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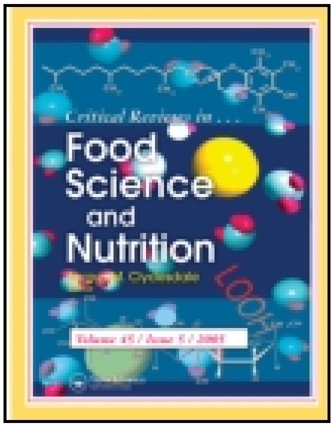

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Opportunities and Challenges in Application of Ultrasound in Food Processing

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Opportunities and Challenges in Application of Ultrasound in Food Processing

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The demand for convenience foods of the highest quality in terms of natural flavor and taste, and which are free from additives and preservatives, has spurred the need for the development of a number of non-thermal approaches to food processing, of which ultrasound technology has proven to be very valuable. Increasing number of recent publications have demonstrated the potential of this technology in food processing. A combination of ultrasound with pressure and/or heat is a promising alternative for the rapid inactivation of microorganisms and enzymes. Therefore, novel techniques like thermosonication, manosonication, and manothermosonication may be a more relevant energy-efficient processing alternative for the food industry in times to come. This review aims at identifying the opportunities and challenges associated with this technology. In addition to discussing the effects of ultrasound on foods, this review covers various areas that have been identified as having great potential for future development. It has been realized that ultrasound has much to offer to the food industry such as inactivation of microorganisms and enzymes, crystallization, drying, degassing, extraction, filtration, homogenization, meat tenderization, oxidation, sterilization, etc., including efficiency enhancement of various operations and online detection of contaminants in foods. Selected practical examples in the food industry have been presented and discussed. A brief account of the challenges in adopting this technology for industrial development has also been included.

Keywords ultrasound, food processing, non-thermal processing

INTRODUCTION

One of the constant challenges that food scientists encounter is the development of new food processing technologies and new food products with specific functionalities. Moreover, increasing consumer demand for good quality and very convenient food products with natural flavor and taste, free from additives and preservatives, engender the need for the development of nonthermal innovative approaches for food processing. With regard to food processing technologies, the development of non-thermal process methods such as high pressure processing, pulsed electric, and magnetic fields, etc., which offer maximum quality and safety of food products have attracted some attention within the food industry. In order to meet the expectation of today's increasingly demanding consumers, the new and alternative food processing methods, as well as novel combinations of existing methods, are continually being sought by industry in an effort to producing better quality foods economically. Due to their important features such as microbial and enzyme inactivation at ambient or lower temperatures, the nonthermal technologies are regarded as potential and powerful tools in food processing. In recent years, there has been a significant increase in the number of scientific papers demonstrating novel and diversified uses of these technologies.

Ultrasound is considered as one such nonthermal processing alternative, which can be used in many food processing operations. It travels through a medium like any sound wave, resulting in a series of compression and rarefaction. At sufficiently high power, the rarefaction exceeds the attractive forces between molecules in a liquid phase, which subsequently leads to the formation of cavitation bubbles. Each bubble affects the localized field experienced by neighboring bubbles, which causes the cavitation bubble to become unstable and collapse, thereby releasing energy for many chemical and mechanical effects. The collapse of each cavitation bubble acts as a hotspot, which generates energy to increase the temperature and pressure up to 4000 K and 1000 atm, respectively. The cavitation collapse in aqueous medium generates shear forces that can produce mechanical

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effects. It can also occur in the bubble itself where any species introduced during its formation will be subjected to extreme conditions of temperature and pressure on collapse, resulting in chemical effects. Collapse of a cavitation bubble on or near a surface is asymmetrical because the surface provides resistance to liquid flow from that side, which results in an inrush of liquid predominantly from the side of the bubble remotes from the surface, which leads to the formation of a powerful liquid jet targeted at the surface. The effect is equivalent to a high pressure jetting, which makes ultrasound suitable for cleaning. This effect can also increase mass and heat transfer to the surface by disruption of the interfacial boundary layers. Cavitation bubble collapse in the liquid phase near a particle can force it into rapid motion. Under these circumstances the general dispersive effect is accompanied by inter-particle collisions that can lead to erosion, surface cleaning, and wetting of the particles, as well as particle size reduction.

Very rapid localized changes in pressure and temperature cause shear disruption, cavitation, thinning of cell membranes, localized heating, and free radical production, which have a lethal effect on microorganisms (Suslick, 1988; Sala et al., 1995; Leighton, 1998). Ultrasound is used as a processing aid in the mixing of materials, foam formation or destruction, agglomeration and precipitation of airborne powders, the improvement in efficiency of filtration, drying, and extraction techniques in solid materials, and the enhanced extraction of valuable compounds from vegetables and food products (McClements, 1995; Mason et al., 2005). Applications of ultrasound in food processing are reviewed by Knorr et al. (2004).

Simultaneous application of ultrasound under pressure alone (manosonication) or in combination with pressure and thermal treatment (manothermosonication) led to increased microbial inactivation. A synergistic and lethal effect of ultrasound treatment in combination with pressure and thermal treatment was shown in the case of *Enterococcus faecium* and *Bacillus subtilis* spores (Raso et al., 1998a; 1998b; Pagan et al., 1999a). This synergistic effect in case of *Bacillus subtilis* spores was attributed to the permeabilization of the outer membranes of bacterial spores by the combined treatment of pressure and ultrasound (Raso et al., 1998b).

The effects of ultrasound on meat proteins produced tenderization in meat tissues after prolonged exposure, and the release of myofibrillar proteins in meat products results in improved water binding capacity, tenderness, and cohesiveness (McClements, 1995). Since the resistance of most microorganisms and enzymes to ultrasound is too high, it requires higher intensity of ultrasound treatment that may produce adverse changes to the texture and other physical properties of the food, thereby affecting the sensory attributes. This may render ultrasound not very useful in case of food preservation. However, this technique may find its use in many other food-processing applications.

Generally, ultrasound equipment uses frequencies from 20 kHz to 10 MHz (Fig. 1). Higher-power ultrasound at lower

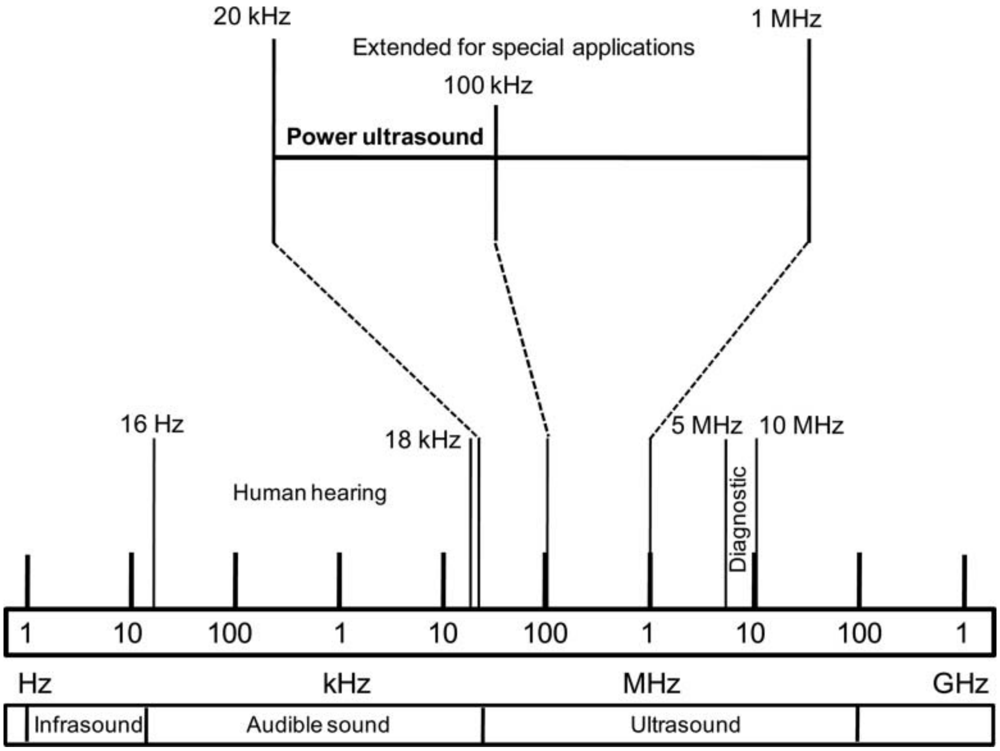

Figure 1 Frequency ranges of sound indicating infrasound (1 Hz-16 Hz), human hearing (16 Hz-18 kHz), power ultrasound (20 kHz-100 kHz), extended for special applications (20 kHz-1 MHz) and diagnostic ultrasound (5 MHz-10 MHz).

frequencies (20 to 100 kHz), which is referred to as "power ultrasound," has the ability to cause cavitations (implosion of gas bubbles) with sound intensities of 10 to 1000 W/cm^2 (McClements, 1995; Feng and Yang, 2005). Low power ultrasound applications involve the use of high frequencies (2–10 MHz) usually at low power (up to 10 W). It causes no physical or chemical alterations in the properties of the material, which is termed as the non-destructive use of ultrasound in providing information about the physicochemical properties of foods, such as composition, structure, and physical state. The ultrasound frequency between 5 to 10 MHz finds its application in diagnostic purposes. In addition, a variety of product characteristics, including composition, texture, structure, fluid level, and thickness and flow rate are monitored using ultrasound (McClements, 1995). The physical, mechanical, or chemical effects of power ultrasound (20 kHz and 100 kHz) are capable of altering material properties (e.g., disrupting the physical integrity, acceleration of certain chemical reactions) through generation of immense pressure, shear, and temperature gradient in the medium through which they propagate. The efficacy of ultrasound for fruit juices and changes in key quality and nutritional parameters for fruit juices has been reviewed (Tiwari et al., 2008a; 2009a). The key findings in the area of ultrasound processing of fruit juice have been summarized in Table 1.

