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Applications of Power Ultrasound in Food Processing

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Annu. Rev. Food Sci. Technol. 2014. 5:263–84

First published online as a Review in Advance on January 9, 2014

The *Annual Review of Food Science and Technology* is online at http://food.annualreviews.org

This article's doi: 10.1146/annurev-food-030212-182537

Keywords

cavitation, inactivation, sonoreactor, food quality, acoustic power density, food component

Abstract

Acoustic energy as a form of physical energy has drawn the interests of both industry and scientific communities for its potential use as a food processing and preservation tool. Currently, most such applications deal with ultrasonic waves with relatively high intensities and acoustic power densities and are performed mostly in liquids. In this review, we briefly discuss the fundamentals of power ultrasound. We then summarize the physical and chemical effects of power ultrasound treatments based on the actions of acoustic cavitation and by looking into several ultrasound-assisted unit operations. Finally, we examine the biological effects of ultrasonication by focusing on its interactions with the miniature biological systems present in foods, i.e., microorganisms and food enzymes, as well as with selected macrobiological components.

INTRODUCTION

Ultrasound is simply a sound wave that operates above the range of human hearing. From a food processing perspective, it can be viewed as a form of high-frequency vibration that generates fluid mixing and shear forces on a microscale. The approach is fundamentally safe and can operate at low temperatures, making it an ideal adjunct to food processing. However, application can be expensive, both from a capital and energy perspective; therefore, its use must be carefully considered.

In general, ultrasonic applications in the food industry can be divided into low- and high-intensity approaches. Low-intensity approaches use small amplitude ultrasonic waves at high frequency (>1 MHz) that do not damage the material through which they propagate. These approaches are normally used for analytical applications, such as the determination of composition, structure, and physical state (McClements 1997, Monin 1998, Ghaedian et al. 1998, Hopkins et al. 2007, Kvame & Vangen 2007, Ninoles et al. 2010). The methods rely on measuring the impact of material properties on wave propagation and are not considered further here.

Conversely, high-intensity applications (also known as power ultrasound) use larger amplitude ultrasonic waves and can alter the physicochemical properties or structure of a material. Power ultrasound typically uses acoustic frequencies between 20 and 100 kHz. Higher-frequency ultrasound (300 to 500 kHz) is used to generate chemical reactions in a field referred to as sonochemistry. This approach has been considered for the enhancement of antioxidant activity (Ashokkumar et al. 2008) but is not the focus here. In this review, we cover a range of food processing operations in which power ultrasound has been considered and in many cases brought to its full commercial potential (Patist & Bates 2008).

FUNDAMENTALS

Ultrasound Generation

In most laboratory and industrial applications, ultrasound is generated by electrical energy supplied to a piezoelectric material referred to as a transducer. These ceramic materials convert the electrical energy into a mechanical vibration of a particular frequency. The amount of energy dissipated is a function of how far the transducer moves up or down in each half cycle [the amplitude (A)] and the frequency (f). Specifically,

$$\text{Energy dissipated} = kf^2A^2, \tag{1}$$

where k is a constant that is a product of the resistive dissipation constant, the inertia of a general oscillator, and other values (Leighton 1994). The transducer is bonded to a surface that can transmit this vibration through the fluid. The energy transferred to the solution, although inducing mechanical effects, is ultimately lost as heat. Thus, ultrasonic processing usually results in a temperature increase, unless cooling is provided. A similar pressure wave can be generated mechanically, for instance by passing fluid through a constriction such as an orifice plate (Pandit et al. 1999, Gogate 2011) and indeed ultrasonic phenomena are often observed in high-pressure homogenizers (Freudig et al. 2002). Ultrasonic jet homogenizers use an alternate approach, where the fluid impact on a sharp blade downstream of the homogenizer orifice creates the acoustic field (Huppertz 2011).

In the laboratory, two types of ultrasonic devices are generally employed. In an ultrasonic horn (**Figure 1*a***), a single transducer is placed within a titanium cylinder, which results in an intense acoustic field in the region immediately below the device, with a vibration amplitude of approximately 100 μm (Hunter et al. 2008). An ultrasonic horn can have a very high energy intensity directly below the device, but this intensity drops off significantly away from the device.

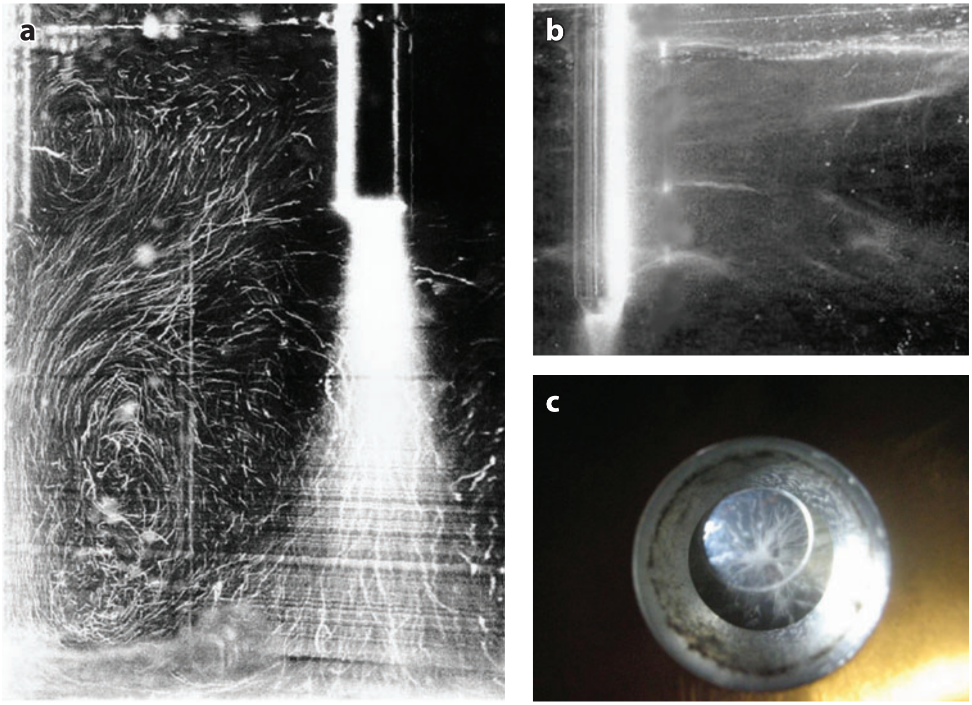

Figure 1

Acoustic streaming and bubble fields induced by a (*a*) standard ultrasonic horn and a (*b*) radial horn. The bubble field induced by a ring transducer is shown in panel *c*. Panels *a* and *b* reprinted from Dahlem et al. (1999) with permission from Elsevier; panel *c* reprinted from Hunter et al. (2008) with permission from Elsevier.

