & Holmes, 2005). McClements and Coupland applied the multiple scattering theory to obtain the mean droplet diameter and droplet size distribution in oil-in-water (O/W) emulsions (Coupland & Julian McClements, 2001; McClements & Coupland, 1996). Ultrasonic velocity measurements also allowed to determine other physical properties of O/W emulsions such as disperse phase volume fraction, solid fat content (Dickinson, McClements, & Povey, 1991; McClements, Dickinson & Povey, 1990a; McClements & Povey, 1987; McClements, Povey, Jury,

Table 2
Applications of low power ultrasound for analysis and quality control of plant food resources.[a]

Application	Measurements	Parameters[b]	Advantages
Fruits and vegetables	Firmness, mealiness, dry weight, oil contents, soluble solids and acidity	V, A	Indirect assessment proper harvesting time, storage and shelf-life
Reconstituted orange juice	Sugar content and viscosity	V	Quality control
Fruit peels	Ripeness	A	Quality control
Plums and tomato	Maturity and sugar content	A	Correlated well with firmness
Potatoes	Defects	A	Quality control
Oils and fat-based products	Density, impedance, celerity, absorption losses coefficient, dynamic viscosity and compressibility modulus	V, A	Nondestructive, noninvasive, simple pulse–echo method
	Composition, purity, quality, density, solid fat, phase transition, polymorphism	V	Authentication of food fat contents, improving Real-time quality control
Cereal product (bread dough)	Extent of mixing and rheological properties	V,A	On-line dough quality control
	Rheological properties, kinetics of bread dough fermentation	V, relative delay, signal amplitude	Non-destructive, Quality control of bread dough Quality control
Batters	Monitor specific quality of batters as it is mixed; consistency	Acoustic impedance	Quality control of sensorial properties
Biscuits and cereal products	Sensory crispness	V, wave amplitude	Quality control of sensorial properties

[a] The literature references for each food application are listed in the corresponding sections/subsections.
[b] V, ultrasonic velocity; and A, attenuation coefficient.

Table 3
Applications of low power ultrasound for analysis and quality control of other food products.[a]

Application	Measurements	Parameters[b]	Advantages
Food oil-in-water (O/W) emulsions	Disperse phase volume fraction, solid fat content, droplet size and size distribution, sedimentation, creaming, coalescence, flocculation, composition, crystallization and melting temperatures, crystallization kinetics and stability	V, A	Quality control and assurance, help optimizing formulations, extending shelf life and long term storage stability, and controlling physicochemical properties of food emulsions and emulsion-based delivery systems
Aerated food products (ice cream, whipped cream, confectionary, bread dough and desserts)	Dispersed gas phase, bubble morphology, mean bubble size and uniformity	V, A	Quality control of aerated food systems
Honey	The physical and mechanical properties, adulteration, high frequency dynamic shear rheology, viscosity and moisture content	V	Quality assurance, Measure continuously the rhelogy of samples flowing through a pipe without disturbing them. Measure the rheology of a sample packed in a container without having to open the container
Food gels			
Tofu	To identify aggregation and the ripening processes/	V, A	Quality control allows to sensitively differentiate between
Carrageenan	textural or gelation	VA	carrageenan types
Food protein	Hydration, solubility, foaming capacity, flexibility, changes in conformation	V	Understanding and controlling the functionality of protein in complex food systems
	Size and concentration of soluble proteins and casein micelle in skimmed milk	A	
	Isoelectric point and precipitation	V, A	
Food freezing			
Gelatin, chicken and beef	Temperature of frozen food and ice content	Time of flight of ultrasonic pulses, V	Quality control, extending the shelf life and preserving the quality of many food products

[a] The literature references for each application are listed in the corresponding sections/subsections.
[b] V, ultrasonic velocity; and A, attenuation.

& Betsanis, 1990), creaming (Dickinson, Ma, & Povey, 1994), sedimentation, coalescence, flocculation (McClements, 1994; McClements et al., 1990) and crystallization rates in edible fat emulsions (Dickinson, Kruizenga, Povey, & van der Molen, 1993; Hodate et al., 1997; Povey, Hindle, Aarflot, & Hoiland, 2006).

Another major application of LPU is for monitoring emulsion crystallization, which is important for the quality of many food emulsion products such as butter, margarine, whipped cream and ice cream. Crystallization and melting of the oil phase in an emulsion are accompanied by changes in their internal structure, morphological properties and molecular packing (Dickinson, Goller, McClements, Peasgood, & Povey, 1990). Based on the difference in sound velocity through solids and liquids, ultrasound velocity measurements have been successfully used to monitor the phase transition and crystallization of various formulations of palm oil, palm mid fraction and palm kernel fats in O/W emulsion system, which helped to gain deep insight into the mechanism of crystallization acceleration induced by the template films of high-melting emulsifier molecules (Awad, 2004; Awad & Sato, 2001, 2002a; Awad & Sato, 2002b; Awad et al., 2001; Hodate et al., 1997). Another useful application of ultrasound velocity measurements is for the assessment of emulsion stability and for studying crystallization kinetic (Povey et al., 2007; Povey et al., 2009). By following the ultrasound velocity as a function of time during cycles of cooling and heating at similar rates, it is possible to assess emulsion stability (Fig. 3a). Same workers also used UVM to measure accurately the volume fraction of crystallized material, nucleation rate and crystallization kinetics of 'monodispersed' cocoa butter emulsion during crystallization (Fig. 3b) (Povey et al., 2009). A temperature scanning UVM was recently used to monitor the complex thermal transitions that occur during the crystallization and melting of triglyceride solid lipid nanoparticles (SLNs). Results suggested that temperature scanning UVM may prove to be a useful alternative to conventional DSC techniques for monitoring phase transitions in colloidal systems (Awad et al., 2008). Compared to DSC, UVM technique is cheaper, more convenient (no special sample handling or transfer to special measurement cell), and the measurements is more rapid, which generates a larger number of data points, thereby giving higher statistical significances (Povey et al., 2009). Importantly, UVM can determine the volume fraction of crystallized phases independent of scanning rates (Dickinson, Goller, McClements, Peasgood, & Povey, 1990), which can be useful for automated testing and quality control (Povey et al., 2009).