Various areas with great potential have been identified for future development and it has been realized that ultrasound has much to offer to the food industry such as inactivation of microorganisms and enzymes, crystallization, drying, degassing, extraction, filtration, homogenization, meat tenderization, oxidation, sterilization, etc., including efficiency enhancement of various operations and online detection of contaminants in foods.

GENERATION OF POWER ULTRASOUND

It is important to understand the manner in which ultrasound is generated and applied to the process. The ultrasonic transducers convert electrical or mechanical energy to sound energy. There are three types of ultrasonic transducers in common usage including liquid-driven transducers, magnetostrictive transducers, and piezoelectric transducers (Mason, 1998).

Liquid-driven transducers are effectively liquid vessel in which process material is forced under pressure by a powerful pump across a thin blade which causes the blade to vibrate. For each vibrational movement, the leading face of a blade produces a pressure wave while a trailing face generates cavitation in the liquid. Magnetostrictive transducers are electromagnetic devices which use magnetostriction, an effect found in some ferromagnetic material, for example, nickel and iron which change in dimension on the application magnetic field. Repeated rapid switching on and off the current generates the vibrations.

Piezoelectric transducers are the most common devices employed for the generation of ultrasound and utilize ceramics containing piezoelectric materials. The active element is the heart of the transducer as it converts the electrical energy to acoustic energy. The active element is basically a piece of polarized material (i.e., some parts of the molecule are positively charged, while other parts of the molecule are negatively charged) with electrodes attached to two of its opposite faces. When an electric field is applied across the material, the polarized molecules will align themselves with the electric field, resulting in induced dipoles within the molecular or crystal structure of the material. This alignment of molecules will cause the material to change dimensions. This phenomenon is known as electrostriction. In addition, a permanently-polarized material such as quartz (SiO_2) or barium titanate ($BaTiO_3$) will produce an electric field when the material changes dimensions as a result of an imposed mechanical force. This phenomenon is known as the piezoelectric effect.

There are numerous types of ultrasonic equipment available, which can be used as sonochemcial reactor. These include ultrasonic bath, ultrasonic probe, parallel or radial vibrating system, etc. Basically, the ultrasonic bath is a tank that contains a process medium with transducers bonded to its base. For ultrasonic baths, power is often low in order to avoid cavitational damage to the tank walls and the power density is low due to a large volume of the processing liquid (Mason, 1998). The ultrasonic probe contains one or several shaped metal horns attached to the transducer to achieve high power intensity. The horn must be designed to resonate at the same frequency as the transducer that drives it.

For the classification of ultrasound applications the energy amount of the generated sound field is the most important criterion. It is characterized by acoustic power (W), acoustic intensity (W/m^2), or acoustic energy density (W/cm^3 or W/mL) (Knorr et al., 2004). The sonication treatment and the cavitation activity in a treatment chamber may vary for the same ultrasound intensity if the sample volume and probe location change. Recently, volumetric acoustic energy density (W/cm^3 or W/mL) has been widely employed to indicate the ultrasonic power level.

Ultrasonic intensity or acoustic energy density can be determined calorimetrically with the help of following equations (Mason et al., 1990; Tiwari et al., 2009b).

$$\text{Ultrasonicintensity} = \frac{4\text{P}}{\pi \text{d}^2} \tag{1}$$

$$\text{Acousticenergydensity} = \frac{\text{P}}{\text{V}} \tag{2}$$

where 'P' is the absolute ultrasonic power and it is defined as $\text{mC}_\text{p}\left(\frac{\text{dT}}{\text{dt}}\right)_{\text{t}=0}$, Cp is the specific heat capacity, and (dT/dt) is the rate of change of temperature during sonication.

SPECIFIC APPLICATIONS OF ULTRASOUND IN FOOD PROCESSING

Inactivation of Microorganisms and Enzymes

The effect of ultrasound on different microbial species is known to be dependent on the shape and size of the

Table 1 Key finding in the area of ultrasound processing of fruit juice

Product	Conditions	Salient results	References
Orange juice			
	20 kHz, Wave amplitude of 89.25 μm for 8 min	The use of ultrasound extended the shelf-life of orange juice by 4 days. Control samples were rejected by the sensory panel after 6 days storage at 4°C due to off-flavor, and ultrasonicated juice after 10 days due to off-odor. Sonication also affected color and decreased ascorbic acid content.	Gómez-López et al., (2010)
	20 kHz, 24.4–61.0 μm, 5–30°C, 0–10 min.	Developed a deterministic modelling approach for non-enzymatic browning and ascorbic acid degradation in orange juice during ultrasound processing. Low temperatures and intermediate amplitude (42.7 μm) resulted in lower non-enzymatic browning and ascorbic acid deterioration and better quality orange juice.	Valdramidis et al. (2010)
	Acoustic energy density levels of 0.42–1.05 W/mL, 0–10 min	The effect of sonication on PME activity and cloud stability of orange juice was studied. The highest PME inactivation level observed was 62% for sonication at the highest energy density level and treatment time. The cloud stability of sonicated orange juice was found to be dependent on PME inactivation and particle size reduction. Sonication at low energy density levels and temperatures resulted in the desired cloud stability.	Tiwari et al., (2009c)
	20 kHz, 2–10 min, pulse durations of 5 s on and 5 s off, amplitude levels 40 to 100%	The effect of amplitude level and sonication time on juice quality parameters was studied. There was no significant difference on pH, °Brix and titratable acidity. However, it resulted in degradation of color, cloud value and an increase in browning index.	Tiwari et al., (2008b)
	Ultrasonic intensity 8.61–22.79 W/cm^2, 0–10 min	Changes in cloud value followed first-order kinetics, whereas browning index, L*, a*, and b* values followed zero-order kinetics. Reaction rate constants were linearly correlated to ultrasonic intensity.	Tiwari et al., (2008c).
	20 kHz, 95 μm-wave amplitude	Combined treatment involving high-intensity ultrasound and short-wave ultraviolet radiation was more effective in simultaneous rather than in series for the inactivation of *Escherichia coli*, *Saccharomyces cerevisiae*, and a yeast in fruit juice	Char et al., (2010).
	600 W, 20 kHz, 95.2-μm wave amplitude	Combination of high intensity ultrasound with mild heat treatment (45°C), and natural antimicrobials (vanillin 1,000 ppm and citral 100 ppm) was reported to be the most effective treatment for the control of *L. monocytogenes* in orange juice.	Ferrante et al., (2007).
	20 kHz, ultrasound amplitude 117 μm	Simultaneous application of heat (72°C) and ultrasound under moderate pressure (200 kPa) to navel oranges increased the inactivation rate of PME in buffer and orange juice by 25 times and 400 times, respectively.	Vercet et al., (1999).
Apple juice			
	20 kHz, ultrasound amplitude 0.4 to 37.5 μm	Ultrasound treatment alone can be effective for inactivation of *E. coli* that had already been exposed to prior acid stress or adaptation, such as those encountered in acidic products for example fruit juices.	Patil et al., (2009).
	23 kHz, 200–700 W, 10–60 min	The effect of ultrasonic treatments on *Alicyclobacillus acidoterrestris* in apple juice was more pronounced at an elevated power level and increased processing time. Approximately 60% and 90% of the cells were inactivated after treating the apple juice with 300-W ultrasound for 30 min and 60 min, respectively. The lowest D value at 36.18 min was found when using 600-W. Changes of sugar content, acidity, haze and juice browning were noted after ultrasonic treatments but did not adversely alter the juice quality.	Yuan et al., (2009).
	22 to 48 kHz	A 5-log reduction was achieved for *L. monocytogenes* and *E. coli* O157:H7 with the use of copper ion water (1 ppm) in combination with sodium hypochlorite (100 ppm for 3 min) followed by extraction of juice and sonication at 44 to 48 kHz.	Rodgers and Ryser (2004).
Tomato juice			
	20 kHz, 24.4 to 61.0 μm, 2 to 10 min and pulse durations of 5 s on and 5 s off.	Power ultrasound is recognised as a potential non thermal technique to inactivate microorganisms pertinent to fruit juices. Yeast inactivation was found to follow the Weibull model. It was concluded that that sonication alone is an effective process to achieve the desired level of yeast inactivation in tomato juice.	Adekunte et al., (2010).
	20 kHz, amplitude of 65 μm and temperatures between 50 and 75°C.	The ultrasonic inactivation kinetics of polygalacturonase (PG) and pectin methylesterase (PME) in tomato juice were studied. Combined ultrasound and heat (thermosonication) enhanced the inactivation rates of both PME and PG.	Terefe et al., (2009).
Strawberry juice			
	20 kHz, amplitude level 40–100%, 2–10 min, pulse durations of 5 s on and 5 s off.	The effect of amplitude level and sonication time was studied on strawberry juice quality. Sonication was found to reduce anthocyanin and ascorbic acid contents by 3.2 and 11%, respectively, at the maximum treatment conditions.	Tiwari et al., (2008d).
	20 kHz, energy density 0.33–0.81 W/mL, 0–10 min, pulse 5 on 5 off.	Ultrasound treatment (energy density 0.81 W/mL and treatment time 10 min) resulted in 5% and 15% reductions in anthocyanin and ascorbic acid, respectively during storage 4 and 20°C for 10 days. However, improved stability for ascorbic acid and anthocyanins retention was higher as compared to control sample.	Tiwari et al., (2009d).