Conversely, an ultrasonic bath delivers more diffuse acoustic energy through a distribution of several transducers spread across the base of the bath. These systems generally provide much lower energy intensity.

Ultrasonic horns can also be used in industrial applications, with systems of up to 16 kW available (**http://www.hielscher.com**). However, in such applications, other devices such as radial horns (Dahlem et al. 1999, Zisu et al. 2010) can provide greater efficiency (**Figure 1*b***). Ring transducers (Faïd et al. 1998, Montalbo-Lomboy et al. 2010, Xu et al. 2011) and radial arrays of transducers (Hodnett et al. 2007, Memoli et al. 2012) can also generate an acoustic field that is focused at the center of a pipe (Ruecroft 2007, Hunter et al. 2008) (**Figure 1*c***). This approach provides a more even acoustic field, with comparable power densities to a standard horn on a volumetric basis (W/cm^3) but with much lower intensities immediately adjacent to the pipe surface (W/cm^2). For example, Hunter et al. (2008) show that for an identical applied power of 400 W and a power density of 12.6 W/cm^3, a standard horn will provide an intensity of 300 W/cm^2 immediately below the probe, whereas a ring transducer provides only 9 W/cm^2 at the pipe surface. This approach can be a disadvantage in applications where a high intensity is required but is of great advantage if the local intensity is less important than the total acoustic energy input. This approach also ensures that metal abrasion of the transducer surface is reduced (Hunter et al. 2008), which can be important in food processing applications. As such, the ultrasonic device must be carefully selected through the coupled use of both acoustic and hydrodynamic modeling (Dahlem et al. 1998).

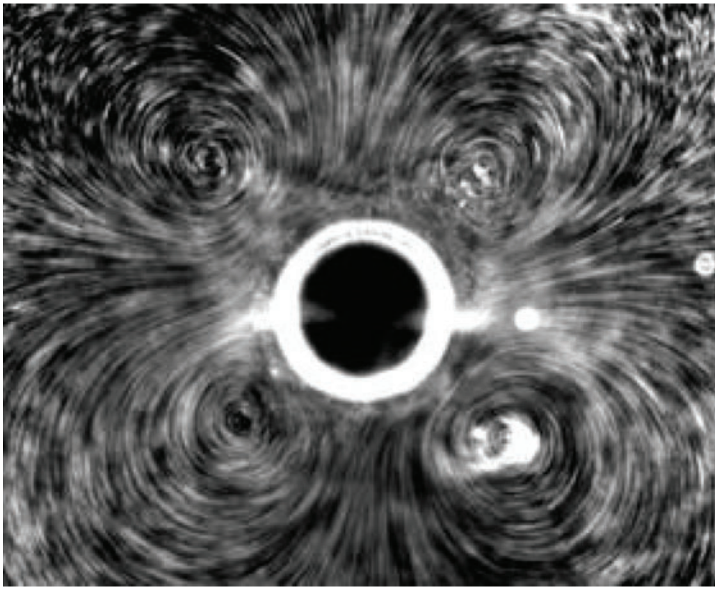

Figure 2

Acoustic streaming around a stationary 181-μm-radius bubble in an acoustic field at 4 kHz. Figure reproduced with permission from Tho et al. (2007).

Cavitation

Ultrasound can generate fluid mixing and shear forces through several effects. Primarily, a sound wave is a wave of low- and high-pressure regions moving through a liquid. The rapid changes in pressure cause fluid motion referred to as acoustic streaming (**Figure 2**). However, cavitation is usually of greater importance in food processing applications. This is the formation of small bubbles at the points of low pressure in the sound wave. These form because the liquid medium is incompressible and cannot readily accommodate the rapid changes in system pressure. The sizes of cavitation bubbles are determined by ultrasound frequency, and a cavitation liquid can contain many thousands of such bubbles. The bubble size can be roughly estimated by the following formula:

$$F \cdot R = 3, \tag{2}$$

where F is the frequency in MHz, and R is the bubble radius in microns (Leighton 1994).

Once formed, these bubbles can undergo coalescence and breakage events that add to the general level of fluid mixing. They will also tend to move toward the nodes and antinodes of the acoustic field, through effects referred to as Bjerknes forces (Leighton 1994). Such bubble movement is also often referred to as acoustic microstreaming. The bubbles can also slowly grow through a process referred to as rectified diffusion.

Most importantly, once these bubbles reach a certain size range, often referred to as the resonance frequency, they will collapse, often violently. This dramatic collapse is referred to as cavitational collapse and is the major mechanism for the generation of shear forces within the fluid. Each collapse event can be considered a microscale implosion event of some magnitude. Indeed, it is estimated that temperatures of 2,000–5,000 K (Suslick et al. 1999) and pressures of 300–1,200 bar (Sehgal et al. 1979, Kazachek & Gordeychuk 2009) can be generated within an implosion event. Many food technologists and engineers will be familiar with similar shear

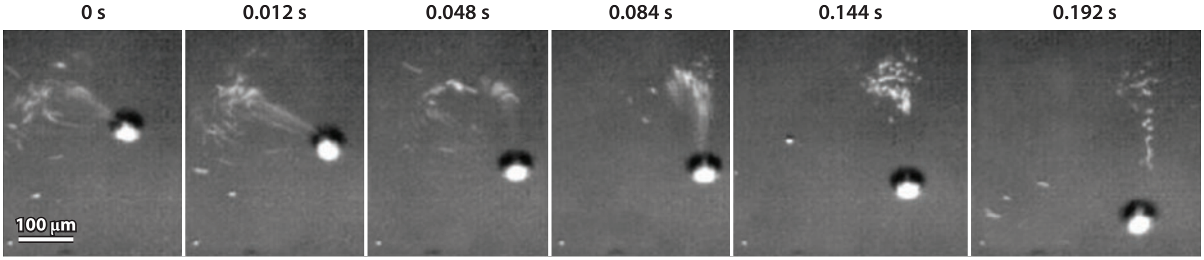

Figure 3

The release of a fountain of microbubbles as a microjet from a bubble in water within the confined space of a 60-kHz sound field. Reprinted from Lee et al. (2007) with permission from the American Chemical Society.

forces in the context of hydrodynamic cavitation, which damages pump impellers through similar pressure fluctuations. Bubbles can implode in a destructive manner, disintegrating into a cluster of daughter droplets, or they can undergo a sequence of repetitive implosions. When a bubble implodes near a surface, it can also generate a microjet of fluid that can have a scouring effect, which is highly relevant to surface cleaning applications (**Figure 3**).