2.3.5. Aerated foods

Aerated foods contain air bubbles distributed in a viscoelastic liquid or solid matrix such as ice cream, whipped cream, confectionary, bread dough and desserts. The quality of whipped products of the food industry is closely linked to the characteristics of the dispersed gas phase, such as the bubble morphology, the mean bubble size and the uniformity of the bubble size distribution (Labbafi, Thakur, Vial, & Djelveh, 2007). Because aerated foods are optically opaque or have delicate structures that are easily damaged, there is a lack of analytical techniques capable of providing information about bubble characteristics in aerated foods. It is known that air bubbles modify the propagation of sound and cause high attenuation to sound waves and prevent their transmission. Tests between 300 kHz and 2.25 MHz confirmed the difficulty of transmitting ultrasound through cake batters as they were mixed over the normal range of low cost transducers due to bubbles (Fox, Smith, & Sahi, 2004). Fox et al. then designed a low cost ultrasound probe with 15 mm diameter transducer (2.25 MHz) to obtain measurements in reflection, which allowed monitoring the specific gravity of batter as indicator of quality and progress of the mixing process (Fox, Smith, & Sahi, 2004). Using pulse–echo technique, a theory was developed to relate ultrasonic reflectance spectra to changes in bubble size and concentration of aerated foods, which could be a useful on-line sensor for monitoring the properties of aerated food samples (Kulmyrzaev, Cancelliere, & McClements, 2000). In other work, ultrasonic spectroscopy was used to characterize a model aerated food system consisting of agar gel in which both bubbles and polystyrene beads are embedded (Strybulevych, Leroy, Scanlon, & Page, 2007). They found a good correlation between ultrasound and image analysis. Importantly, both experiment and theory demonstrated that the ultrasonic signatures of bubbles and solid inclusions can be distinguished, even when the inclusions are of comparable sizes. Leroy et al. (2008) used ultrasound velocity and attenuation measurements over a large range of frequencies to investigate the bubble size distribution in dough (Leroy, Fan, Strybulevych, Bellido, Page, & Scanlon, 2008). They reported that the shape and position of the velocity and attenuation

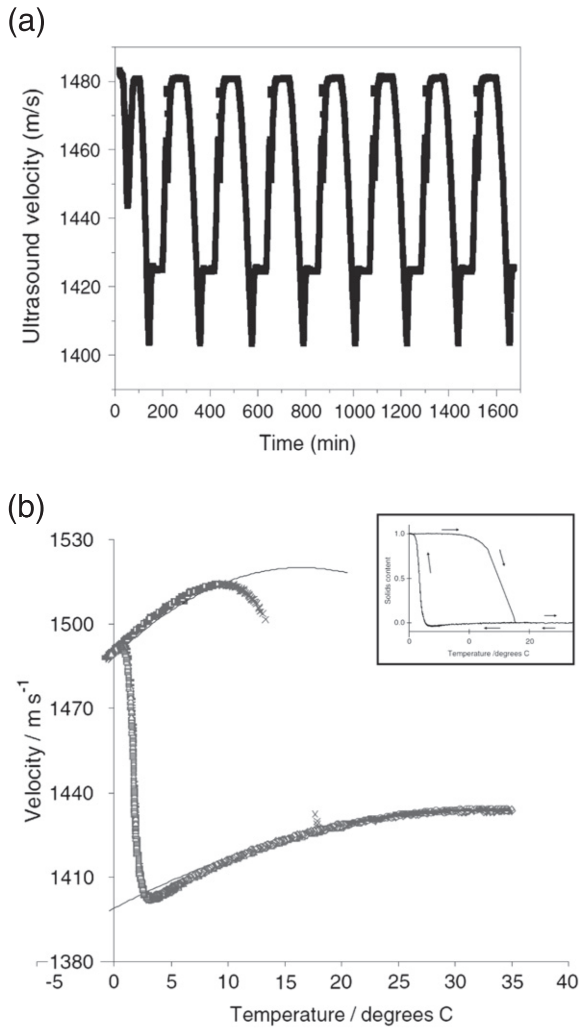

Fig. 3. (a) Assessment of the stability of oil-in-water emulsion droplets by ultrasound velocity during continuous heating/cooling cycles. The temperature was cycled at 2 °C/min between 0 and 40 °C for 270 h. The size distribution did not change during the experiment. (b) Sound velocity plotted against temperature for two heating/cooling cycles of the same emulsion. The polynomial fits for the temperature dependence of the velocity of sound in the liquid and crystallized state are shown as lines on the graph ($r^2 > 0.98$). The inset shows the crystalline solid content computed from the data and the arrows indicate the direction of temperature change.
Adapted from Povey et al. (2007).

peaks were affected by the bubble concentration in dough and the time after mixing.

2.3.6. Honey

Honey is a popular natural sweetener that has high nutritional value and medicinal effects (Miraglio, 2001). Honey is used as a functional food additive and as a preservative due to its activities as antioxidant and antimicrobial against food-borne microorganisms (Bogdanov, Jurendic, Sieber, & Gallmann, 2008). Recently, honey was found to promote lower weight gain, adiposity, and triglycerides compared to sucrose (Nemoseck et al., 2011). The functional values of honey are highly dependent on the concentrations of its components including carbohydrates, amino acids, minerals, aromatic substances, pigments, waxes and pollen grains. Honey can be adulterated by adding amounts of sucrose, commercial glucose, starch, chalk, gelatins, water and other substances. To ensure the quality and detect frauds, a variety of analytical techniques has been used to analyze honey composition such as sugar type by HPLC (Abdel-Aal, Ziena, & Youssef, 1993); differences in stable carbon isotope ratio between honey and its protein fraction by GC–MS system (Padovan, De Jong, Rodrigues, & Marchini, 2003) and adulteration by sugar syrups using NMR spectroscopy (Bertelli, Lolli, Papotti, Bortolotti, Serra, & Plessi, 2010). A list of the analytical methods that are used to prove the authenticity of honey has been reported (Anklam, 1998). LPU has also been used to determine the physical and mechanical properties of honey. Singh and Dwivedi reported changes in the physical properties of honey such as density, viscosity and homogeneity, which were accompanied by changes in ultrasound velocity due to adulteration (Singh & Dwivedi, 1995). For quality control, ultrasound velocity measurements can thus be an effective way to detect adulterated honey products or ensure the authenticity of natural honey products. Other workers also used LPU to compare different honeys by measuring the high frequency dynamic shear rheology, viscosity and moisture content (Cereser Camara & Laux, 2010; Kulmyrzaev & McClements, 2000).

2.3.7. Food gels

Tofu is a cholesterol free, rich source of proteins, minerals, and PUFA. It is an inexpensive, nutritious and versatile meat or cheese substitute with bland taste and porous texture (Rekha & Vijayalakshmi, 2011). It is usually considered as a salt- or acid-coagulated water-based gel, with soya lipids and proteins and other constituents trapped in its gel networks (Kohyama, Sano, & Doi, 1995). Ting, Kuo, Lien, and Sheng (2009) followed the progress of tofu ripening by measuring the ultrasonic velocity and attenuation at a 1 MHz frequency using a non-contact and non-destructive LPU. They found that the ultrasonic power attenuation follows first order kinetics as same as the firmness by textural analysis. The authors suggested the applicability of LPU as a real-time indicator of tofu maturity on the production line (Ting et al., 2009).

LPU has also been used to compare the gelation of several carrageenans in aqueous solutions by following ultrasonic velocity and attenuation. The decrease in ultrasonic velocity is assumed to correlate with the aggregation of carrageenan molecules in ordered conformation and the increase in attenuation may be related to the friction between gel network and water molecules. Therefore, ultrasound appears to be a suitable technique for the control of carrageenan and its molecular properties in quality control. In particular, it allows to sensitively differentiate the gelation behavior of different carrageenan systems (Wang, Rademacher, Sedlmeyer, & Kulozik, 2005).