(Continued on next page)

Table 1 Key finding in the area of ultrasound processing of fruit juice *(Continued)*

Product	Conditions	Salient results	References
Guava juice			
	35 kHz, 30 min.	The effect of carbonation and sonication was studied on the quality of guava juice. Ascorbic acid content was found to be significantly higher in samples treated with carbonation and sonication than in the control. Carbonation provided more nuclei for cavitations that permitted the elimination of dissolved oxygen in the juice. In addition, such a treatment also gave rise to a greater cloudiness and PPO activity.	Cheng et al., (2007).
Blackberry juice			
	20 kHz, 37.5 μm to 61.0 μm, 0–10 min, pulse durations of 5s on 5s off.	Significant changes in color and anthocyanins with insignificant changes in pH, titratable acidity, and degree brix were obtained in case of blackberry juice.	Tiwari et al., (2009e)
Red grape juice			
	20 kHz, 24.4—61.0 μm, 0–10 min, pulse durations of 5 s on and 5 s off	Significant changes in anthocyanins and color. Highest degradation of malvanidin-3-O-glucosides (48.2%) cyanidin-3-O-glucosides (97.5%) and delphinidin-3-O-glucosides (80.9%) at 61.0 μm for 10 min.	Tiwari et al., (2010)

microorganisms (bigger cells being more sensitive than smaller ones, and coccal forms are more resistant than rod-shaped bacteria), type of cells (Gram-positive and aerobic being), and physiological state (younger cells being more sensitive than older ones, spores being much more resistant than vegetative cells) (Piyasena et al., 2003).

Sala et al. (1995) and Pagan et al. (1999a;1999b) demonstrated the potential of ultrasound to inactivate emerging pathogenic microorganisms such as *Listeria monocytogenes*, a number of strains of *Salmonella* spp., *Escherichia coli*, or *Staphylococcus aureus,* which are increasingly found in outbreaks of food poisoning.

Ugarte et al. (2006) pointed out that the combination of ultrasound with thermal effect enhanced the destruction of *E. coli* in apple juice as compared to thermal inactivation alone (Fig. 2). A continuous ultrasound system in combination with steam injection has shown up to fourfold higher inactivation rates of *E. coli* and *Lactobacillus acidophilus* in several liquid foods such as milk and fruit juices (Zenker et al., 2003). D'Amico et al. (2006) showed that ultrasound treatment combined with mild heat (57°C) for 18 min resulted in a 5-log reduction of *L. monocytogenes* in milk, a 5-log reduction in total aerobic bacteria in raw milk, and a 6-log reduction in *E. coli* O157:H7 in pasteurized apple cider.

The control of *L. monocytogenes* in orange juice could be achieved by combining high intensity ultrasound with mild heat treatment and natural antimicrobials (Ferrante et al., 2007). The inactivation of *Saccharomyces cerevisiae* was enhanced by incubating with low molecular weight chitosan prior to ultrasound (Guerrero et al., 2005). Scouten and Beuchat (2002) indicated the decontamination of alfalfa seeds inoculated with *Salmonella* or *E. coli* O157 by combined treatments of ultrasound and $Ca(OH)_2$, which could be an alternative to chlorine treatments to avoid contamination. Seymour et al. (2002) reported microbial

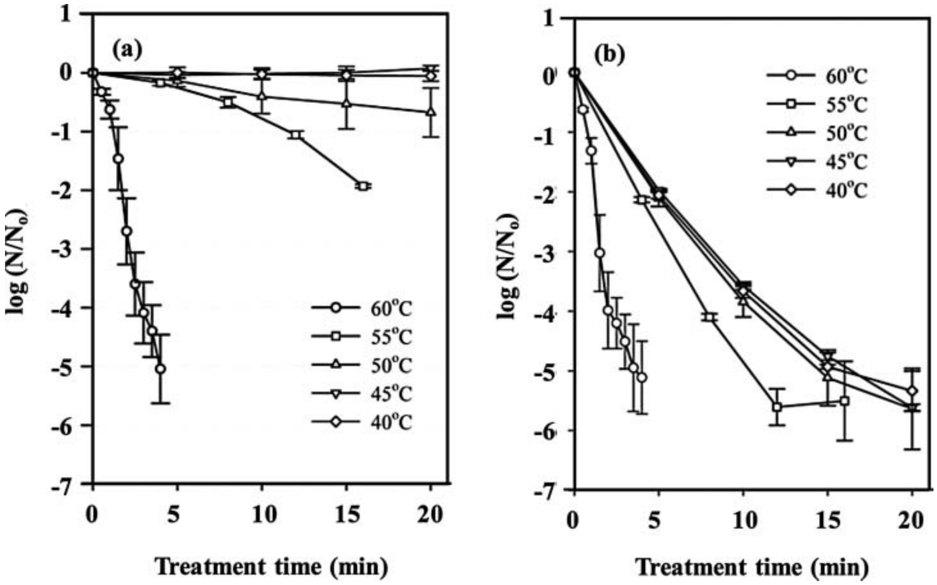

Figure 2 (a) Thermal and (b) power ultrasound inactivation of *Escherichia coli* K12 in apple cider at different temperatures (with permission from Ugarte et al. (2006). *J. Food Sci.* **71**: E102-E108).

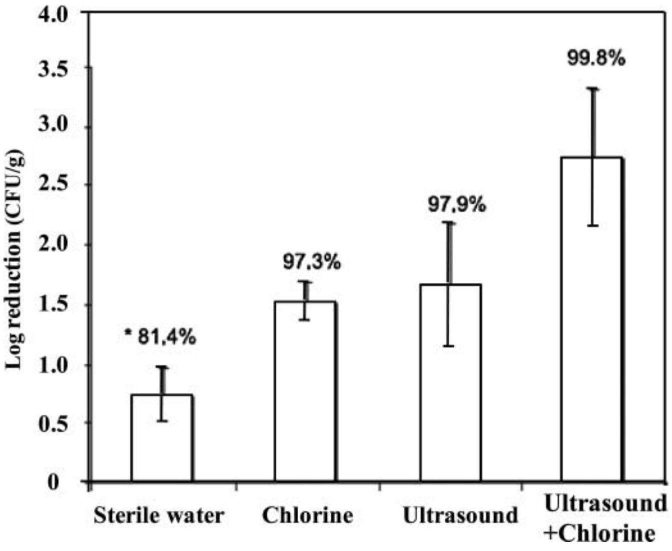

Figure 3 The effects of ultrasound and chlorine on the decontamination efficiency of Salmonella typhimurium on iceberg lettuce. Remaining bacteria were enumerated before and after washing to assess bacterial attachment (n = 5) (with permission from Seymour et al. (2002) *Int. J. Food Sci. Technol.* **37**: 547–557).

decontamination on the surface of minimally processed fruits and vegetables (lettuce, cucumber, carrots, parsley and others) by ultrasound (Fig. 3). Zhou et al. (2009) demonstrated that the use of ultrasound (21.2 kHz, 2 min) enhanced the efficacy of selected sanitizers (such as water, chlorine, acidified sodium chlorite, peroxyacetic acid, and acidic electrolyzed water) in reduction of *Escherichia coli* O157:H7 populations on spinach. Acidified sodium chlorite reduced *E. coli* population by 2.2 log cycles over that of water wash, while the reduction from other sanitizers was about 1 log cycle. Ultrasonication significantly enhanced the reduction of *E. coli* cells on spinach for all treatments by 0.7 to 1.1 log cycle over that of washes with the sanitizer alone. The combination of ultrasound with chlorine treatment was found to result in 4 log reduction of *Salmonella* on poultry surfaces (Lillard, 1994).

The use of the combination of heat and ultrasound at ambient pressure was reported to be successful in inactivating food-quality related enzymes such as peroxidase (Gennaro et al., 1999; Yoon et al., 2000) and lipoxygenase (Thakur and Nelson, 1997). A combination of heat ultrasound and pressure (manothermosonication) treatment was demonstrated to be much more efficient than heat treatment alone for inactivating enzymes such as lipoxygenase, POD, and PPO (Lopez et al., 1994). Villamiel and Jong (2000) reported a synergistic effect of ultrasound and moderate temperatures (60–75°C) on endogenous milk enzymes such as alkaline phosphatase, g-glutamyltranspeptidase, and lactoperoxidase. Manothermosonication treatment was found to be several times faster than the heat treatment alone in case of proteases and lipases in ultra heat treated milk, pectin methylesterase in orange or tomato, and polygalacturonase in tomato (Vercet et al., 1997; 1999; 2002). Tiwari et al. (2009c) studied the inactivation kinetics of pectin methylesterase in sonicated orange juice and indicated that a fraction conversion model adequately described the pectin methyl esterase (PME) inactivation. Wu et al. (2008) studied the effect of sonication time as well as amplitude on PME activity and demonstrated that the thermosonication at 60 and 65°C could be a useful method for obtaining tomato juice with a low residual PME activity and high viscosity (Fig. 4).

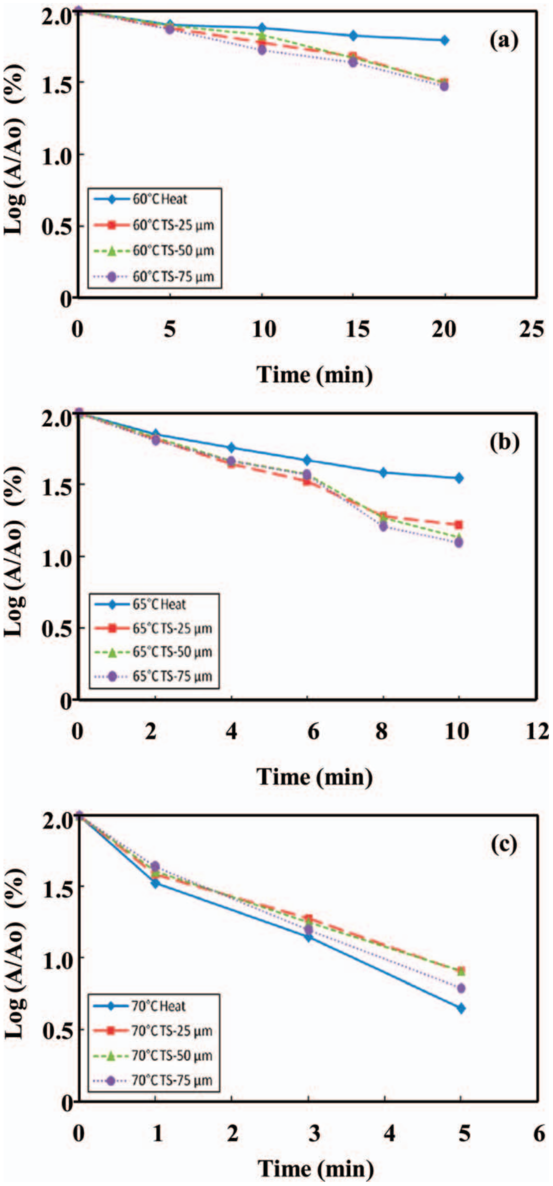

Figure 4 Effect of sonication amplitude and sonication time on the inactivation of tomato PME at 60, 65, and 70°C. (with permission from Wu et al. (2008) Effect of thermosonication on quality improvement of tomato juice, *Innovat. Food Sci.Emerg. Technol.* **9**: 186–195). (color figure available online.)