The effectiveness of the ultrasound is strongly dependent on the nature of the field generated (see section below) but is also influenced by the acoustic frequency and the temperature and pressure applied. Lower frequencies generate larger bubbles and thus a more violent cavitational collapse with higher localized temperatures and pressures. However, as frequency is increased, there are more collapse events per unit time, and this can provide a more uniform, albeit less intense, acoustic field. Fluid properties such as density and viscosity, the vapor pressure of the liquid, and the presence of surfactants have also been shown to impact the extent and violence of the cavitation (Ashokkumar et al. 2007, Leong et al. 2011).

Care must be taken in the selection of an appropriate acoustic energy or amplitude. Although there is usually a tendency to believe that adding more energy is better, this is not always the case. If too much energy is applied within a high-intensity field such as that provided beneath an ultrasonic horn, then a stagnant cloud of bubbles can form that shields the transmission of further acoustic energy. In this instance, a decline in process efficiency can be observed (Kentish et al. 2008). Similarly, prolonged use of an ultrasonic horn can lead to pitting of the sonicating surface that reduces the amplitude that can be obtained. In this case, the horn should be removed and polished to restore the original surface.

In industrial applications, the ultrasound is often applied with a moderate positive pressure (overpressure or backpressure) over the sonicating fluid. Increasing the external pressure increases the cavitation threshold, and hence fewer bubbles are formed; however, the collapse of these bubbles is more violent, and this approach can be more effective in generating high shear fields (Henglein & Gutierrez 1993, Sauter et al. 2008). Similarly, increasing the processing temperature results in a greater vapor pressure within each bubble, which cushions the collapse event, but more bubbles are formed. Indeed as the boiling point of the liquid is approached, massive numbers of bubbles can be generated.

Sonoreactors

Most power ultrasound treatments involve passing ultrasonic waves through a liquid medium, often water or a liquid food, to perform the task. A container or treatment chamber is used to confine the liquid and allow the ultrasound to interact with the food being processed. Such a treatment vessel is often called a sonoreactor. Traditionally, there are two types, i.e., probe system and ultrasonic bath, depending on the average sound intensity (W/cm^2) of the ultrasound emitting surface(s) and the mean acoustic energy delivered into the liquid medium. The probe-type sonoreactors feature a high sound intensity (W/cm^2) at the probe surface and a high acoustic power density (APD) (W/m^3) in the reactor. The probe is often in direct contact with the food. Processes that require a high energy input, such as cell rupturing, extraction, enzyme inactivation, etc., are often performed with a probe or a radial horn. Tank-type ultrasound treatment devices have a lower sound intensity and APD, due to the larger volume of the liquid in the chamber, as well as the large surface area that emits the ultrasound. Ultrasonic baths often find application in surface cleaning, sonocrystallization, freezing and other applications that need a relatively low APD.

To overcome problems associated with the traditional sonoreactors, several new reactor designs have been proposed. For instance, probe systems often leave metal ions and particles from the probe in the treated food. In an effort to eliminate such contamination, Freitas et al. (2006) introduced a noncontact process. The liquid product was kept free from contamination by holding it in a glass tube and placing it in a sonoreactor chamber. Dion (2011) also designed a contamination-free sonoreactor that utilized a relatively large-volume confined acoustic cavitation zone, away from the inner wall of a tubular reactor so as to avoid surface erosion due to cavitation. Due to the nature of waves, acoustic field distribution in an ultrasound treatment chamber is not uniform. This may be less of a concern for certain treatments, especially for probe-type systems. However, a standing wave formation and the resulting nonuniform field are undesirable for many ultrasonic bath applications. Variable frequency technology may provide a feasible means to improve acoustic field distribution (Prokic 2011). It also helps to increase cavitation activity.

PHYSICAL AND CHEMICAL IMPACTS OF POWER ULTRASOUND

Ultrasonic Cutting

Ultrasonic cutting or ultrasound-assisted cutting is a size-reduction unit operation utilizing the vibrational energy of ultrasound that superposes with a conventional blade movement to improve cutting quality. An ultrasonic cutting machine is composed of an ultrasonic transducer, horn, cutting knife (tool head), and power supply (Schneider et al. 2011). A traditional food-cutting process with a sharp blade includes several phases, i.e., deformation, separation, and detaching of the food to be cut. In ultrasonic cutting, due to the high-frequency vibration of the cutting blade, the food and cutter experience alternating contact and separation, resulting in a high deformation rate but small deformation, reduced total cutting force, avoidance of transversal cracks and crumbling, and reduction of cutting surface roughness (Schneider et al. 2002). During cutting, the energy of the ultrasound also heats and even partially melts the material.

By not requiring a sharp blade edge or the application of a lot of pressure, an ultrasonic cutter minimizes broken edges and damaged material. Due to the vibration of the cutter, friction is reduced and the material does not stick to the blade, making it particularly effective for cutting viscoelastic and viscoplastic foods. It is also good for fragile and frozen foods, heterogeneous products (cakes, pastry, and bakery products), and products that cannot be cut by a pressing force (Arnold et al. 2009). Moreover, it is especially useful when cutting foods containing particles with a stiffness and elasticity different from the surrounding bulk, as well as foods with layers having different mechanical properties (Arnold et al. 2011). The quality of the food cutting by an ultrasonic cutter is affected by the geometry of the blade, the direction of vibration of the knife relative to the movement of the food, and the frequency and amplitude of the ultrasound (Arnold et al. 2011).

Viscosity Modification

The shear forces induced by acoustic cavitation have proved highly effective in reducing the viscosity of a range of food products (Karaman et al. 2012). This viscosity reduction can occur either through the disruption of aggregates, through the disruption of hydrophobic interactions, or by a reduction in polymer chain length (Szent-Györgyi 1933). For example, ultrasound has been effectively used to reduce the polymer chain length of polysaccharides (Iida et al. 2008) such as dextran (Lorimer et al. 1995) and pectin (Seshadri et al. 2003). Ultrasound can also facilitate the dissolution of starch granules, which in turn can improve the gelatinization process (Zuo et al. 2009, Jambrak et al. 2010).

Ashokkumar and coworkers (Ashokkumar et al. 2009, Chandrapala et al. 2011, Zisu et al. 2011) have shown that the viscosity of dairy fluids can be reduced through the disruption of whey protein aggregates by simple shear. For example, in a pilot scale trial, a whey protein retentate solution of 33 wt% total solids was sonicated at 20 kHz using a 4-kW unit at an energy density of 260 J/ml. The average protein aggregate size reduced from 0.75 to 0.35 μm, while the viscosity fell from 64 to 43 centipoise (Zisu et al. 2010). Conversely, at higher energy densities, others find that protein aggregation can be exacerbated (Stathopulos et al. 2004, Gülseren et al. 2007) and viscosity can increase (Kresic et al. 2008). These effects are thought to stem from the disruption of the native conformation of the proteins that exposes hydrophobic residues that are more likely to associate with other proteins (Chandrapala et al. 2011). Similarly, the strength of dairy gels formed with sonication is enhanced (Zisu et al. 2011).