2.3.8. Food proteins

LPU has been used for many years for estimating protein hydration, solubility, foaming capacity, flexibility, compressibility and volume (Gekko & Noguchi, 1979; Guzey, Kim, & McClements, 2004; Povey, Golding, Higgs, & Wang, 1999; Suzuki, Tamura, & Mihashi, 1996). The ultrasound velocity is related with the compressibility of protein, which enables to detect the state of protein (Heremans & Smeller, 1998). Ultrasonic attenuation measurements were also used to distinguish between soluble proteins and casein micelle in skimmed milk, which enabled to determine their size and concentration (Griffin & Griffin, 1990). Pavlovskaya, McClements and Povey (1992) studied the properties of aqueous solutions of a globular protein by measuring density, ultrasonic velocity and attenuation. They found the compressibility, density and attenuation of the solutions to be linearly dependent on protein concentration. Importantly, the attenuation measurements were sensitive to the isoelectric point and precipitation of protein. Bryant and McClements also used ultrasonic attenuation to detect whey protein aggregation near the isoelectric point (Bryant & McClements, 1999).

2.3.9. Ultrasonic monitoring of food freezing

Freezing is important for extending the shelf life and preserving the quality of many food products. Sigfusson et al. used ultrasound to measure the time of flight of an ultrasonic pulse moving parallel to the direction of heat flux in blocks of gelatin, chicken and beef during freezing (Sigfusson, Ziegler, & Coupland, 2004). They were able to calculate the percentage of the food frozen as a function of time, which gave reasonable prediction of the time for complete freezing. In other study, the ultrasonic velocity increased approximately linearly with the ice content in frozen sucrose solutions (Gülseren & Coupland, 2008). Aparicio et al. (2008) used ultrasound to determine the temperature of food and the ice content by measuring the speed of sound (Aparicio, Otero, Guignon, Molina-García, & Sanz, 2008). According to the authors, the method is quick and suitable for online monitoring of frozen, freezing and thawing systems, and can be adapted to a large variety of containers, geometrical situations and water contents.

3. High power ultrasound

The propagation of ultrasound through a biological material induces compressions and decompressions (rarefactions) of the medium particles, which imparts a high amount of energy. High power ultrasound with frequency higher than 20 kHz has mechanical, chemical and/or biochemical effects, which are used to modify the physicochemical properties and enhance the quality of various food systems during processing (Mason, Chemat, & Vinatoru, 2011). The mechanical effect has many applications such as extraction of flavors, degassing, destruction of foams, emulsification, enhancement of crystallization and modifying polymorphism (Higaki, Ueno, Koyano, & Sato, 2001). The chemical and biochemical effects are effective tools for sterilizing equipments, preventing contamination of food processing surfaces by pathogenic bacteria and removal of bacterial biofilms (Baumann, Martin, & Hao, 2009). High power ultrasound can be applied using sonication baths or ultrasonic immersion probes with different lengths, diameters and tip geometries depending on applications. High intensity focused ultrasound using lens-shaped transducers is another technique that is used in medicine to destroy diseased or damaged tissue through ablation.

3.1. Principles of high power ultrasound

In general, energy, intensity, pressure, velocity and temperature are the main parameters affecting power ultrasound. High power ultrasound can be described by the following pattern (Patist & Bates, 2008):

$$P_a = P_{amax} \cdot \sin(2\pi f t). \tag{4}$$

P_a is the acoustic pressure (a sinusoidal wave), which is dependent on time (t), frequency (f) and the maximum pressure amplitude of the wave (Muthukumaran, Kentish, Stevens, & Ashokkumar, 2006). $P_{a\ max}$ is related to the power input or intensity (I) of the transducer:

$$I = P_{amax}/2\rho v \tag{5}$$

where ρ is the density of the medium and v is the sound velocity in the medium.

With low intensities (or high frequencies), acoustic streaming is the main mechanism (Leighton, 1994; Leighton, 2007). Acoustic streaming is the motion and mixing within the fluid without formation of bubbles (Alzamora, Guerrero, Schenk, Raffellini, & López-Malo, 2011). Higher intensities (low frequencies) induce acoustic cavitation (Mason, 1998) due to the generation, growth and collapse of large bubbles, which causes the liberation of higher energies (Alzamora, Guerrero, Schenk, Raffellini, & López-Malo, 2011).

3.2. Application of power ultrasound in food processing

Cavitations can be classified into acoustic, hydrodynamic, optics and particle, based on the mode of generation (Gogate, Tayal, & Pandit, 2006). Only acoustic and hydrodynamic cavitations are able to generate intensities required to induce chemical and physical changes in different food systems (carbohydrates, protein, lipids, etc.). The different ways in which cavitation can be used beneficially in food processing application are the reduction of reaction time, the increase in the reaction yield, and using less forcing conditions (temperature and pressure) compared to the conventional routes. The reduction period of the desired reactions are reduced in addition to enhanced selectivity of the reaction pathways (McClements, 1995). According to Suslick, 1989 (Suslick, 1989); the chemical effects of ultrasound occur not from a direct interaction with molecular species, but from the acoustic cavitation phenomenon, the formation, growth and implosive collapse of cavities (gas bubbles) in liquids, that release high amounts of highly localized energy. The collapse of cavitation bubbles near solid surfaces forms asymmetrical microjets, which cleanse surfaces from contaminants. In addition, microjets generated near the interface between two immiscible liquids (e.g., oil and water) facilitate emulsification (Thompson & Doraiswamy, 1999). With cavitation, the water molecules can be broken to form free radicals, which intensifies chemical reactions, induces crosslinking of protein molecules in an aqueous medium (Cavalieri, Ashokkumar, Grieser, & Caruso, 2008) and enhances the rate of mass transport reactions due to the generation of local turbulence and liquid micro-circulation (acoustic streaming) (Gogate & Pandit, 2011; Gogate, Tayal, & Pandit, 2006). Hydroxide radicals (OH^-) and hydrogen atoms are generated from the dissociation of the water molecules in aqueous solutions as a result of the high temperature and pressure of the collapsing gas bubbles associated with cavitation (sonolysis) (Riesz & Kondo, 1992). There are also evidences that free radicals are formed by cavitation in non-aqueous solutions and polymers. However, the cavitation works better in aqueous media compared to organic media. Free radical formation by ultrasound may or may not be beneficial (Earnshaw, 1998). There are concerns regarding potential oxidative damage associated with free radicals, which is considered as a disadvantage for preserving phenols but it may enhance antioxidant efficiency for flavenoids (Ashokkumar, Sunartio, Kentish, Mawson, Simons, Vilkhu, Mawson, Simons, & Bates, 2008). In addition, oxidation caused by free radicals may be beneficial to some types of chocolate, but detrimental to others. It may assist flavor development in plain chocolates, but may give rise to an unpleasant taste in milk ones. In applications where free radicals have deleterious effects, the use of high frequencies is preferred as the number of bubbles as well as free radicals will be reduced (Beckett, 1999). Another way is to add radical quenchers such as ethanol or ascorbic acid. It is thus important to realize that HPU is not a standard technology and that the relationship between the duration, intensity and frequency of ultrasonic waves and their effects on the technological and functional properties of food must be strongly considered for every application (Soria & Villamiel, 2010).