The ultrasound in combination with pressure and/or heat is a promising alternative for the rapid inactivation of microorganisms and enzymes, and therefore, techniques like thermosonication, manosonication, and manothermosonication may be a more relevant energy-efficient processing alternative for the

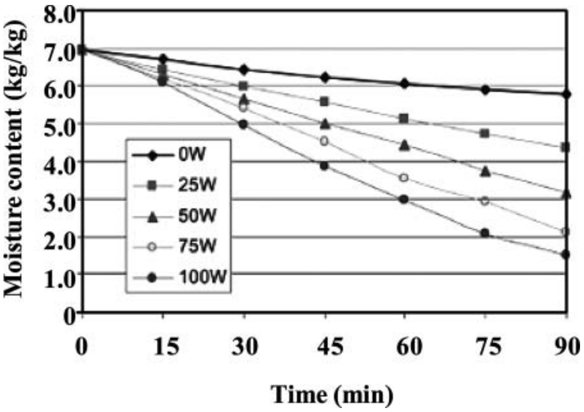

Figure 5 Influence of ultrasonic power on the kinetics of the direct contact ultrasonic dehydration process of carrot cylinders (with permission from Gallego-Juarez et al. (2007). *Drying Technol.* **25**: 1893–1901).

food industry in times to come. The use of ultrasound and combined technologies, mechanisms, and effects of ultrasound combinations are discussed by Demirdöven and Baysal (2009).

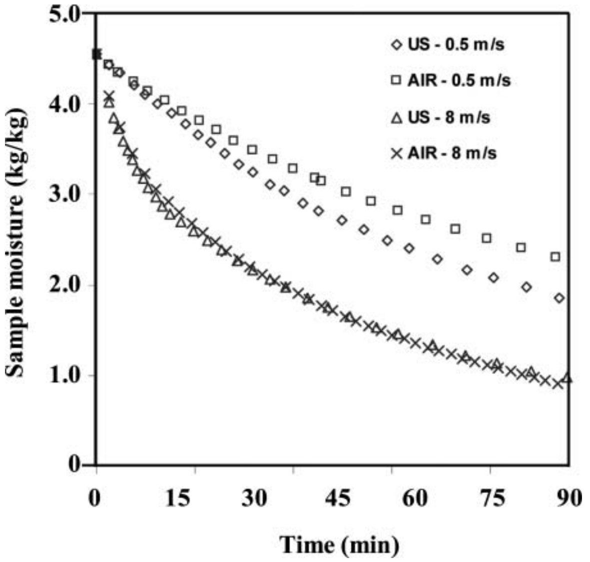

Figure 6 Comparison of the persimmon moisture evolution during drying at higher and lower air velocities with and without ultrasound application (with permission from Carcel et al. (2007a). *Drying Technol.* **25**: 185–193).

Ultrasound for Enhancing the Efficiency of Existing Unit Operations

Ultrasound Assisted Drying

The use of ultrasound in combination with or prior to hot air drying was shown to have potential in increasing the drying rate without significantly affecting the quality of the product.

Gallego-Juarez et al. (2007) indicated that high intensity ultrasound in combination with hot air systems resulted in adequate drying rates for vegetable drying even at lower temperatures. Ultrasound enhanced the mass transfer during drying of carrot. The curves obtained up to a maximum applied power of 100 W reveal a direct increase of the drying effect with the acoustic intensity (Fig. 5). Since, the product was dehydrated at low temperature, the product quality was found to improve (Garcia-Perez et al., 2007). The use of ultrasound as a treatment prior to drying of mushrooms, Brussels sprouts, and cauliflower reduced the drying time significantly (Jambrak et al., 2007). At the lowest air velocities, the drying kinetics of persimmon in ultrasound assisted drying were faster than the drying without ultrasound. However, when the air velocity increased, the improvement caused by using ultrasound is not marked due to disruption of the acoustic field by the flow (Fig. 6) (Carcel et al., 2007a).

During the ultrasonic pretreatment, banana, melon, and pineapple were found to lose sugar, it could be used to produce dried fruits with lower sugar contents. Ultrasound induced disruption of cells and formation of microscopic channels in the fruit structure but did not induce breakdown of the cells. Further, air drying of ultrasonically pretreated banana and melon (*Curcumis melo*) fruits resulted in an increase in effective water diffusivity during air drying leading to a reduction in the drying time of about 25% (Fernandes and Rodrigues, 2007; Rodrigues and Fernandes, 2007; Fernandes et al., 2008; 2009). Azoubel et al. (2009) also indicated that the application of ultrasound during drying of banana could increase the moisture diffusivities, which in turn reduced process time leading to the economy of energy. The rehydration of ultrasonically treated and finally dried sample showed that the percentage rehydration was higher as compared to that of untreated samples.

It can also be exploited for the dehydration of heat sensitive foods, which can be dehydrated more rapidly and at a relatively lower drying temperature. The potential benefits due to the application of ultrasound regarding enhancement of the rate of mass transfer in case of dehydration and osmotic dehydration have been reviewed by Mason et al. (2005).

Ultrasound Assisted Osmotic Dehydration

The use of ultrasound in combination with osmotic dehydration results in higher rate of water loss and solute gain at a lower solution temperature, while preserving the natural flavor, color and heat-sensitive nutritive components. It is due to increased cell wall permeability (lower resistance) owing to the formation of microscopic channels, which facilitated the transport of water and solute.

Application of ultrasound to osmotic dehydration of apple was found to accelerate the “water out” and “solute in” mass transfer rates (Simal et al., 1998). Due to ultrasound pretreatment, water as well as solute diffusion coefficients were found to increase up to 117 and 137%, respectively (Carcel et al., 2007a). In comparison with pulsed-vacuum treatment, ultrasound treatment resulted in higher water loss and lower solid gain in case of apple (Fig. 7, Yun and Yanyun, 2008). The higher loss of firmness due to ultrasound treatment in comparison to pulsed-vacuum-treated samples was due to severe cell deformation and

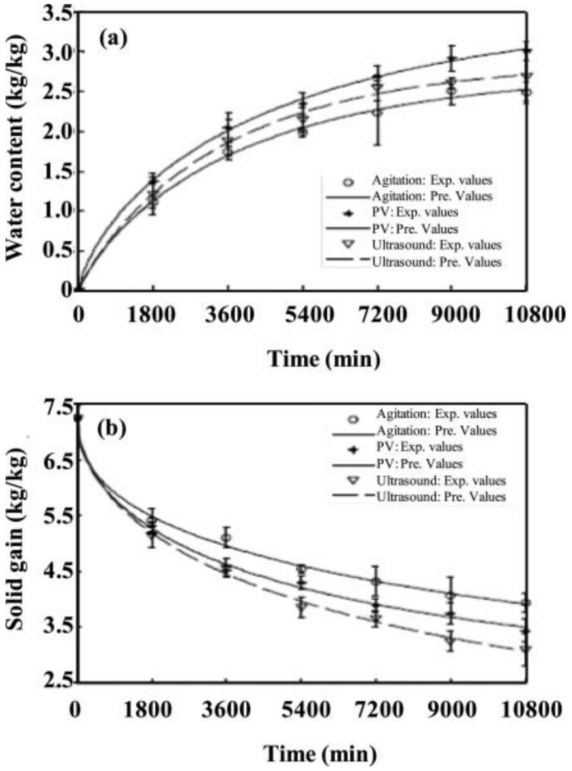

Figure 7 (a) Water content and (b) soluble solid uptake in apple tissues under different osmotic treatments for 3 h. Agitation: agitation at 55 rpm; PV: pulsed-vacuum with 13 MPa vacuum for 5 min + atmospheric pressure for 5 min + 13 MPa vacuum for 5 min, then atmospheric pressure; Ultrasound: ultrasonic wave at 50/60 Hz and 185 W (with permission from Yun and Yanyun (2008) *J. Food Eng.* **85**: 84–93).

structure collapse (Fig. 8) (Yun and Yanyun, 2008). Similarly, Deng and Zhao (2008) also indicated that application of ultrasound led to a higher glass transition temperature, lower water activity, moisture content and rehydration rate, severer structure collapse, and less cavities and calcium uptake than pulsed-vacuum treatment. Stojanovic and Silva (2007) also indicated that application of ultrasound enhanced the water diffusion rates during osmotic dehydration of rabbiteye blueberries; however, it was coupled with the loss of anthocyanins and phenolics. In case of osmotic dehydration of melon, the water diffusivity in the beginning of the process (for less than 30 min) was found to decrease due to incorporation of sugar. Whereas, it increased when the process was continued for a longer time (more than 1 h) due to the breakdown of cells (Fernandes et al., 2008). The increased loss of water and uptake of soluble solids during brining of bell pepper due to ultrasound was also reported by Gabaldon-Leyva et al. (2007) (Fig. 9).

Ultrasound treatment finds its application in brining of cheese and meat products. In case of cheese brining, the rate of water removal and sodium chloride gain increased when ultrasound was applied (Sanchez et al., 1999). Whereas, in case of pork loin (longissimus dorsi) during brining, the final moisture content was significantly higher than the initial moisture content and the sodium chloride content was proportional to applied ultrasonic intensity (Carcel et al., 2007b).