Of particular interest in this respect is the use of ultrasound on whey containing solutions downstream of a heat treatment step. The ultrasound disrupts aggregates formed during the thermal treatment, and these cannot reform. Thus, the process provides a heat-stable dairy powder or fluid, which can be of great importance in downstream food manufacturing (Ashokkumar et al. 2009).

In a similar manner, Anese et al. (2013) have shown that ultrasound can disrupt tomato cell structure and decrease the degree of pectin esterification. This leads to an increase in gel-like properties due to hydrogen bonding and hydrophobic interactions among the de-esterified pectin molecules.

Emulsification

Power ultrasound can be effective in the formation of an emulsion through two mechanisms. Firstly, the acoustic field produces interfacial waves between the oil and liquid phases that can become unstable, resulting in the formation of large oil droplets in the aqueous phase (Li & Fogler 1978). Secondly, the shear forces can be effective in breaking up these large droplets of oil to form smaller droplets (Li & Fogler 1978). Ultimately, the minimum droplet size that can be achieved within the emulsion is a function of the surfactant used and the surfactant-to-oil ratio (Rao & McClements 2011), as this determines the interfacial energy between the two phases. However, ultrasound can be an effective alternative to homogenization and microfluidization in achieving this objective with minimal energy input. In particular, Leong et al. (2009) showed that the use of a slight overpressure resulted in smaller droplet sizes for an equivalent energy input (**Figure 4**). Ultrasound can also be more effective as the crevices and confined spaces that are necessary elements of homogenizers and microfluidizers are avoided, allowing a sanitary environment to be more readily achieved.

If the emulsion droplet size can be reduced to below 50 nm, then the droplets become invisible to the naked eye, resulting in a translucent liquid. This approach can be important when oil-soluble nutraceuticals or vitamins need to be added into an aqueous phase product such as a sports drink. Small droplet sizes can lead to improved mouthfeel and product texture; additionally, such

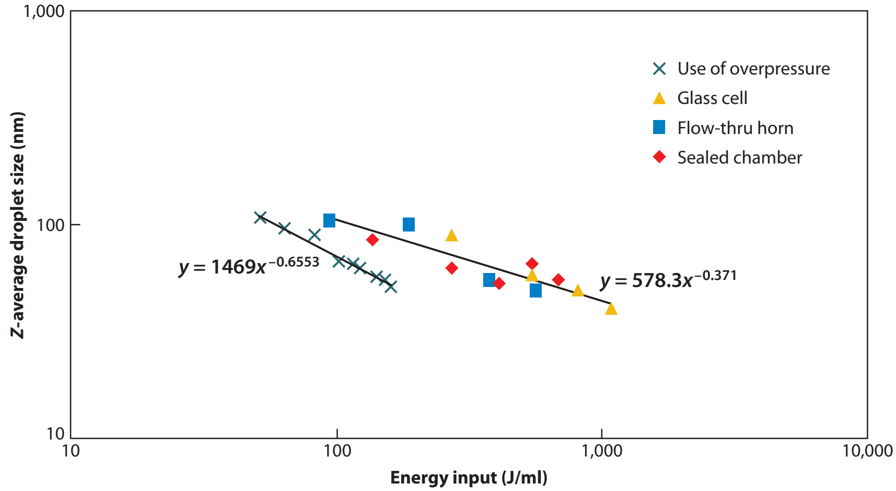

Figure 4

Emulsion droplet size achieved from sonication using a range of laboratory devices across a range of specific energy inputs. The emulsion was formed from a mixture of 5.6 wt% sodium dodecyl sulphate and 13.6 wt% polyethylene glycol in a 15-wt% sunflower oil/water emulsion. The lines and equations represent linear regression of the data for atmospheric pressure experiments and those with overpressure. Reprinted from Leong et al. (2009) with permission from Elsevier.

nanoemulsions are more stable and tend less toward Ostwald ripening or gravitational separation (McClements 2011, Silva et al. 2012). Recent studies on the use of ultrasound to generate such food nanoemulsions include the emulsification of D-limonene in water using sorbitan trioleate and polyoxyethylene (20) oleyl ether surfactants (Li & Chiang 2012) and of lemon oil in water using Tween 80 surfactant (Rao & McClements 2011). Heffernan et al. (2011) showed that ultrasound was effective in generating cream liqueurs with droplet sizes of 81–94 nm that were shelf stable. However, a liqueur with fat droplets smaller than this (75 nm) separated upon shelf storage. It was argued that this occurred due to overprocessing, so that gaps appeared in the interfacial protein membrane (Heffernan et al. 2011). Zahid et al. (2012) have also shown that chitosan-loaded nanoemulsions generated using ultrasound can be more effective than conventional chitosan in combating fungal infections in tropical fruit.

In a contrary approach, ultrasound can also be used to break emulsions and enhance the separation of an oil and aqueous phase. Through the use of Bjerknes forces (Nii et al. 2009), oil and fat globules can be made to aggregate, which facilitates their coalescence and separation from an aqueous solution. Enhanced ultrasonic separation of milk fat (Juliano et al. 2011, 2013), canola oil (Nii et al. 2009) and palm oil (Juliano et al. 2013) has been reported using this approach.

Nebulization

Nebulization differs from the other applications described here, in that it generally operates at higher frequencies, in excess of 1 MHz, rather than in the power ultrasound range. When such an acoustic field is applied to a shallow liquid film, a series of interfacial waves are generated at the surface. Small droplets pinch off from these waves, generating a very fine mist or aerosol. For a frequency of 1 MHz, the droplet size is typically 3 to 4 μm (Jimmy et al. 2008). More generally, Lang (1962) has shown that the size of the droplets formed in ultrasonic nebulization is related to the ultrasonic frequency (f, in Hz) through

$$d_n = 0.34 \left(\frac{8\pi\gamma}{\rho f^2} \right)^{1/3}, \tag{3}$$

where d_n is the number mean diameter in meters, γ is the surface tension of the liquid in kg/m^2, and ρ is the density of the liquid in kg/m^3.

Such acoustic nebulization is the standard method used in medical nebulizers to deliver a range of aerosol drugs such as in asthma treatment. More recently, the approach has been considered for the concentration of surface-active species (Jimmy et al. 2008, Suzuki et al. 2006). Such species will accumulate at an interface. In the fine mists generated by nebulization, the interfacial area is extended several hundred fold, and hence these mists contain much greater concentrations of such surface-active species than the original bulk solution (Rassokhin 1998). Research in this field has specifically focused on the concentration of ethanol for rice wine production (Sato et al. 2001; Nii et al. 2006; Suzuki et al. 2006, 2012). A fivefold increase in the enrichment of ethanol has been observed (Nii et al. 2006). Further, it has been argued that this approach requires lower energy, as there is no need to provide the latent heat associated with distillation processes. A greater enhancement in ethanol concentration is also claimed, relative to such distillation (Nii et al. 2006).