The following subsections will describe some of the applications of high power ultrasound in food science and technology. A summary of the various applications including the mechanisms, parameters and effects of ultrasound are shown in Tables 4–6.

3.2.1. Sonocrystallization

Crystallization is a considerably important process in many food industries such as chocolate, butter, margarine, whipped cream and ice cream. To obtain food products with specific sensory attributes (e.g., texture, hardness, smoothness, mouthfeel), fat crystallization must be controlled by temperature, cooling rate and application of shear or ultrasound. Power ultrasound in the range of 20 kHz and up to the MHz range has contributed as an effective tool for influencing the crystallization of liquids and melts (i.e., sonocrystallization), which is used in fat fractionation such as separating stearin (high melting) and olein (low melting) from a triglyceride oil. Ueno et al. investigated the effect of power ultrasound (at 20 kHz and 100 W for 2 s) on the crystallization behavior of model triglycerides (tripalmitin and trilaurin). Ultrasonication decreased the crystallization induction times of both triglycerides, increased nucleation rate due to

Table 4
Applications and characteristics of high power ultrasound in some food processes.[a]

Application	Effect/mechanism	Parameters	Advantages
Sonocrystallization			
• Crystallization kinetics of model triglycerides (tripalmitin and trilaurin).	Cavitation induces formation of nucleation active sites and create smaller crystals with modified properties.	20 kHz and 100 W for 2 s	• HPU decreased crystallization induction times, increased nucleation rate, and modified polymorphic crystallization, microstructure, texture and melting behavior.
• Functional properties of Anhydrous milk, palm kernel oil, shortening		20 kHz for 10s	• Tunable by varying sonication time, power, duration of the acoustic pulse and crystallization temperature
Emulsification			
• Edible nanoemulsions	Collapse of cavitation forms high energy microjets near interfaces	Irradiation time and power, oil viscosity and interfacial tension	• Facilitate the formation of small (40 nm) nanoemulsions • Decreased amount of surfactants • More stable droplets • High loading
De-foaming			
• To prevent decay and oxidation, enhance freshness, and quality, and extend shelf life. maximize production and avoid problems in process control and equipment operation	Dissolved gas/oxygen move towards cavitation bubbles, which grow in size by coalescence then rise releasing the entrapped gas to the environment	20 kHz in pulsed operation (1 s/1 s)	• Effective procedure to remove foam and dissolved oxygen (80% of foam reduction) with very low energy consumption 40 kJ/l) in super-saturated milk. • Control of excess foam produced during the filling operation of bottles and cans on high-speed canning lines and in fermenting vessels and other reactors of great dimensions
Food proteins			
• Whey protein	Cavitation	Power (20, 40, 500 kHz) and time	• Increased protein solubility and foaming ability
• Whey protein isolate • Whey protein concentrate	Cavitation	20 kHz, 15 min	• Increased solubility • Significant increase in apparent viscosity
• Soy protein isolates (SPI) • Soy protein concentrate (SPC)	Cavitational forces of ultrasound treatment with probe, and microstreaming and turbulent forces after treatment with baths	20 kHz probe and ultrasound bath (40 and 500 kHz)	• Significant changes in conductivity and rheological properties, increased solubility for SPC and increased specific surface area • Less energy and shorter time compared to traditional and current technology

[a] The literature references for each application are listed in the corresponding sections/subsections.

high-pressure pulses associated with collapsing cavitation bubbles, and modified their polymorphic crystallization (Ueno, Ristic, Higaki, & Sato, 2003). Suzuki, Lee, Padilla and Martini (2010) also used a sonicator operating at an acoustic frequency of 20 kHz for 10 s using 50 W of electrical power to investigate the effect of power ultrasound on the functional properties of anhydrous milk, palm kernel oil, and shortening. They found that power US modified the microstructure, texture, and melting behavior. Power US induced primary and secondary nucleation,

Table 5
Applications and characteristics of high power ultrasound in food enzymes, microbial inactivation and extraction of food bioactives.[a]

Application	Effect/mechanism	Parameters	Advantages
Food enzymes			
• Pectic enzyme, • Soybean lipoxygenase, • Horseradish peroxidase • Orange PME	Cavitation	Ultrasound intensity, combined low pressure and heat	• Increased the inactivation rate
• Intensifying glucose production from grain sorghum	Cavitation	sonication time and intensity (1 min at 100% amplitude)	• Liquefact DE increased by 10–25% • Decreased the average particle size of the slurry from 302 to 115 μm • Increased saccharification by about 8%.
•Enzymatic hydrolysis of rice straw	Cavitation	20 and 24 kHz for 80 min	• Enhanced the saccharification process • Accelerated enzymatic hydrolysis • Cost-effective and lower amount of toxic wastes • Safe, environmentally friendly and less energy intensive
• Glucose oxidase (GOX)	High-intensity acoustic energy	23 kHz at 4 °C for different periods of time (10–60 min)	• Reduced glucose content of the juice • Reduced-alcohol white wine from grape juice • No adverse effect on enzymatic activity
Microbial inactivation			
• Food pasteurization • Microbial inactivation	Physical, mechanical and chemical effects of acoustic cavitation	frequency, wave amplitude and volume of bacterial suspension	• Minimizing of flavor loss in sweet juices • Greater homogeneity • Significant energy savings • Deagglomerate bacterial clusters/inactivate bacteria
		Combined with pressure, and/or heat and antimicrobials	• Killing or removing *Salmonella* and *E. coli* • Enhances the mechanical removal of attached or entrapped bacteria on the surfaces of fresh produce
Ultrasound assisted extraction			
• Herbal oil, protein, polysaccharides, bioactive ingredients	Cavitation generates high shear forces and microbubbles that enhances surface erosion, fragmentation and mass transfer	Time Frequency Temperature	• High yield of extracted materials and fast rate of extraction • Minimum effect on extractable materials • Works in GRAS solvents • Enhance the extraction of heat sensitive bioactive and food components at lower processing temperatures

[a] The literature references for each application are listed in the corresponding sections/subsections.