Ultrasound-Assisted Extraction

Ultrasound in combination with conventional extraction is a potential technique in enhancing the rates and extent of mass

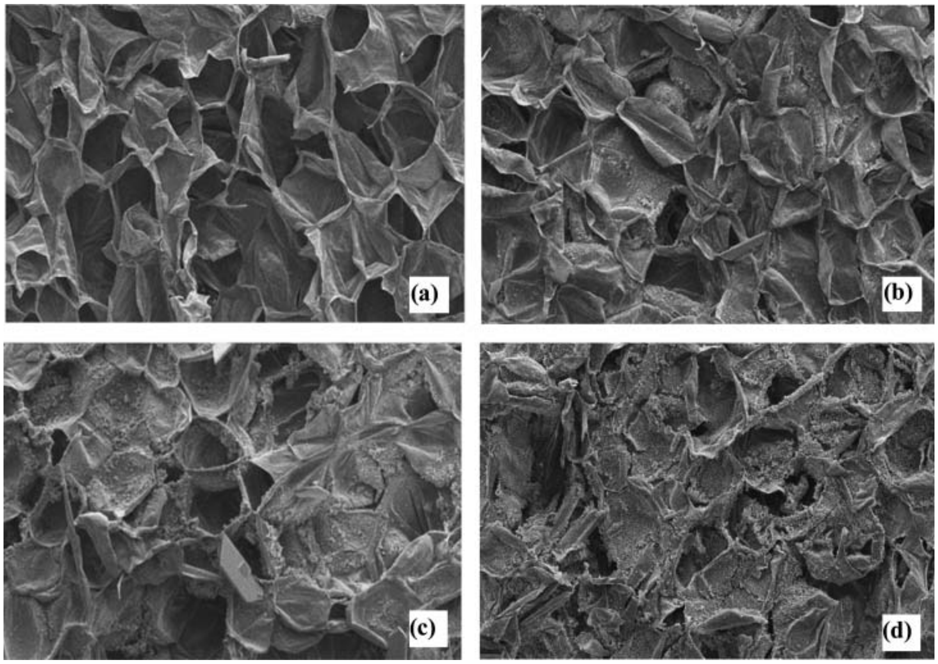

Figure 8 Scanning electron microscopy (SEM) micrographs of fresh apple and treated apple samples at the end of 3 h osmotic treatment. (a) Fresh control; (b) osmotic treatment with agitation 55 rpm; (c) pulsed-vacuum (PV) with 13 MPa vacuum for 5 min + atmospheric pressure for 5 min + 13 MPa vacuum for 5 min, then atmospheric pressure; (d) osmotic treatment with ultrasound at 50/60 Hz and 185 W (with permission from Yun and Yanyun (2008) *J. Food Eng.* **85**: 84–93).

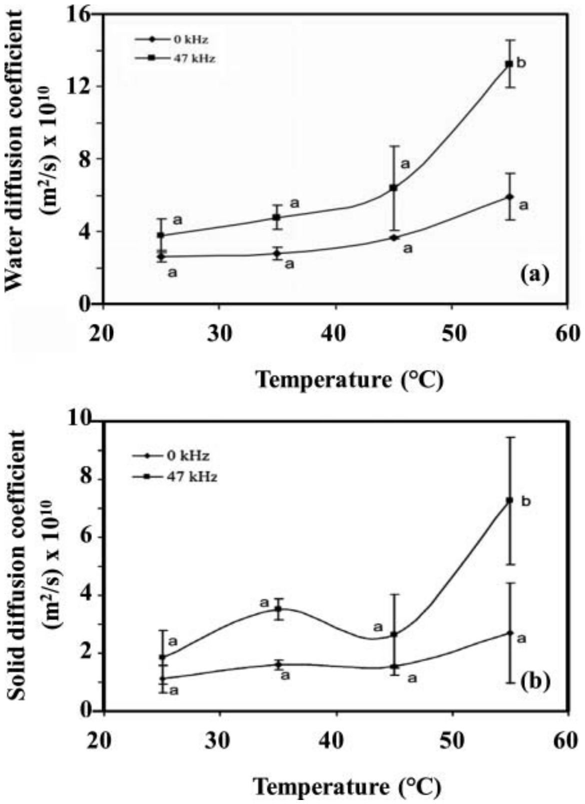

Figure 9 (a) Water loss and (b) total solid diffusion coefficient in brine red bell peppers strips at different brine temperatures with and without ultrasound treatments (means with the same letter are not significantly different by Tukey test at $p < 0.05$) (with permission from Gabaldon-Leyva et al. (2007) *J. Food Eng.* **81**: 374–379).

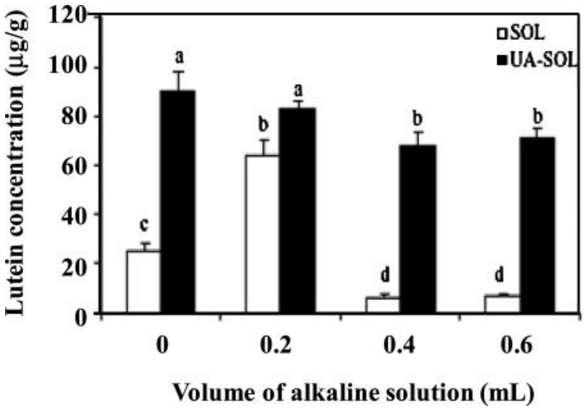

Figure 10 Extraction yields of lutein from hen egg yolk using the solvent (SOL) and ultrasound-assisted solvent (UA-SOL) extraction methods at different levels of saponification. Significant difference ($p < 0.05$) between two extraction yields is expressed by different letters (with permission from Xiaohua, Y. et al. (2006) *J. Food Sci.* **71**: C239–C241).

transfer to and from the interfaces. The beneficial effects of ultrasound are derived from its mechanical effects on the process by increasing penetration of the solvent into the product due to disruption of the cell walls produced by acoustical cavitation. Moreover, it is achieved at lower temperatures and hence more suitable for enhancing the extraction of thermally unstable compounds (Wu et al., 2001).

Ultrasound-assisted solvent extraction of aqueous extraction of crushed grapes and *S. platensis* resulted in enhanced extraction of anthocyanins (Vilkhu et al., 2008) and phycocyanin (Furuki et al., 2003), respectively. Extraction yields of lutein from hen egg yolk was found to increase during solvent extraction, when the process was coupled with ultrasound (Fig. 10, Xiaohua et al., 2006). A combination of microwave and ultrasound treatments was also found to increase the extraction of pigments from strawberries (Cai et al., 2003). Higher extraction in a shorter time with reduced microbial count in case of date syrup extract was reported by Entezari et al. (2004). Vilkhu et al. (2008) demonstrated that ultrasound extraction of grape marc (a solid waste of the winemaking industry) resulted in up to 35% increase in phenolic compounds, which provides the characteristic color and flavor to wine.

Application of ultrasound accelerated the efficiency of extraction and preserved structural and molecular properties of hemicelluloses, cellulose, xyloglucan, and water-soluble xylans extracted from buckwheat hulls (Hromadkova and Ebringerova, 2003), sugarcane bagasse (Sun et al., 2004), apple pomace (Caili et al., 2006), and corn cob waste (Ebringerova et al., 1998), respectively. Chua et al. (2009) indicated that application of ultrasound resulted in increased extraction yield of phosphatidylethanolamine and phosphatidylcholine from palm-pressed fiber. Scanning electron micrographs of palm-pressed fiber surface before and after the ultrasound treatment indicated that ultrasound-assisted extraction produced significant rupture on the surface (Fig. 11), which played an important role in breaking up vegetal cell walls to enhance extraction yield. Ultrasound treatment to corn in the conventional wet milling process enhanced starch separation and increased final starch yield in addition to higher paste viscosities and whiteness (Zhang et al., 2005).

In ultrasound assisted extraction processes, the extraction yield of geniposide, anthraquinones carnosic acid, and ginsenosides (tri-terpene saponins) from Gardenia fruit (Bing et al., 2006) roots of *M. citrifolia* (Hemwimol et al., 2006), from rosemary (Albu et al., 2004), ginseng roots (Tang and Eisenbrand, 1992), respectively were found to be higher as compared to respective controls.

Application of high-intensity ultrasound was shown to improve the extraction of edible oil from soybeans. The oil yield increased with increasing ultrasonic intensity (Fig. 12, Haizhou et al., 2004; Babaei et al., 2006). Karki et al. (2010) indicated that the use of ultrasound significantly improved the total sugar released and protein yield from defatted soy flakes dispersed in water by 50 and 46%, respectively, as compared to control, which in turn is expected to reduce the overall cost of production of soy protein from its flakes. Zhang et al. (2008) indicated that the ultrasound-assisted extraction technique was shown to be very efficient in the extraction of oil from flaxseed. The yield of flaxseed oil increased with increasing extraction time, ultrasonic power, and ratio of liquid to solid; however, it decreased

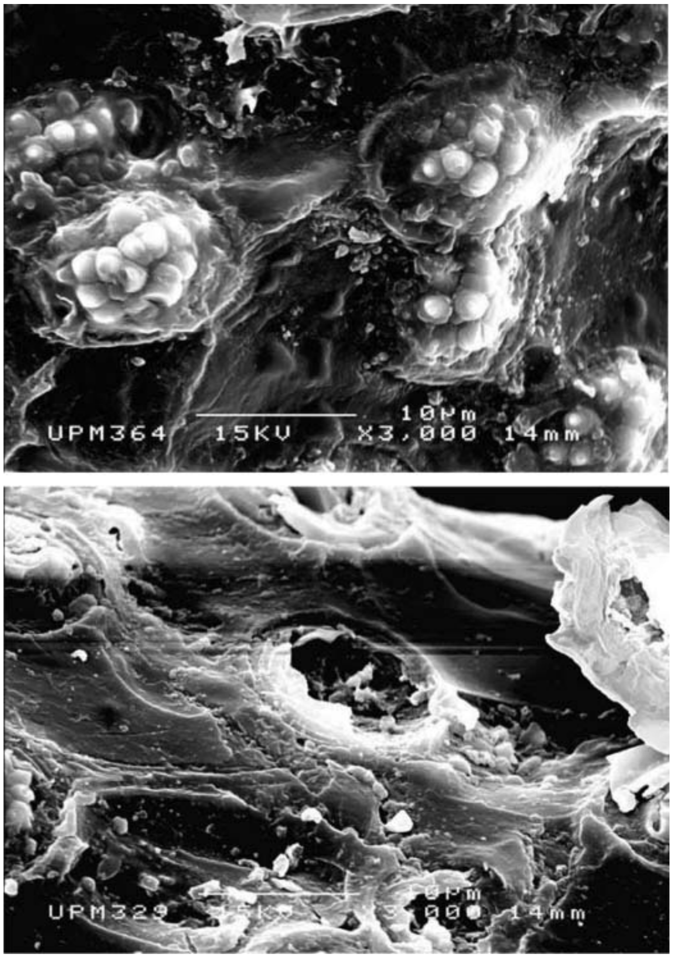

Figure 11 Scanning electron micrographs of palm-pressed fiber surface, (a) before sonication; (b) after 30 min sonication at 20% amplitude and 0.2 W/s cycle. Ultrasound-assisted extraction produced significant rupture on the surface of PPF (with permission from Chua et al. (2009) *J Food Eng.* **92**: 403–409).