An interesting potential application of ultrasonic nebulization is for the fumigation of fresh food produce (Vardar et al. 2012) and the sanitization of food service equipment (Kritzler & Sava 1999). In this case, a disinfectant such as a hydrogen peroxide solution is atomized, either by an ultrasonic nozzle [which operates at a lower frequency (25–125 kHz) and produces droplets of 20 to 100 μm] or by nebulization. The fine aerosol that is generated can penetrate small cavities and crevices and as such provides effective disinfection. The volume of the disinfectant solution is substantially reduced relative to liquid phase disinfection, and the exposure of workers to the solution can be minimized.

Sonocrystallization and Freezing

Power ultrasound has been shown to enhance the nucleation of crystals from solution. The extent of the metastable zone is reduced so that nucleation can occur faster (Li et al. 2006), at lower solids concentrations (Bund & Pandit 2006) and/or higher temperatures (Chow et al. 2003), or without the need for the addition of seeding agents (Genck & Bayard 2001, Patel & Murthy 2012) or antisolvents (Ruecroft et al. 2005). The reasons for these changes are still subject to debate. They are generally understood to occur because the cavitation bubble provides a heterogeneous surface for nucleation (Wohlgemuth et al. 2009). However, others argue that nucleation is induced by the rapid local cooling rates (10^7–10^{10} K/s) that occur following a cavitation event, the high local pressure that occurs during bubble implosion (Hickling 1965), or the cavitation events overcoming the excitation energy barriers associated with nucleation (Luque de Castro & Priego-Capote 2007). However, Arends et al. (2003) have shown that such changes can occur in the absence of transient cavitation, which conflicts with these arguments.

The sizes of the crystals produced through sonication are generally smaller, and the agglomeration of the newly formed crystals is also reduced (Ruecroft et al. 2005). The crystal morphology is also often altered (Ruecroft et al. 2005). These size and morphology effects can be related to the shear forces associated with ultrasound that act to slow growth processes (Nalajala & Moholkar 2011) and to break up nascent agglomerates (Ratsimba et al. 1999). An additional advantage of a sonocrystallization approach is that the cleaning action of the ultrasound also helps to remove crystals from the heat transfer surfaces of the crystallization vessel as they form, thus enhancing the heat transfer efficiency of the process (Mason 2007).

This approach has been considered for the crystallization of lactose from whey solutions. A lactose recovery of 92% was obtained in 5 min of sonication time from a reconstituted lactose solution of 17.5 w/v% versus 15% using conventional stirring (Bund & Pandit 2006). Authors have also shown the approach to be effective in the nucleation of ice crystals (Chow et al. 2005), thus implying that the freezing process can be improved. This approach has been used to accelerate immersion freezing of potato cubes (Comandini et al. 2013) and to increase cell viability after the freezing of lactic acid bacteria (Kiani et al. 2013). However, the application of this approach to the making of ice cream has been less successful. This is because sonication acts to remove air from the solution, through the coalescence and subsequent degassing of cavitation bubbles. A good ice cream is one in which the air content is maximized, and hence ultrasonically induced ice creams lack the texture and sensory feel of a traditional product.

Another application of interest in food processing is the use of ultrasound to enhance the crystallization of fat (**Figure 5**). Power ultrasound decreases the induction time for crystallization to occur (Higaki et al. 2001) and provides smaller crystals (Martini et al. 2008). The smaller crystals

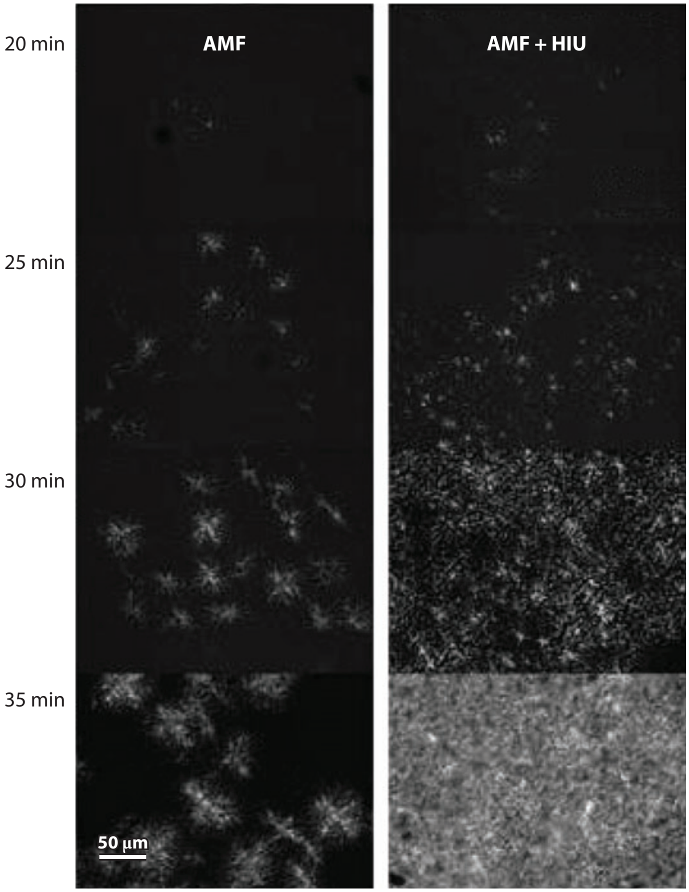

Figure 5

The microstructure of anhydrous milk fat (AMF) crystals formed at 26°C in the absence and presence of high-intensity ultrasound (HIU). The ultrasound caused crystals to form earlier and the crystal size to be smaller. Reprinted from Martini et al. (2008) with kind permission from Springer Science and Business Media.

can lead to modified physicochemical properties such as melting behavior, which can be useful for the development of ingredients that are free of trans-fatty acids (Suzuki et al. 2010). A more stable polymorph can be crystallized (Ueno et al. 2003) that can be useful in reducing fat bloom during chocolate manufacturing (Baxter et al. 1997). As discussed above, Arends et al. (2003) have shown that such fat crystallization can be induced by low-intensity ultrasound in the absence of transient cavitation. The use of lower-intensity sonication eliminates the off flavors that are often noticed when higher-intensity ultrasound is employed (Arends et al. 2003).