Table 6
Applications and characteristics of high power ultrasound in frozen and dried food products.[a]

Application	Effect/mechanism	Parameters	Advantages
Food freezing			
•Oil-in-water emulsions •Frozen food plants (potatoes and apples)	Acoustic cavitation promotes ice nucleation by micro-bubbles but also enhances the heat and mass transfer	Output power Time	• Chemically non-invasive • Operates in a non contact mode • Accelerates freezing rate • Improves quality • Less extracellular voids and cell disruption/breakage
• Molded frozen products (e.g., sorbets and ice lollipops)			• Smaller ice crystals and uniform crystal size distributions • Improves the adhesion to the supporting wooden stick
Ice cream manufacture	Acoustic cavitation	Pulse time	• Induces crystal fragmentation • Prevents incrustation on the cold surface • Decreases freezing time • Improves sensory flavor, texture and mouth feel
Freeze concentration			
• Fruit juices, milk, beer, wine, coffee, and tea	Cavitation at low supercooling induces less nucleation sites and enhances the crystal growth of water into large crystals water	Supercooling degree of the system Duration	• Large ice crystals facilitates concentration of freeze concentrate • Complete preservation of aroma, flavor, color • Energy and cost saving
Freeze drying			
• Fresh food products (e.g., potatoes)	Cavitation at high supercooling increases nucleation active sites	Output power Time	• Formation of small crystals • Cells integrity is preserved
Thawing of frozen foods			
• Frozen beef, pork and cod	Acoustic energy	frequency and intensity	• Thawing time is reduced • Quality is preserved
Food drying process			
•Vegetables •Fruits	Cavitation compressions and expansions induced by sound waves	Air velocity Temperature Acoustic energy	• Reduction in the treatment time and a final moisture content • Product qualities were well preserved after rehydration, and the energy consumption was low

[a] The literature references for each application are listed in the corresponding sections/subsections.

which yielded small crystals and increased hardness. This effect could also be tuned by controlling sonication time, power, duration of the acoustic pulse and crystallization temperature.

The physical mechanism of sonocrystallization has been recently investigated by comparing to a mechanically agitated crystallization system (Nalajala & Moholkar, 2011). Results indicated that the nature of convection in the medium is a crucial factor affecting nucleation rate and growth rate of crystals. The authors stated that the convection in a sonicated system has two components, microturbulence (or micro-convection) and shock waves, which are generated by cavitation bubbles, and have different impact on nucleation and crystal growth. This was evident from the result that nucleation rate shows an order of magnitude rise with sonication, while the growth rate (and hence the dominant crystal size) reduces with sonication as compared to the mechanically agitated system. Sonocrystallization is an important technology for the large scale production of many food applications. It is also cost-effective and easy to operate, modify or control.

3.2.2. Emulsification

Emulsification is the process of mixing two immiscible phases(e.g., oil and water) with the aid of a surface active agent (emulsifier) into homogeneous dispersion or emulsion. Unless the mixing is spontaneous such as with the formation of microemulsions, the process requires an energy input by means of mechanical agitation or ultrasonication to facilitate the formation of small droplets. With ultrasonication, the collapse of cavitation releases forms high energy microjets near interfaces and facilitate emulsification (Thompson & Doraiswamy, 1999). Compared to mechanical agitation, the use of ultrasound required less amounts of surfactants and produced smaller and more stable droplets (Abismail, Canselier, Wilhelm, Delmas, & Gourdon, 1999; Behrend, Ax, & Schubert, 2000; Canselier, Delmas, Wilhelm, & Abismail, 2002; Juang & Lin, 2004). A study showed that increasing irradiation time and/or ultrasonic irradiation power increases the dispersed phase volume and decreases droplets size, and these effects were strongly dependant on viscosity of the oil and interfacial tension (Gaikwad & Pandit, 2008). In other study, oil-in-water emulsions prepared using HPU showed a low degree of droplet flocculation, which increased the creaming stability of emulsion (Pongsawatmanit, Harnsilawat, & McClements, 2006). Recently, ultrasound has been used to prepare transparent edible nanoemulsions with very small droplets (40 nm) using the right proportions of emulsion components and ultrasound power (Leong, Wooster, Kentish, & Ashokkumar, 2009). Ultrasound emulsification systems are cost saving, easy to use and integrate to existing industrial lines to improve the quality of emulsified products such as milk homogenization before cheese-making to improve the yield of cheese (Soria & Villamiel, 2010), and thermosonication to simultaneously pasteurize milk and disintegrate large milk fat globule (Bermudez-Aguirre, Mawson, & Barbosa-Canovas, 2008).

3.2.3. Defoaming

Foams are thermodynamically unstable colloidal systems in which gas is stabilized as a separate phase dispersed in a liquid matrix (Villamiel, Verdurmen, & Jong, 2000). De-foaming is the process of removing bubbles and air from liquids. In the food industry, it is important to remove air and oxygen from milk and drinks to prevent decay and oxidation, which enhance freshness, and quality, and extend shelf life. It is also important to avoid foams to maximize production and avoid problems in process control and equipment operation. High-intensity ultrasound (20 kHz) in pulsed operation (1 s/1 s) has been described as an effective procedure to remove foam and dissolved oxygen (80% of foam reduction) with very low energy consumption (40 kJ/l) in super-saturated milk (Villamiel et al., 2000). Recently, a stepped-plate air-borne ultrasound defoamer was developed and commercially applied to control the excess foam produced during the filling operation of bottles and cans on high-speed canning lines and in fermenting vessels and other reactors of great dimensions (Gallego-Juárez et al., 2010; Juárez, Corral, Vitini, Aparicio, De Sarabia, & Blanco, 2010; Rodríguez et al., 2010).

3.2.4. Food proteins

Whey proteins are widely used as ingredients in many food products for several functional properties including emulsification, gelatin, thickening, foaming, and fat and flavor binding capacity (Bryant & McClements, 1999; Mason, 1998). The application of HPU (using 20 kHz probe) influenced the functional properties of whey protein such as solubility and foaming ability, while a higher frequency (40 kHz) ultrasound had less effect. Ultrasound treatment with 500 kHz bath did not have effect on foaming properties of whey protein model solutions (Jambrak, Mason, Lelas, Herceg, & Herceg, 2008). The flowing behavior and thermophysical properties of whey protein isolate (WPI) and whey protein concentrate (WPC) under the influence of high pressure (HP, 500 MPa, 10 min), ultrasound (US: 20 kHz, 15 min) and tribomechanical activation (TA: 40,000 rpm) were studied (Kresic, Lelas, Jambrak, Herceg, & Brncic, 2008). Results revealed considerable variation in the rheological and thermophysical properties of commercial WPC, and WPI due to the compositional difference in protein and non-protein components which acted differently upon high pressure, ultrasound and tribomechanical treatments. Pressurization exhibited lower solubility of WPC and WPI compared to control, while increased solubility as a result of ultrasound treatments and tribomechanical activation occurred.

Soy proteins are also important ingredients due to their functional properties in the food products and many health benefits. Jambrak, Lelas, Mason, Kresic and Badanjak (2009) treated soy protein isolates (SPI) and soy protein concentrate (SPC) with ultrasound 20 kHz probe and ultrasound baths (40 and 500 kHz) system. Treatment with 20 kHz probe ultrasound lead to significant changes in conductivity, increased solubility for SPC, significantly increased specific surface area that is of interest in food texture and increased values of emulsion activity index. The authors commented about the feasibility of using ultrasound treatment for producing soy products and creams with less energy and shorter time compared to traditional and current technology.