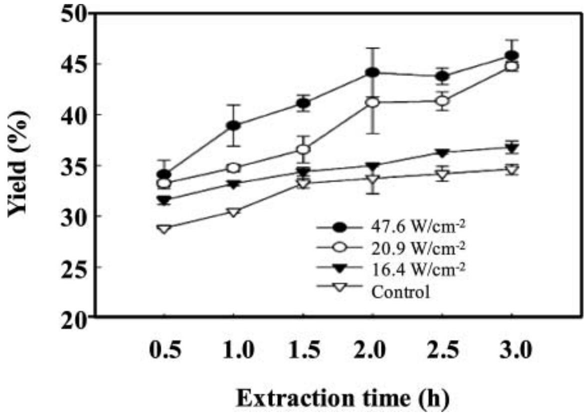

Figure 12 Oil yield as a function of extraction time for soybean variety TN 96–58 using high-intensity ultrasound at ultrasonic intensities of 0, 16.4, 20.9, and 47.6 W/cm^2 using hexane as a solvent at 25°C (with permission from Haizhou et al. (2004) High intensity ultrasound-assisted extraction of oil from soybeans. *Food Res. Int.* **37**: 731–738).

with an increase in temperature as compared to conventional solvent extraction (control) (Fig. 13). The fatty acid compositions of the oils extracted by the ultrasound-assisted method and the conventional method were not affected significantly by the application of ultrasound.

Similarly, higher yields of carvone and limonene from caraway seeds were also reported by Chemat et al. (2004). Higher extraction of health promoting phenolic compounds from wheat bran (Jing et al., 2008; Wang et al., 2008) and coconut shell (Rodrigues and Pinto, 2007) were also reported. This technique also resulted in enhanced content of tea polyphenols, amino acids, and caffeine in tea with improved sensory quality of tea (Xia et al., 2006).

Zhu et al. (2009) demonstrated that ultrasound could increase the efficiency of reverse micellar extraction of defatted wheat germ protein. The extent of extraction in the first step of reverse micellar extraction (i.e., forward extraction) was increased from 37 to 57%, which led to 45.6% final protein extraction efficiency. Yaldagard et al. (2009) pointed out that ultrasound increased the extraction of α-amylase from the flour of malted barley using sodium phosphate buffer as a solvent. The efficiency of extraction was also found to increase with an increase in temperature, ultrasonic power, and sonication time. Jacques et al. (2007) pointed out that the ultrasonic treatment resulted in improved extraction of caffeine and palmitic acid from leaves of *Ilex paraguariensis*.

Extraction of flavonoids from bamboo leaves could be performed at lower temperature in combination with ultrasound, rather than using extraction at 80°C (Xu et al., 2000). However, the extraction of isoflavones from ground soybeans was increased by 15% (Rostagno et al., 2003). Kwun et al. (2009) demonstrated that the use of ultrasound improved the extraction of isoflavones from the kudzu roots waste. Moreover, the combination of ultrasound with conventional vacuum evaporation reduced the concentration time for extracts from 45 to 24 min. Khan et al. (2010) and Londoño-Londoño et al. (2010) also indicated that the use of ultrasound could enhance the extraction of polyphenols (especially flavanones) from orange peel.

Ultrasound Assisted Filtration

Application of ultrasound in conventional and membrane filtration results in agglomeration of fine particles and also the supply of sufficient vibrational energy to keep particles suspended thereby avoiding the clogging and hence leaving more free channels for liquid flow (Tarleton and Wakeman, 1997). Ultrasound assisted filtration has been demonstrated to operate more efficiently and for much longer periods without maintenance. The filtration rate of motor oil through a sandstone filter was increased by 18 times by ultrasound assisted filtration (Fairbanks and Chen, 1971). Ultrasound was found to enhance the efficiency of the continuous belt drying process or deliquoring of sewage sludge or fruit pulps. For instance, conventional filtration for dewatering of coal slurry reduced the moisture from 50 to 40%, whereas involvement of ultrasound reduced the moisture content up to 25% (Senapati, 1991).

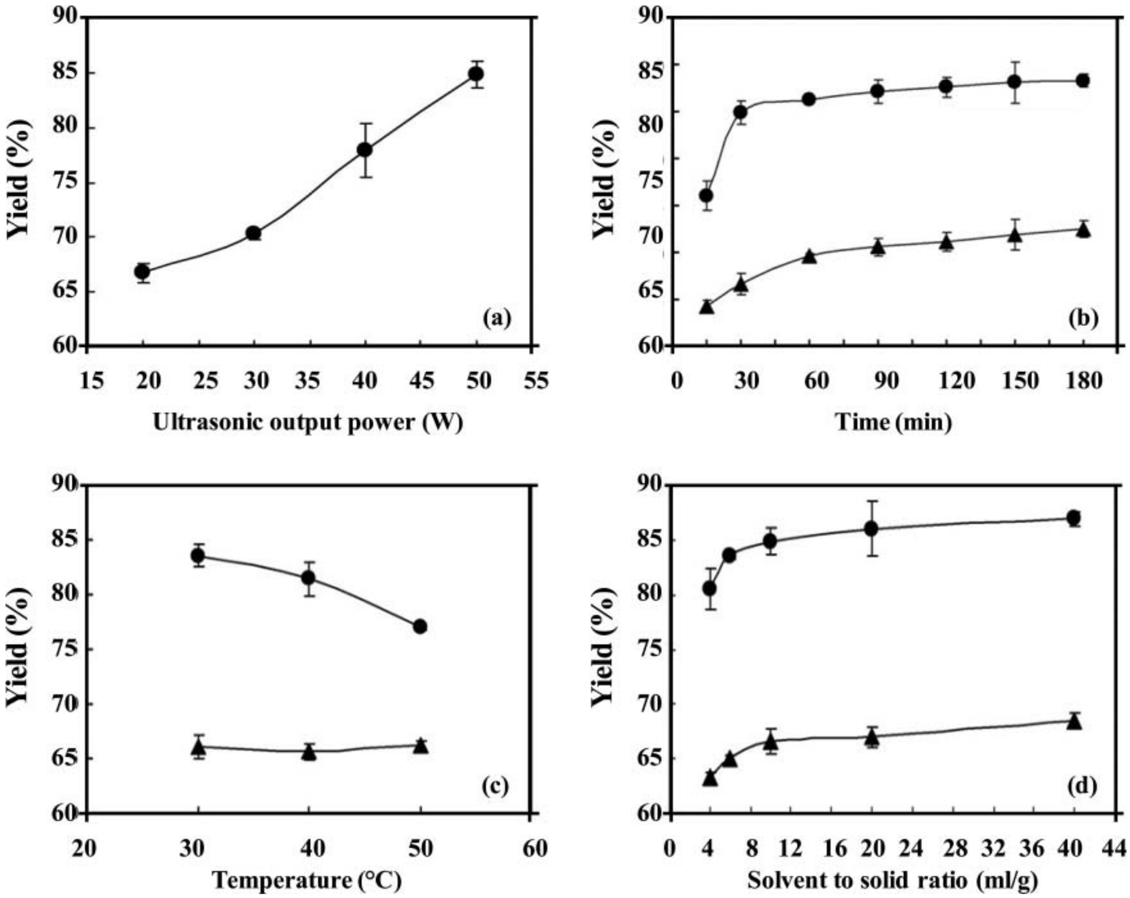

Figure 13 (a) Effect of ultrasonic output power on the yield of flaxseed oil (b) Effect of ultrasonic extraction time on the yield of flaxseed oil; (c) effect of solvent temperature on the yield of flaxseed oil; (d) Effect of solvent to solid ratio on the yield of flaxseed oil (▲ conventional solvent extraction, ● ultrasound assisted extraction) (with permission from Zhang et al. (2008) *Sep. Puri. Technol.* **62**: 192–198).

In membrane filtration, concentration polarization is a necessary evil. Application of ultrasound to membrane processes does not influence the intrinsic permeability of membranes. However, it increases the flux by breaking the concentration polarization and cake layer at the membrane surface. The liquid jet and cavitation mechanisms led to particle release from the fouled membrane (Kyllonen et al., 2005).

A comparison of ultrasonically-assisted and classical stirred dead-end ultrafiltration indicated that low frequency ultrasound can be effectively used to improve the performance of dead-end ultrafiltration. This enhancement is due to the removal of part of the boundary layer from the membrane surface. This agitation is due to convective currents as well as physical effects due to cavitation. The concentration polarization phenomenon is therefore affected by this action of ultrasonic waves (Simon et al., 2000). Cavitation always takes place when the high power ultrasonic energy is applied to a liquid. In the case of lower-power ultrasonic energy, however, the acoustic streaming and turbulence play a main role on the flux of ultrafiltration system. It was reported that the flux increases from 70 to 81 Lm^{-2} h^{-1}) under ultrasonic irradiation for 10 min with a frequency of 20 kHz and a power density of 82.9 W/cm^2 (Li et al., 2002). Kokugan et al. (1995) found that the steady state flux with ultrasonic waves (28 kHz, 240 W) is four to six times greater than that obtained without ultrasound. Tenga et al. (2006) studied the effect of ultrasound on the flux and solute rejection in cross-flow ultrafiltration of binary bovine serum albumin and lysozyme. Ultrasonic irradiation, apart from increasing the ultrafiltration flux, also increased the lysozyme rejection to some extent.