Surface Cleaning

Ultrasound-assisted surface cleaning is one of the most widespread applications of ultrasound, having been used for decades in industries such as aerospace, aircraft, and jewelry and in surgical, optical, and electronic equipment (Gale & Busnaina 1995). Ultrasonic cleaning utilizes sonic agitation of the cleaning liquid at a selected frequency between 20 and 200 kHz to remove particles and contaminants from product surfaces. Megasonic cleaning (above 800 kHz) has also been developed for the removal of nanoparticle contaminants from delicate surfaces such as semiconductor wafers and integrated circuit assemblies. Target particles may include microorganisms attached to food surfaces. For the removal of foodborne pathogens from a product surface, the process is also termed surface decontamination.

Ultrasonic cleaning is performed in a cleaning tank or bath. From piezoelectric transducers mounted on the bottom of the tank, longitudinal ultrasonic waves are transmitted through the water. A sanitizer or detergent is often added to aid in the cleaning process. Several cleaning mechanisms have been proposed in the literature, and most of them are related to acoustic cavitation and the physical events in water triggered by cavitation: The implosion of cavitating bubbles creates shock waves, water jets, and microstreaming. High-speed water jets are formed when a bubble implodes near a solid surface, impinging on the surface of the solid and helping to remove contaminants. Microstreaming refers to swift currents, as fast as 0.6 m/s, generated around cavitating bubbles. The shear forces generated by microstreaming also dislodge particles from solid surfaces. Acoustic streaming is produced by a bulk movement of the liquid and is another principal mechanism in ultrasonic cleaning (Awad 2011). Acoustic streaming in the boundary layer, also known as Schlichting streaming, is of importance for the removal of particles from surfaces. The acoustic streaming carries away the loose particles, preventing them from reattaching to the surface (Awad & Nagarajan 2010). Mass transport to the boundary layer is also enhanced by acoustic streaming, a process that helps the sanitizer penetrate the stagnant boundary layer. It has also been reported that streaming exerts steady viscous stresses on surfaces, helping to remove surface layers (Gale & Busnaina 1995). In an ultrasonic cleaning process, cavitation and acoustic streaming work together, but the relative contribution of each is a function of frequency (Awad & Nagarajan 2010). At lower frequencies, cavitation dominates the cleaning process, whereas at higher frequencies, especially when the time between sonic pulses is too short for the formation of cavitation bubbles, acoustic streaming does.

The applications of ultrasonic cleaning in the food industry include the removal of chemical deposits such as scaling and fouling from equipment surfaces, as well as biological deposits such as biofilms on food surfaces. In membrane separation processes, fouling is a hurdle limiting the flux and performance of the membrane operation. Ultrasound irradiation (sonication) can be an effective membrane cleaning method, although the energy density must be limited to ensure that membrane life is not reduced and that the energy cost is not too high. Cavitation and acoustic streaming produced by sonication provide vigorous mixing that breaks concentration polarization and caked-on layers on membrane surfaces (Kyllonen et al. 2005). Ultrasonic pulses can also break absorbed foulants and dislodge bacterial biofilm on membrane surfaces. Parameters such as ultrasound frequency, APD, feed properties, membrane materials, cross-flow velocity, temperature, and pressure need to be optimized to achieve the best effects (Muthukumaran et al. 2005).

Baumann et al. (2009) reported a combination treatment of ultrasound and ozone to remove a *Listeria monocytogenes* biofilm from stainless steel chips. With a 0.5-ppm ozone addition, an ultrasound treatment (20 kHz, 0.4 W/ml) for 60 s at room temperature completely removed the *L. monocytogenes* biofilm. Ultrasound has also been employed in the cleaning of wine barrels to remove tartrates and residual solids and to disinfect the barrels by removing the spoilage-causing yeast *Brettanomyces/Dekkera*. The ultrasonic approach was reported to yield a much greater reduction in cell numbers compared to traditional methods, providing considerable cost savings (Yap et al. 2008). Surface decontamination of food products with power ultrasound has been investigated in recent years in efforts to disinfect poultry (Lillard 1994), fresh produce (Ajlouni et al. 2006, Zhou et al. 2009), and vegetable seeds (Scouten & Beuchat 2002, Kim et al. 2006). Ultrasound combined with chlorine has been used to sanitize in-field coring knives that could serve as a vehicle for the transmission of pathogens to lettuce heads (Zhou et al. 2012b). The ultrasound treatment reduced *Escherichia coli* O157:H7 survival counts to below the detection limit on both the blade and welding joint by a 30-s treatment when the chlorine concentration was as low as 1 ppm. Zhou et al. (2012a) developed and tested a pilot scale continuous-flow ultrasonic produce washer. With a relatively uniform acoustic field distribution in the ultrasonic washing channel, an ultrasound treatment achieved 1.0 and 0.5 log CFU/g additional reductions of *E. coli* cells inoculated on spinach for single-leaf and batch-leaf washes, respectively, relative to the chlorine-alone wash.

Foaming and Defoaming

The cavitation bubbles formed during sonication are themselves never of sufficient number to form a foam. However, sonication has been used to form foams by placing the sonication horn at the air-fluid interface. In this approach, air bubbles are entrained in the mixture as sonication proceeds. This approach has been used to generate aerated gelatin and β-lactoglobulin gels for food applications (Zuniga et al. 2011). The use of this approach in protein solutions can also lead to the formation of stable air-filled microcapsules, as the protein is cross-linked under the influence of the acoustic field (Suslick et al. 1994). This approach has been successfully commercialized for the production of ultrasound contrast agents used in medical imaging. However, it has also been proposed as a mechanism to encapsulate volatile aromas and flavors (Vilkhu et al. 2008) within food matrices. The placement of the horn at a liquid-liquid interface, rather than an air-liquid interface can also provide liquid-filled microspheres (Suslick & Grinstaff 1990) that might similarly be used to encapsulate oil-based ingredients within an aqueous food matrix.

Sonication can also be effective when used in conjunction with traditional foam-generation techniques such as air sparging. The foam cell size produced by the sparger is reduced by the shear effects of ultrasound resulting in finer foam that is less susceptible to Ostwald ripening (Lim & Barigou 2005a,b). This approach can be used directly to change the texture and structure of food ingredients. However, it can also be useful in enhancing the separation of surface-active species such as proteins in a foam fractionation approach (Vo et al. 2011).