3.2.5. Food enzymes

Enzyme inactivation is an important process for enhancing the stability, shelf life and quality of many food products. Power ultrasound is used to increase or inactivate enzymatic activities depending on ultrasound intensity. Ultrasound combined with low pressure and heat (manothermosonication or MCT) increased the inactivation rate of tomato pectic enzyme (Lopez, Vercet, Sanchez, & Burgos, 1998; Vercet, Sánchez, Burgos, Montañés, & Lopez Buesa, 2002), soybean lipoxygenase (Lopez & Burgos, 1995a), horseradish peroxidase (Lopez & Burgos, 1995b) and orange PME (Vercet, Lopez, & Burgos, 1999). Ultrasound frequency–power density combination were determined to be the scale-up parameters of MCT yielding maximum efficiency with the deactivation dynamics is the same whether the treatment is performed in batch or in continuous mode (De Gennaro, Cavella, Romano, & Masi, 1999).

Another application of power ultrasound is for intensifying glucose production from grain sorghum, an important drought-resistant cereal crop used in food (Shewale & Pandit, 2009). Liquefaction (using *Bacillus licheniformis* α-amylase) and saccharification (using amyloglucosidase) processes were optimized with the use of normal sorghum flour as a starting material for the production of glucose. Due to ultrasound treatment, the liquefact DE increased by 10–25% depending upon sonication time and intensity. Ultrasound treatment of 1 min at 100% amplitude was found to decrease the average particle size of the slurry from 302 μm to 115 μm, which resulted in an increased percentage of saccharification by about 8%. Recent work has also reported an acceleration of enzymatic hydrolysis of rice straw after ultrasonic pretreatment (Wongsorn, Kangsadan, Kongruang, Burapatana, & Pripanapong, 2010).

Glucose oxidase (GOX) is a catalase enzyme used in the production of reduced-alcohol white wine from grape juice by reducing glucose content of the juice (Pickering, Heatherbell, & Barnes, 1998). Liquid-phase reactions based on ultrasonication is one of the most popular and prioritized pathways for non-covalent approaches to achieve biological functionalization of nanomaterials (Mason & Lorimer, 2002). To examine whether the use of power ultrasound would affect the stability and function of biomacromolecules, Guiseppi-Elie et al. (2009) studied the effect of ultrasonication (23 kHz at 4 °C) for different periods of time (10, 30 and 60 min) on the enzymatic stability, conformational and catalytic activity of the enzyme GOX (Guiseppi-Elie, Choi, & Geckeler, 2009). Their results indicated that ultrasonication does not appear to adversely affect the enzymatic activity of GOX, which may have great potential in food and beverages for non-destructive processing of other biological enzymes.

3.2.6. Ultrasound and microbial inactivation

Thermal pasteurization and sterilization are two common techniques that are used for the inactivation of microorganisms in food products. Nevertheless, the effectiveness of these methods requires long time exposure to high treatment temperatures, which leads to deterioration of functional properties, sensory characteristics (e.g., off flavor) and nutritional value of food products (Lado & Yousef, 2002; Piyasena, Mohareb, & McKellar, 2003). Less energy-intensive preservation methods including high-pressure processing, ionizing radiation, pulsed electric field, microfiltration, ultraviolet radiation and HPU are cost-efficient and environmentally friendly. In combination with heat, these methods can accelerate the rate of food sterilization, thereby lessening the duration and intensity of thermal treatment and the resultant damage (Piyasena et al., 2003). In particular, the use of HPU has shown several advantages compared to heat pasteurization such as minimization of flavor loss in sweet juices, greater homogeneity and significant energy savings (Crosby, 1982). Many researches have been done to understand the mechanism played by ultrasound on the disruption of microorganisms (Alliger, 1975; Baumann, Martin & Feng, 2005; Bermudez-Aguirre, Corradini, Mawson, & Barbosa-Canovas, 2009; Earnshaw, Appleyard, & Hurst, 1995; Garcia, Burgos, Sanz, & Ordonez, 1989; Guerrero, López-Malo, & Alzamora, 2001; Guerrero, Tognon, & Alzamora, 2005; Hughes & Nyborg, 1962; Lo'pez-Malo, Guerrero & Alzamora, 1999; Raso, Palop, Pagan, & Condon, 1998; Wrigley & Llorca, 1992), which has been explained by acoustic cavitation and its physical, mechanical and chemical effects that inactivate bacteria and deagglomerate bacterial clusters or flocs (Joyce, Phull, Lorimer, & Mason, 2003). It has also been shown that the mortality rate is highly dependent on ultrasound frequency, wave amplitude and volume of bacterial suspension (Raso, Palop, Pagan, & Condon, 1998). While a frequency of about 20 kHz is usually applied for microbial inactivation, the resistance to ultrasound treatment of spores, and Gram-positive and coccal cells are higher than vegetative, Gram-negative and rod-shaped bacteria (Feng, Yang, & Hielscher, 2008). In addition, it also varies among different strains. For example, *Escherichia coli* and *Saccharmyces cerevisiae* were reduced by more than 99% after ultrasonication, whereas *Lactobacillus acidphilus* was reduced by 72% and 84% depending on the media used (Cameron, McMaster, & Britz, 2008).

To improve the microbial inactivation in liquid foods, ultrasound is combined with other treatments such as pressure (manosonic), heat (thermosonic), both pressure and heat (manothermosonic) and antimicrobials (Earnshaw, Appleyard, & Hurst, 1995; Lee, Heinz, & Knorr, 2003; López-Malo, Guerrero, & Alzamora, 1999; Piyasena et al., 2003; Raso & Barbosa-Canovas, 2003; Raso, Palop, Pagan, & Condon, 1998; Villamiel & de Jong, 2000). Compared to HPU alone, these treatments are more energy-efficient and effective in killing microorganisms. Raso and co-workers studied the influence of temperature and pressure on the lethality of ultrasound on the pathogenic bacteria *Yersinia enterocolitica* (Raso, Pagan, Condon, & Sala, 1998). Although ultrasound had a low lethal effect in ambient temperature and pressure, the lethality levels greatly increased with increasing static pressure and/or temperature. An improved inactivation of *E. coli* was observed when HPU was combined with heat (Knorr, Zenker, Heinz, & Lee, 2004). Similarly, a synergistic lethal effect was also observed between heat and ultrasound under pressure on the inactivation of *Salmonella senftenberg* 775 W (Alvarez, Manas, Virto, & Condon, 2006). Other workers have shown that combining ultrasound (38.5–40.5 kHz) with chemical antimicrobials enhanced the killing or removal of *Salmonella* and *E. coli* O 157:H7 on alfalfa seed (Scouten & Beuchat, 2002), and reduced a number of bacteria in water samples (Phull, Newman, Lorimer, Pollet, & Mason, 1997).

Seymour et al. described the potential of using HPU for fresh produce decontamination, which is due to the mechanical effect generated by cavitation bubbles. They stated that cavitation enhances the mechanical removal of attached or entrapped bacteria on the surfaces of fresh produce by displacing or loosening particles through a shearing or scrubbing action, achieving an additional log reduction when applying to a chlorinated water wash (Seymour, Burfoot, Smith, Cox, & Lockwood, 2002).