The application of ultrasound is an effective and promising approach to enhance the ultrafiltration process for natural products, and for both mechanical and chemical cleaning of fouled membranes. Sonication has also been suggested as a possible tool for cleaning membranes in the dairy industry in order to reduce the reliance on chemicals and the problems encountered in physical cleaning methods. Sonication will cause agglomeration of fine particles and supply sufficient agitation energy to the system to keep these particles partly suspended. This leaves more free channels for solvent elution. It can reach crevices that are not easily reached by conventional methods (Li et al., 2002). Cavitation phenomena produced by the ultrasonic wave may also help to displace the cake on the membrane structure (Cui and Taha, 2003; Qiao et al., 2007) which in turn promotes fouling prevention and facilitates improved separation rates (Cui and Wright, 1996; Srijaroonrat et al., 1999; Muthukumaran et al., 2004).

In a stirred dead-end ultrafiltration process, ultrasound was found to efficiently enhance the permeate flux, reduce the filtration resistances, and improve the flux recovery in fouled membrane cleaning in case of *Radix astragalus* extract as the feed solution. Low frequency and high power ultrasound is more effective in enhancing flux and improving flux recovery. Both cavitation and ultrasound induced vibration on top of the mechanical shear are the two possible mechanisms for the enhancement of permeate flux and permeability recovery by ultrasound irradiation (Cai et al., 2009).

Zhu and Liu (2000) demonstrated that ultrasonic technology can be successfully applied for the enhancement of permeate flux up to 200% in case of membrane distillation. Ultrasonic cavitation and acoustic streaming are the two major mechanisms of ultrasonic enhancement on membrane distillation. Narayan et al. (2002) demonstrated that application of ultrasound (1.2 MHz) enhanced the transmembrane flux in the range of 22–205% for the concentration of sugarcane juice using osmotic membrane distillation. The increase in flux is due to the mild circulation currents induced by ultrasound, which influences the hydrodynamic boundary layer, thereby reducing the effect of concentration polarization phenomena.

Feng et al. (2006) pointed out that on-line ultrasonic cleaning could be used to remove fouling from a polyamide based reverse osmosis membrane during cross-flow filtration of carboxyl cellulose solution. The permeate flux of the membrane increased significantly, with virtually no decrease in rejection in the presence of ultrasonication (Fig. 14), which suggested that ultrasonic defouling may be a very useful approach for the future development of reverse osmosis membranes.

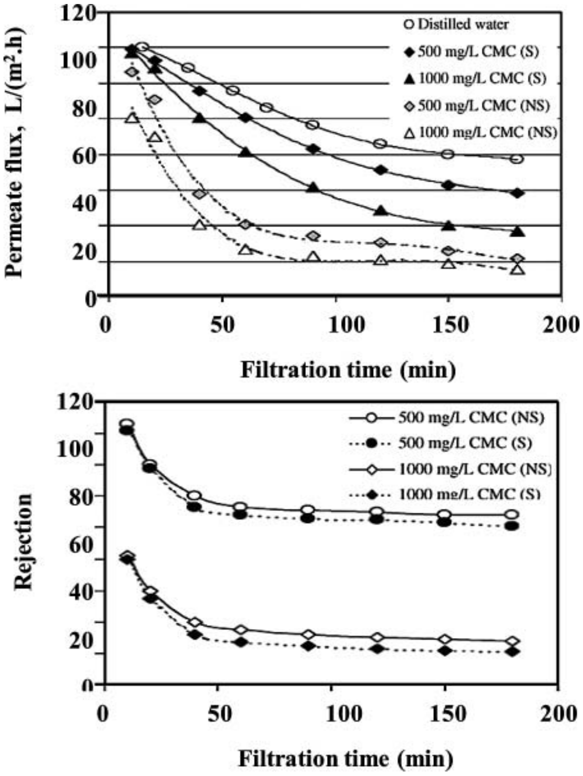

Figure 14 Effect of ultrasound treatment on the permeate flux of membrane filtration for CMC solutions. S and NS indicate sonication and no sonication, respectively. The maximum standard deviation of the observations of the permeate flux did not exceed 1.7% of the averages indicated in the figure (with permission from Haizhou et al. (2004) High intensity ultrasound-assisted extraction of oil from soybeans. *Food Res. Int.* **37**: 731–738).

Ultrasound Assisted Freezing

Ultrasound is known for assisting and/or accelerating various freezing operations of high value food and pharmaceutical products. Formation of ice crystals during freezing consists of two phases namely ice nucleation and crystal growth. It has been demonstrated that cavitation bubbles once reached the critical nucleus size can serve as nuclei for ice nucleation and increase the nucleus number (Suslick, 1988; Mason et al., 1996). Along with it, microstreaming associated with cavitation occurs when the oscillating bubbles produce a vigorous circulatory motion, thus setting up strong eddy currents (Scheba et al., 1991), which is used to enhance heat and mass transfer in freezing process at the ice/liquid interface and thus increasing freezing rate (Li and Sun, 2002; Zheng and Sun, 2005).

Fragmentation of already formed ice crystals is another phenomenon occurring due to the passage of ultrasound in a dense and incompressible medium, which resulted in fracture of ice formed on the cold surface (dendritic front), which was clearly seen to fragment ice and dispersed into the unfrozen bulk liquid (Acton and Morris, 1992).

Application of ultrasound intermittently during immersion freezing was demonstrated to result in a significant increase in freezing rate. A comparison of freezing curves for potato with ultrasound (power level of 15.85 W, 2 min) and without ultrasound indicated that the application of power ultrasound reduced the freezing time required for the product temperature to be reduced from 0 to −7°C from 8.7 min to 6.9 min (Li and Sun, 2002; Fig. 15). Moreover, fast freezing induced by power ultrasound reflects in the improvement of quality of the frozen foods. Ultrasound-assisted frozen potatoes exhibited a better cellular structure as less extracellular void and cell disruption/breakage as compared to control (Sun and Li, 2003; Fig. 16). It may be attributed to the increase in the nucleation rate in extracellular region and crystal fragmentation due to cavitation. Delgado et al. (2009) indicated that ultrasound-assisted ($0.23\ W/cm^2$, 0°C or −1°C for 120 s, with 30 s intervals) immersion freezing of apple samples enhanced the freezing rate up to 8% as compared to control, which may be induction of primary nucleation due to ultrasound.

Crystal fragmentation and microstreaming effects due to ultrasound makes it a very beneficial candidate during partial freezing of ice cream inside the scraped surface freezer. Crystal fragmentation results in the reduction of size distribution of ice crystals resulting in product with much better texture (Russell et al., 1998). Similarly, microstreaming results in the prevention of incrustation on freezing surfaces, which may result in the

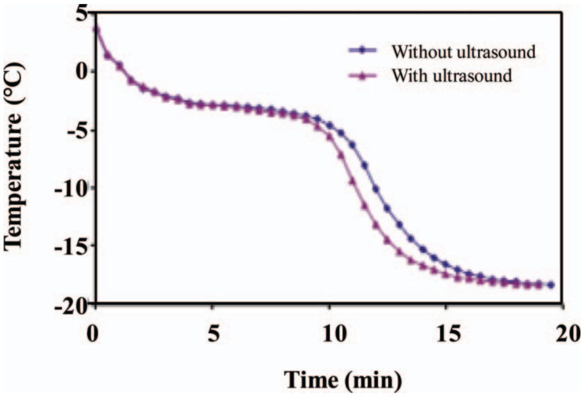

Figure 15 Influence of power ultrasound on the freezing rate during immersion freezing of potato slices (with permission from Li and Sun, 2002) *J. Food Eng*. **55**: 277–282). (color figure available online.)

requirement of mechanical scraper obsolete (Zheng and Sun, 2006).

Acton and Morris (1992) demonstrated that the exposure of sucrose solution to ultrasound at 1°C of supercooling formed a few large crystals, whereas, 5°C of supercooling resulted in smaller size crystals in large number. Application of ultrasound at low degree of supercooling results in a few nuclei unlike higher degree of supercooling, which will grow extensively in subsequent phase of crystal growth and enhance the efficiency of freeze drying or concentration processes.

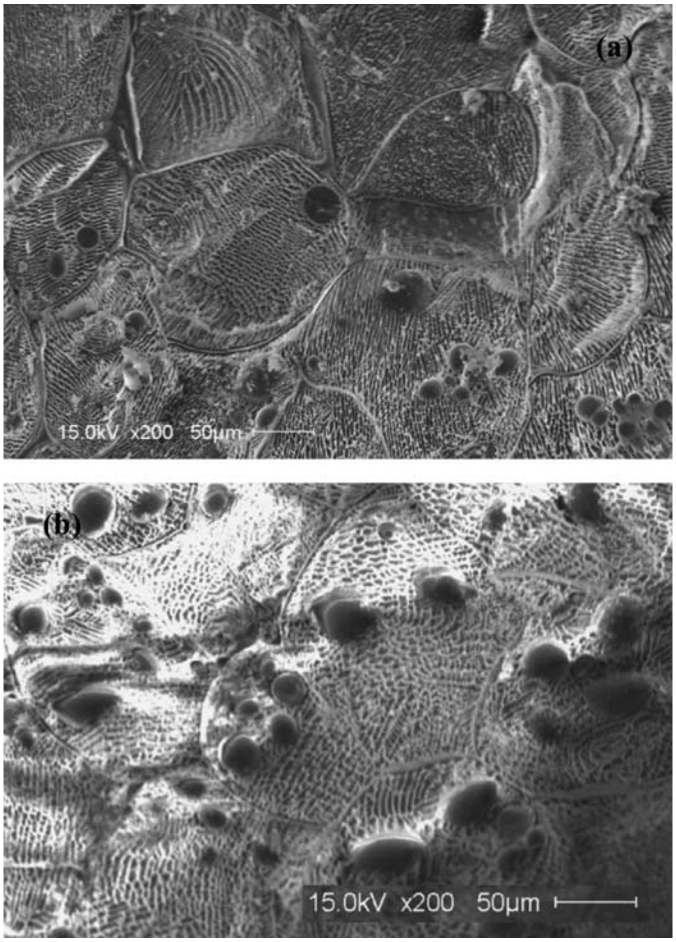

Figure 16 Cryo-SEMmicrograph for potato tissue by immersion freezing showing disruption of cells and separation of cells (a), as compared with Cryo-SEM micrograph for potato tissue by ultrasonically assisted immersion freezing under power of 15.85 W showing much better preserved microstructure (b) (with permission from Sun and Li, 2003) *J Food Eng.* **57**: 337–345).