Somewhat counterintuitively, airborne ultrasound has also been shown to be highly effective in reducing the extent of foaming (Dedhia et al. 2004, Riera et al. 2006). The use of ultrasound in a gaseous medium is generally avoided as the power attenuates very quickly so that the effects are usually small. However, the use of a powerful ultrasonic transducer in the air space directly above a foaming solution has been shown to be effective in destroying the foam (Riera et al. 2006) (**Figure 6**). This may be due to a partial vacuum on the foam bubble surface being generated

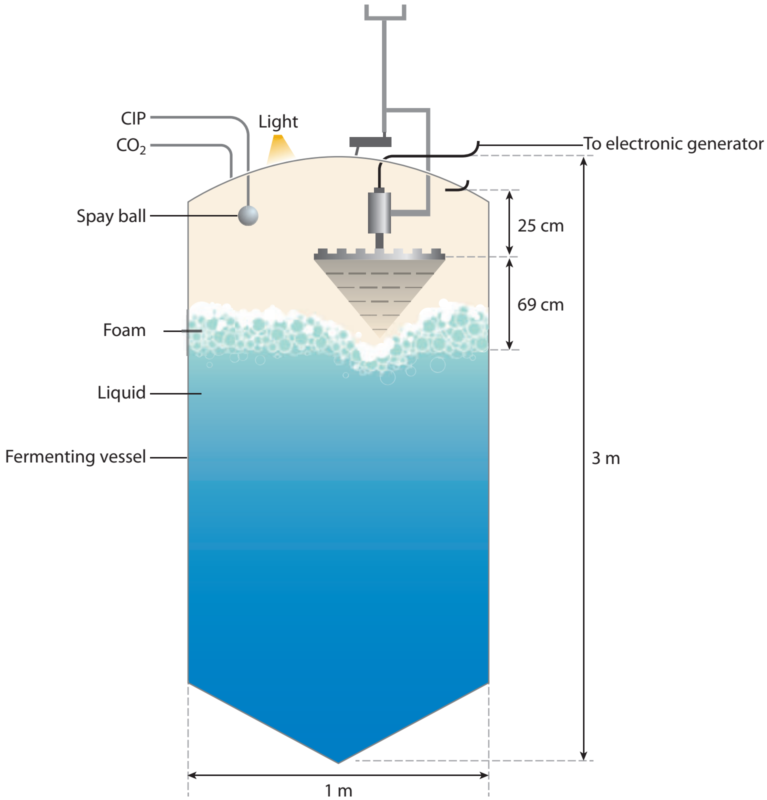

Figure 6

A schematic of the use of a high-intensity focused ultrasonic defoamer in a process vessel to reduce foam height. Abbreviation: CIP, clean in place. Reprinted from Riera et al. (2006) with permission from Elsevier.

by the high acoustic pressure, the impingement of radiation pressure on the bubble surface, the resonance of the foam bubbles that create interstitial friction causing bubble coalescence, cavitation, atomizing from the liquid film surface, and/or acoustic streaming (Boucher & Weiner 1963, Gallego-Juárez 1999). This approach has many applications in the food industry where such foams can occupy valuable volumes in process vessels and restrict the filling rate on bottling lines.

INTERACTION OF POWER ULTRASOUND WITH BIOLOGICAL SYSTEMS

Effects of Ultrasound on Microorganisms

The interaction between acoustic energy and microorganisms is complicated. Ultrasound can either increase or decrease microbial activity. In most cases, ultrasound is used as a processing aid to inactivate microbes for the purpose of securing food safety. Relatively high APDs are required to do this. Another application is in the area of fermentation or biotransformation, where the purpose is to enhance microbial proliferation and thus increase product yield. The APD requirement for this function is lower than that needed to inactivate the organisms. The focus of this section is on microbial inactivation related to food preservation.

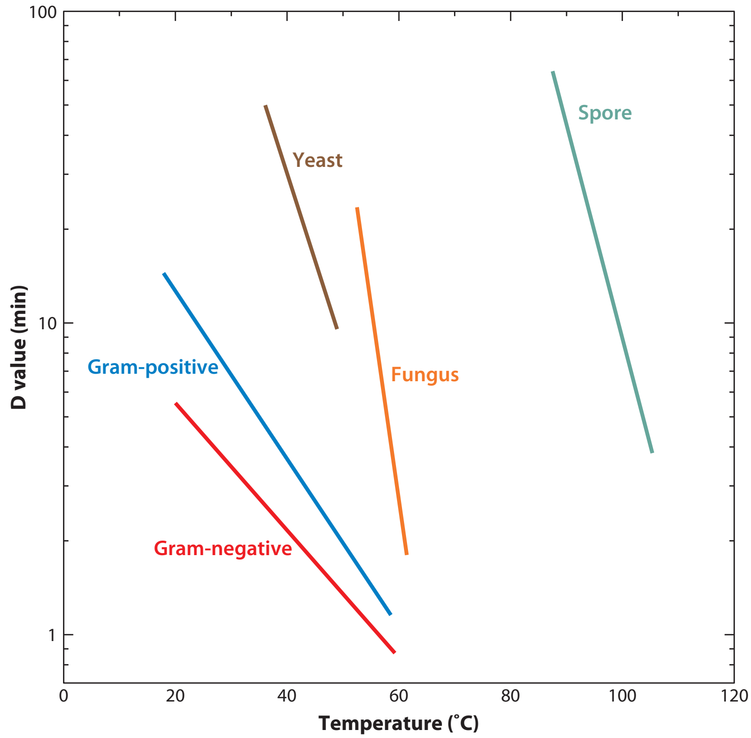

Figure 7

D values of five groups of bacteria with respect to temperature. Reprinted from Feng (2011) with permission from Springer.

There are many hypotheses and arguments about the mechanisms for microbial inactivation by ultrasound. At relatively high APD levels, cavitation is believed to be responsible for the microbial inactivation. Transient cavitation will produce localized hot spots, shock waves, water jets at solid-liquid interfaces, and free radicals, whereas stable cavitation will produce microstreaming accompanied by high shear (Mason & Lorimer 2002). All these effects contribute to damaged cell walls and membranes, resulting in cell death. Because the microbial inactivation is attributed to factors other than heat, ultrasound is viewed as a nonthermal food processing modality. There are multiple reports of ultrasound-induced cell damage (Raso et al. 1998, Lee et al. 2009), and the ruptured and disintegrated cells cannot be revived. This may be considered an advantage of ultrasound over some other nonthermal food processing methods in which sub-lethally damaged cells can recover if they encounter the right environmental conditions (temperature, pH, water activity, and nutrients).

The resistance of microorganisms to ultrasound treatments varies. From the D-value chart of five groups of microorganisms, the resistance to ultrasound inactivation is in the order of spores > fungi > yeasts > gram-positive cells > gram-negative cells (**Figure 7**), assuming the application of first-order inactivation kinetics (Feng 2011). The resistance of viruses to ultrasound is high, but not enough data are yet available to compare it directly with the resistance of other microorganisms. Even for the same organism, the resistance to sonication among different strains can be different (Baumann et al. 2005). It is also well known that bacterial cells attached to a surface are more difficult to inactivate, even without the formation of a biofilm.