3.2.7. Food freezing

Freezing is an important preservation technique that is used in the food industry to maximize the shelf life and preserve the quality of food products. Upon freezing, water transforms into ice crystals, which preserve the food structure (Delgado, Zheng, & Sun, 2009). Ice crystallization involves two stages; nucleation followed by the growth of nuclei into crystals whose size and number will depend on the rate of freezing (Martino, Otero, Sanz, & Zaritzky, 1998). While rapid freezing rates generate small ice crystals, slow freezing rates induce the formation of large ice crystals, which damage the physical structure (i.e., texture) and deteriorate the food quality. Therefore, proper methods of freezing are required to control the ice crystal size in frozen foods. Common methods for food freezing include air blast, plate contact, circulating brine and liquid nitrogen, high pressure assisted freezing and ultrasound-assisted freezing (Heldman, 1992; Knorr, Zenker, Heinz, & Lee, 2004; Li & Sun, 2002b; Sanz et al., 1999). HPU has gained considerable interest in food processing and preservation due to its ability to control/modify nucleation and crystal growth (Acton & Morris, 1992, 1993; Mason, Paniwnyk, & Lorimer, 1996). In addition, HPU is chemically non-invasive, operates in a non-contact mode and does not present legislative difficulties (Acton & Morris, 1992; Delgado, Zheng, & Sun, 2009). Acton and Morris applied power ultrasound to control freeze drying, freezing of oil-in-water emulsions and tempering of chocolate (Acton & Morris, 1992). Several studies have indicated the potential of using HPU in accelerating the freezing rate and improving the quality of frozen food plants such as potatoes (Li & Sun, 2002a; Sun & Li, 2003) and apples (Delgado, Zheng, & Sun, 2009). HPU treated frozen potatoes exhibited a better cellular structure as less extracellular void and cell disruption/breakage appeared than those without acoustic treatment (Sun & Li, 2003). The most important effect of power ultrasound in food freezing is due to the acoustic cavitation, which not only promotes ice nucleation by micro-bubbles but also enhances the heat and mass transfer due to the violent agitation created by the acoustic microstreaming (Zheng & Sun, 2006).

Power ultrasound was also applied during the production of molded frozen products such as sorbets and ice lollipops to provide product with much smaller ice crystals and uniform crystal size distributions, which also improved the adhesion of the lollipop to the supporting wooden stick (Price, 1992).

3.2.8. Ice cream manufacture

Freezing is also the most important step during the manufacture of ice cream. Ice crystallization in ice cream determines its final quality (Petzold & Aguilera, 2009). A narrow ice crystal size distribution is necessary for production of high quality ice-cream with smooth texture and desired sensory characteristics (Russell, Cheney, & Wantling, 1999). HPU treatment of ice cream inside the scraped surface freezer induces crystal fragmentation by cavitation bubbles, and also prevents incrustation on the cold surface due to the high heat transfer rate (Mason, 1998; Zheng & Sun, 2006). Mortazavi and Tabatabaie have shown that increasing the ultrasound pulse time significantly decreased the freezing process time of ice cream, and improved sensory flavor, texture and mouth feel (Mortazavi & Tabatabaie, 2008).

3.2.9. Freeze concentration and freeze drying

Freeze concentration of aqueous foods such as fruit juices, milk, beer, wine, coffee, and tea, is a major unit operation in the food industry (Deshpande, Cheryan, Sathe, Salunkhe, & Luh, 1984). This processing technology offers many advantages including complete preservation of the aroma (including the volatile aroma that characterizes freshly squeezed juice), color, and flavor in the concentrated juice (Dette & Jansen, 2010). In addition, the nutritional and sensory quality of freeze-concentrated fruit juices is higher than those concentrated conventionally by means of evaporation due to the low processing temperatures (Deshpande, Cheryan, Sathe, Salunkhe, & Luh, 1984). Freeze concentration involves fractional crystallization of water into pure crystals that can be easily separated from the concentrated fluid (Fellows, 2000). To enhance the separation efficiency of the freeze concentrate, the water is crystallized into large ice crystals (Schwartzberg, 1990). The size of the ice crystals will be determined by the nucleation and crystal growth events, whose rates are controlled by the degree of supercooling. HPU can be used to induce the formation of a few nucleation active sites at low supercooling. Therefore, crystal growth will dominate nucleation, and leads to formation of large crystals, which enhances the freeze concentration process (Zheng & Sun, 2006). Botsaris and Qian used ultrasonic radiation for the nucleation of ice crystals at low supercooling. This permitted the use of an inexpensive plain heat exchanger for minimizing ice scaling in the heat exchanger, and higher coolant temperatures lead to savings of capital refrigeration costs (Botsaris & Qian, 1999).

Freeze-drying, or lyophilization, is the sublimation/removal of water content from frozen food. The dehydration occurs under a vacuum, with the plant/animal product solidly frozen during the process. Shrinkage is eliminated or minimized, and a near-perfect preservation results. Freeze-dried food lasts longer than other preserved food and is very light, which makes it perfect for space travel. HPU increases the freezing rate and improved the quality of fresh food products such as potatoes by enhancing the heat and mass transfer process (Li & Sun, 2002a; Li & Sun, 2002b; Sun & Li, 2003). Ultrasonically assisted immersion freezing under an optimum ultrasonic power of 15.85 W maintained the integrity of the cells of frozen potato tissue and improved the structure (Sun & Li, 2003). Acton and Morris applied HPU irradiation on sucrose solution at high supercooling to increase the number of nucleation active sites, which resulted in the formation of small crystals (Acton & Morris, 1992). Acoustic cavitation improves the heat transfer, reduces crystal size, minimizes cell dehydration and maintains product original shape (Powrie, 1973).

3.2.10. Thawing of frozen foods

Thawing of frozen foods is a slower process, which may cause food damage due to chemical and physical changes, and microbial decay (Li & Sun, 2002b). A rapid thawing at low temperature and excessive dehydration of food are recommended to assure food quality (Fennema, Powrie, & Marth, 1973; Kalichevsky, Knorr, & Lillford, 1995). Li and Sun have reviewed food thawing by various methods including high-pressure, microwave, ohmic and acoustic thawing (Li & Sun, 2002b). The use of acoustic energy for thawing frozen food reported 50 years ago had many negative aspects such as poor penetration, localized heating and high power requirement hindered its application (Brody & Antenevich, 1959; Li & Sun, 2002b). More recent studies have been carried out to investigate the effectiveness of HPU for thawing frozen foods by varying ultrasound parameters such as frequency and power (Kissam, 1985; Kissam, Nelson, Ngao & Hunter, 1982; Kolbe, 2003; Miles, Morley & Rendell, 1999). Miles et al. reported that overheating occurred near the surface of frozen foods at high intensities as well as at high and low frequencies, which is due to the increase in attenuation with frequency, and the onset of cavitation at low frequencies (Miles et al., 1999). They were able to overcome this problem by adjusting frequency (500 kHz) and intensity (0.5 $W \cdot cm^{-2}$) for frozen beef, pork and cod, which were thawed to a depth of 7.6 cm within about 2.5 h (Miles et al., 1999). In other work, a block of frozen Pacific cod was exposed to 1500 Hz acoustic energy and up to 60 W continuous input to the transducer (Kissam et al., 1982). The block thawed in 71% less time than water-only controls, and the acoustic waves did not alter the quality of the flesh.