Zheng and Sun (2005; 2006) have reviewed the application of ultrasonic waves in the freezing process and dealt in detail the initiation of ice nucleation, control of crystal size distribution, prevention of incrustation on freezing surface, improvement in product quality, as well as existing problems.

Ultrasound Assisted Detection of Foreign Bodies

Ultrasound has been shown to be a useful technique in detecting foreign bodies such as pieces of solid matter, including metal, glass, stone and plastic in foods. The technique also provides a rapid, non-destructive detection of impurities and defects in the selected food materials. Ultrasound reflection technique with an echo classifier to detect and identify foreign bodies in processed cheese, margarine and cherry marmalades. The detection of selected foreign bodies was possible in homogeneous and non-homogeneous food products at 20–75 mm and 50 mm probing depth, respectively (Haeggstrom and Luukkala, 2001). A non-contact type ultrasound imaging technique for detection of foreign objects in cheese and poultry was also developed (Cho and Irudayaraj, 2003a; 2003b).

Detection of foreign bodies such as glass fragments in a glass bottle using ultrasound poses a challenging task because the fragment may settle down or get stuck to the wall of a bottle. It may result in superimposition of the echoes from the inner surface of the bottle with the signals returned from the fragments posing a difficult situation to distinguish the signals by spectrum analysis. Several methods were reported by many researchers based on various algorithms such as the ones based on amplitude ratios between the echoes from the container's outer and inner surfaces (Zhao et al., 2004), neural networks with short time Fourier transform (Zhao et al., 2006), root mean squares method in combination with other methods (Zhao et al., 2007a), and maximum component integration based on the short-time Fourier transform algorithm (Zhao et al., 2007b). Zhao et al. (2009) adopted another algorithm based on the longitudinal (vertical) tracing of a center frequency component obtained using short time Fourier transform in conjunction with a transversal (horizontal) differentiation of the image pixels. This method is demonstrated to have improved ability to detect small glass fragments contained inside a glass bottle.

Miscellaneous Applications

Ultrasound can be used to measure a wide variety of different properties of foods. It can be used to determine particle sizes in emulsions or suspensions in a manner similar to light scattering. Thickness of materials using ultrasonic devices can also be measured in the case where it is difficult to measure using conventional techniques, for instance thickness of chocolate layers on confectionery, fat or lean tissue in meat, liquids in can and egg shells, etc. It can also be used to measure the speed at which a food material flows through a pipe. Ultrasound can be used to measure the composition of various foods such as sugar concentration of aqueous solution, salt concentration of brine, triacylglycerols in oils, droplet concentration of emulsions, alcohol content of beverages, air bubbles in aerated foods, composition of milk, ratio of fat to lean in meals, and biopolymer concentration in gels (McClements, 1995). Ultrasound in combination with image analysis was used to differentiate between fine grain bread (with small cells) and coarse grain bread (with larger cells) by measuring phase velocity and attenuation of ultrasonic waves in transmission and reflection experiments (Lagrain et al., 2006). Gómez et al., (2008) pointed out that physical properties of batters (density, viscosity, and rheology) and cakes (volume, symmetry, volume index, height, and density) were correlated with ultrasonic measurements and can be used to control the cake manufacturing process.

Ultrasound can be used to monitor these phase transitions (melting or crystallization) as the ultrasonic properties of the material change significantly during phase change. The ultrasonic velocity in solids is significantly greater than that in liquids. The variation in ultrasonic velocity during phase change helps to monitor crystallization and melting behavior in a variety of bulk and emulsified food fats, including margarine, butter, meat, and shortening.

It can be used as a means of mixing tomato ketchup or soups in industrial processes by subjecting the mixture through a narrow opening where the ultrasonic vibrations are generated. For ultrasound emulsification, increasing the energy input in sonication reduced the droplet size with minimum re-coalescence of smaller new droplets. The treatment of oil-in-water emulsions by ultrasound produces much smaller drop sizes than mechanical agitation does under the same conditions, leading to more stable emulsion (Canselier et al., 2002). The use of ultrasound resulted in a lower microcapsule size and higher aroma retention than those obtained by the mechanical mixing in case of encapsulation of liquid cheese aroma in different carbohydrate matrices by spray drying (Mongenot et al., 2000). Ultrasound in combination with the microfluidization technique resulted in emulsions with droplet size below 0.5 μm, otherwise, microfluidizer alone gave 1.0 μm droplet size (Mahdi et al., 2007)

Ultrasound was found to prevent fouling of milk in a concentric pipe heat exchanger over 2 h of heating. Reduction in fouling was due to the reduction of temperature at solid-liquid interface as well as induced movement of the depositing species (Lin and Chen, 2007). Application of ultrasound in the case of evaporation of sugar juice in a tubular evaporator markedly reduced scaling and increased cleaning speed by softening the scale layer (Lu et al., 2005).

Wambura et al. (2008) showed the feasibility of ultrasound to enhance the rice parboiling by reducing processing time. It was demonstrated that combined soaking and gelatinization of rough rice at 75°C with sonication resulted in moisture content of 48% after 3 hours, which was generally achieved in 10 hours in conventional soaking, indicating 70% time reduction due to ultrasound. The sonication also resulted in partial gelatinization after 4 hours, which was achieved at 80°C without sonication.

Challenges in Ultrasound Processing

The challenges remain prior to widespread adoption of the technology is the non-standardized reporting of methodology and control parameters. Standardized reporting in terms of energy density, probe types, and sample volumes would facilitate techno-economic assessment prior to industrial application. Still, it is required to conduct substantial research and development activities to understand, optimize, and apply this complex process to its full potential. The technology needs to be rigorously tested and proved to be safe while being commercially viable.

Most of the studies are based on the frequency of ultrasound available commercially (20 or 40 kHz). Use of different frequencies in ultrasound along with varying parameters such as temperature, treatment time, and acoustic power should be studied.

The ultrasonic technique finds its use in many applications such as monitoring the concentration of aqueous solutions and suspensions, determining droplet size and concentration in emulsions, monitoring crystallization in fats, and monitoring creaming profiles in emulsions and suspensions; in particular, for on-line determination of these properties during processing. It is a rapid, precise, non-destructive, and non-invasive technique that can be applied to a concentrated or optically opaque system. Moreover, it can easily be adapted for on-line measurements, which would prove useful for monitoring food processing operations.

The presence of small gas bubbles in a sample can attenuate ultrasound so much that sometimes an ultrasound wave cannot propagate through the sample. This problem can be overcome by taking reflection rather than transmission measurements, even though the signal from the bubbles may interfere with other components. A lot of information about the thermophysical properties such as densities, compressibilities, heat capacities, and thermal conductivities of a material is needed in order to make theoretical predictions of its ultrasonic properties. Theoretical analyses of the data from systems containing many components with unknown properties are therefore scanty.

Low intensity ultrasound is somewhat inexpensive and finds its use in the food industry. The usefulness of high-intensity ultrasound for modifying certain physical and chemical properties of foods has been realized for many years. Nevertheless, it was only very recently that manufacturers have begun to adapt laboratory-scale equipment for large-scale processing operations. The increasing use of high-intensity ultrasound depends largely on the availability of low cost instrumentation that is proven to have significant advantages over alternative technologies.

Many foods such as plant tissues, aerated foods, and some semicrystalline fats (chocolates) have a very high level of attenuation, which can make measurement extremely difficult. The use of a shorter path length may not be feasible in a real process due to cleaning, fouling, and other practical restrictions. The use of lower frequency reduces the spatial resolution. In some cases there are a number of sample variables changing simultaneously, and that will affect the ultrasonic properties. In this situation, the simple sensor may not be enough, resulting in broad and difficult to resolve peaks. If it is difficult to get very precise and uniform temperature control throughout the sample, additional errors in further measuring the property based on temperature may be introduced. The presence of air in the sample results in huge impedance mismatch between gas bubbles and other food materials, which causes reflection by air bubbles and a very strong scattering. Ultrasound can thus be used as a technique for detecting included air, which is not otherwise readily visible.

CONCLUDING REMARKS

Destruction of microorganisms and inactivation of enzymes at low or moderate temperatures without changing organoleptic and nutritional properties show that the ultrasound based technologies may have a high potential in the development of new generation value-added food processing. Even if these technologies are not likely to completely replace traditional processing methods, they can certainly complement or be integrated with the existing ones. Nevertheless, their improved physico-chemical and sensory properties imparted to foods offer emerging and exciting opportunities for the food industry. These technologies can be integrated to other unit operations such as blanching, drying, osmotic dehydration, rehydration, frying, extraction, freezing, and thawing, for improving process efficiency. New methods regrettably tend to require investments. High capital expenditure may limit their application initially, but this will be offset by higher product quality as well as by selection of appropriate economies of scale. The progress of this technology and its commercialization will further result in the reduction of equipment cost in the near future, and safe, nutritious products will be available to all consumers at an affordable cost. The results discussed in this review should provide encouragement to future scientists to begin more comprehensive research and development leading to the introduction of newer, safer, energy efficient, and economic techniques that can result in the development of industrially significant food processing unit operations.

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