Microbial inactivation of foodborne pathogens is aimed at two applications. One is the pasteurization of liquid foods, and the other is the surface decontamination of solid products. In pasteurization, besides killing the bacteria to reach the benchmark reduction of 5 log cycles, the effects of ultrasound on product quality are also an important consideration. To inactivate foodborne pathogens without compromising food quality, high-intensity, short-time (HIST) ultrasound treatments are desirable. This can be done by combining ultrasound with other lethal factors such as heat, low static pressure, ultraviolet light, chemical antimicrobials, etc. Lee et al. (2013) achieved a 5-log reduction of *E. coli* K12 populations in apple cider in 1.4 min with manothermosonication (400 kPa/59°C), in 3.7 min when sonication was combined with a lethal temperature, and in 15.9 min with a treatment of sonication alone (Ugarte-Romero et al. 2006). In ultrasound surface decontamination applications, two technical hurdles have to be overcome to achieve an effective and reliable (repeatable) microbial inactivation. The first is nonuniformity of the acoustic field in an ultrasonic treatment chamber. The second is the blockage of the ultrasonic waves by the product to be processed. For instance, with fresh produce, leaves far away from the ultrasound-emitting surface will receive less or no treatment than those near the surface due to blockage. Special measures must be taken to address both the nonuniformity and blockage issues. Zhou et al. (2012a) developed a pilot scale continuous-flow ultrasonic washing system for fresh produce sanitation. The special arrangement of the ultrasound-emitting unit (transducers) and the use of submerged water jets ensured a nearly uniform ultrasound treatment and the system achieved an increase in microbial reduction by 73 to 92% over washing with a sanitizer alone.

Effects of Ultrasound on Food Enzymes

One objective of food processing is to reduce the activity of enzymes that degrade food quality. For liquid foods, ultrasonication can be used as an alternative to thermal processing to inactivate food enzymes, with the aim of minimizing the quality degradation caused by heat. Enzyme inactivation with power ultrasound requires a relatively long treatment time (O'Donnell et al. 2010). To shorten the time, a combined treatment of ultrasound with other inactivation methods has often been investigated. For instance, pectinmethylesterase (PME) in orange juice must be inactivated to maintain cloudiness, an important quality index for orange juice (Vercet et al. 1999). The current industrial practice is to apply a thermal process at 90°C for 1 min to inactivate the PME. With an ultrasound + mild heat + low pressure (70°C, 400 kPa) process, a 30-s treatment reduced the PME activity by 94.6%, corresponding to a D value of 31.7 s (Lee et al. 2005). The treated orange juice had less browning compared to the thermally processed juice and maintained good cloudiness during 49-day storage at 4°C.

Enzyme inactivation by sonication is attributed to the physical and chemical effects of cavitation. The shear forces produced by cavitation cause the breakdown of hydrogen bonding and van der Waals interactions in the polypeptide chains, leading to modification of the secondary and tertiary structures of the protein. As a result, the enzyme activity will usually be lost. The hydroxyl and hydrogen-free radicals produced by cavitation may react with some amino acid residues that participate in enzyme stability, substrate binding, or in the catalytic activity of the enzyme, causing a consequent change in the enzyme activity. The effectiveness of ultrasound inactivation depends on the chemical structure of the protein, and therefore different enzymes have marked differences in their resistance to ultrasound treatment. Ultrasound parameters such as frequency, power density, and uniformity of the acoustic field; enzyme-related factors such as enzyme type, concentration, and pH; as well as the treatment temperature and food matrix all influence the inactivation efficacy (Mawson et al. 2011, Tiwari & Mason 2012).

Power Ultrasound and Biocomponent Separation

Power ultrasound treatment has been used as a means to separate biological components. One such application is protein-starch separation. In the dry milling industry, some by-products that are rich in starch are sold at low prices. Zhang et al. (2005a) used sonication to treat degermed corn flour (67.5% starch) and hominy feed (46.4% starch), and a starch recovery of 97.3–99.5% was achieved. In traditional wet milling operations, SO_2 is widely used to steep the corn to break the disulfide linkages and release the starch particles. To reduce the negative environmental impact of SO_2, new SO_2-free processes have been proposed, but the starch yield has been low. Zhang et al. (2005b) applied sonication to the fine fiber stream in a new SO_2-free process and obtained a starch yield of 66.9–68.7%, very close to the yield (68.9%) from the SO_2 steeping process. Power ultrasound has also been tested for tomato peeling to eliminate the need for a high-concentration lye solution. Rock et al. (2010) applied ultrasound treatment without the addition of any chemical to peel Roma tomatoes. An ease-of-peeling score of 5.0 (very easy to peel) using power ultrasound treatment at 97 ± 3°C for 45 s was achieved using a probe system. They showed that the ultrasonic peeling had the lowest percentage of peeling loss (4%) among the five treatments, compared to peeling losses of 25–28% for the mechanical methods used in commercial operations. In ultrasound treatment, the physical effect of cavitation may help weaken the tomato skin network, resulting in separation of the epicarp from the pericarp. Sonication may also enhance the diffusion of hot water or chemical solution into the epicarp of the tomato skins, thus enhancing the separation of skin and endosperm and reducing peeling losses.

RESEARCH NEEDS

Although the application of power ultrasound in the food industry has been a topic of research and development for a few decades, there is still the need to generate more systematic data about the responses of microorganisms, food enzymes, and food components (proteins, carbohydrates, lipids, nutrients, plant and animal cells, etc.) to ultrasound treatment. The kinetic information of a target organism or enzyme and selected food quality indexes are critical for the design of ultrasound-assisted processes for achieving the required inactivation level while minimizing quality changes. Great attention needs to be paid to details in ultrasonic system design and operation to generate reproducible data. This requires a good understanding of the underlying physics of ultrasound and a careful design of the ultrasonic treatment chamber (sonoreactor) with a known acoustic field distribution. The reporting of all important operational parameters, including APD measured with power delivered to the reactor, sample volume, dimensions of the reactor, probe location, temperature history, frequency, amplitude, and pulsation duration, will provide the means to understand the work done by different labs (Feng et al. 2009). For high-APD applications, reactors with no or minimal metal abrasion are needed. With such food-grade sonoreactors, food treated by ultrasound can be evaluated by a sensory panel to evaluate the consumer acceptance of the product. To facilitate HIST treatment, ultrasound units employing variable-frequency techniques are desirable to eliminate the standing-wave issue and produce enhanced cavitation activity.

CONCLUSIONS

Ultrasound is viewed as a clean technology due to its popular applications in medical imaging, with a high potential for consumer acceptance compared to other chemical and physical food processing concepts. Current research and development efforts have demonstrated that power ultrasound is a promising aid in a spectrum of food processing and preservation operations. More research and development are needed to look into both high-APD and low-APD applications with an emphasis on their effects on product quality, kinetics, process design criteria, and equipment and operational costs.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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