3.2.11. Food drying process

Drying or dehydration, the oldest method of food preservation, is based on the use of thermal energy such as sun, hot air, smoking, drum and convection drying (Cohen & Yang, 1995). However, heat can deteriorate the quality of the final product causing undesirable food flavor, color, vitamin degradation and loss of essential amino acids (Min, Chunli, & Xiaolin, 2005; Mousa & Farid, 2002; Zhang, Tang, Mujumdar, & Wang, 2006). Ultrasonic dehydration is a very promising technique since it can be utilized at low temperature, which prevents the degradation of food at high temperatures. Power ultrasound also improves heat and mass transfer phenomena in drying processes (Cárcel, Garcia-Perez, Riera, & Mulet, 2011). Acoustic dehydration relies on cavitation (Tarleton & Wakeman, 1998) and also on the effects of compressions and expansions induced by sound waves passing through the food medium, which generates high forces and maintains the moisture inside the capillaries of the material thus making the moisture removal easier (De la Fuente-Blanco, Riera-Franco de Sarabia, Acosta-Aparicio, Blanco-Blanco, & Gallego-Juárez, 2006). The application HPU for the dehydration of vegetables using forced-air drying assisted by air-borne ultrasound and ultrasonic dehydration have been carefully studied by the Power Ultrasonic Group of the Institute of Acoustics in Spain (De la Fuente-Blanco et al., 2006; Gallego-Juįarez, Riera, de la Fuente Blanco, Rodrıguez-Corral, Acosta-Aparicio, & Blanco, 2007). They designed a multi-sample ultrasonic dehydration prototype system with a high-power rectangular plate transducer (20 kHz, 100 W) and a series of sensors to study mechanical and thermal effects on vegetable samples, and to evaluate the feasibility at the industrial level. According to the authors, it represents a basic tool for testing dehydration treatments of different products as a previous stage to industrial scale. In addition, it will facilitate the advancement in the study of the mechanisms involved in the ultrasonic dehydration process (Gallego-Juįarez et al., 2007).

Gallego-Juárez and co-workers have utilized an air-borne power ultrasound generator and a procedure in which ultrasonic vibrations are applied in direct contact with the product to be dried and under a certain static pressure (Gallego-Juárez et al., 2007). They designed a prototype based on a high power rectangular plate transducer, working at a frequency of 20 kHz with a power capacity of about 100 W, and measured the water content of carrot samples after different times of application of high-intensity ultrasonic fields in combination with forced air at various temperatures and flow velocities. Results showed a direct increase of the drying effect with the acoustic intensity when the other thermomechanical parameters (temperature, flow rate, suction …, etc.) are kept constant. This offered a reduction in the treatment time and a final moisture content of less than 1%. In addition, the product qualities were well preserved after rehydration, and the energy consumption was low (Gallego-Juárez, Rodriguez-Corral, Moraleda, & Yang, 1999; Gallego-Juárez et al., 2007).

The effect of ultrasonic pre-treatment prior to air-drying on dehydration of bananas (Fernandes & Rodrigues, 2007), melons (Fernandes, Gallão, & Rodrigues, 2008), pineapple (Fernandes, Linhares, & Rodrigues, 2008), papaya (Fernandes, Oliveira, & Rodrigues, 2008), sapotas (Falade & Igbeka, 2007), Malay apple (Oliveira, Gallão, Rodrigues, & Fernandes, 2011) and carrot (Cárcel, Garcia-Perez, Riera, & Mulet, 2011) has been investigated. In general, the effective diffusivity of water in the fruit increased after the application of ultrasound, which reduced air-drying time (Fernandes & Rodrigues, 2008). In other work, osmotic dehydration combined with ultrasonic energy reduced total processing time and increased effective water diffusivity in strawberries compared to osmotic dehydration, which alone increased processing time (Garcia-Noguera, Oliveira, Gallão, Weller, Rodrigues, & Fernandes, 2010). Combined effects of microchannel formation by HPU treatment and osmotic pressure differential were largely responsible for reducing drying time.

In addition, HPU enhanced water loss and shortened drying time of mushrooms, Brussels sprouts and cauliflower (Jambrak, Mason, Paniwnyk, & Lelas, 2007). Importantly, the rehydration properties (weight gain, %) were found to be the best for freeze-dried samples which showed weight gains for mushrooms (45.3%), Brussels sprouts (21.4%) and cauliflower (51%). This indicated the great advantages of using HPU in the food industry for freeze drying of plant food (Jambrak, Mason, Paniwnyk, & Lelas, 2007).

3.2.12. Ultrasound assisted extraction

A major application of HPU is for facilitating the extraction process of a variety of food components (e.g., herbal, oil, protein, polysaccharides) as well as bioactive ingredients (e.g. antioxidants) from plant and animal resources (Vilkhu et al., 2008). The action of HPU is due to cavitation, which generates high shear forces and microbubbles that enhances surface erosion, fragmentation and mass transfer resulting in high yield of extracted materials and fast rate of extraction. As reported by Vilkhu et al. in their extensive review, the major advantages of ultrasound are minimum effect on extractable materials, avoidance of organic solvents as its action also works in GRAS solvents, reduction in extraction time, which can potentially enhance the extraction of heat sensitive bioactive and food components at lower processing temperatures and potentially in large industrial scales (Vilkhu et al., 2008).

4. Concluding remarks

Ultrasound is an emerging technology in food science and technology. The tunable frequency of ultrasound diversified its applications in the areas of food analysis, processing and quality control. The application of low power (high frequency) ultrasound provides a non-invasive, cheap and simple techniques that can be used for estimating the food composition (fish, eggs, dairy, etc.), monitoring physicochemical and structural properties (emulsions, dairy products and juices) and detecting contamination by metals and other foreign materials (canned food, dairy foods, etc.). Monitoring the composition and physicochemical properties of food during processing and storage is important for the production of food products with high performance, quality and stability. The simplicity, portability and low cost of ultrasound devices make them essential elements in research laboratories, pilot plants and large food factories. High power (low frequency) ultrasound, on the other hand, modifies the food properties by inducing mechanical, physical and chemical/ biochemical changes through cavitation, which reduces reaction time and increases reaction yield under mild conditions compared to conventional route. By maximizing production while saving energy, power ultrasound is considered a green technology with many promising applications in food processing, preservation and safety. In addition, probes that generate high power ultrasound are cheap, portable and modifiable to suit different purposes in the food industry. Over the decades, researchers were able to optimize many ultrasound applications either for the testing or processing of food products. Efforts are continued to integrate fully automated ultrasound systems to the food production lines, which will help reduce cost, save energy and ensure the production of high value and safe food products.

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