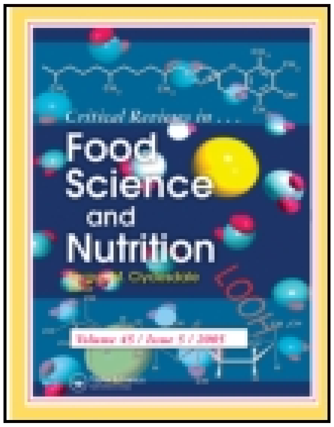

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Enhancement of Food Processes by Ultrasound: A Review

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In food processing, the applications of ultrasound can be divided into two categories, namely replacing traditional technologies and assisting traditional technologies. In the latter case, the processing efficiency is enhanced and the disadvantageous of traditional technologies during processing are improved. These ultrasonic effects can be defined as ultrasonic enhancement of food processes. This review is focused on the use of ultrasound to enhance various food processes, including extraction, freezing, thawing, brining, oxidation, filtration, and drying/dehydration. The major functions of ultrasound in enhancing these processes and the factors which can affect the ultrasonic enhancement are elucidated. In the meantime, the strategies of modeling these processes enhanced by ultrasound are provided. Future studies should pay more attention to elucidate the ultrasonic effects during freezing, thawing, brining, oxidation, and filtration processes. Furthermore, when it comes to design the ultrasound equipment at the industrial level, it is better to quantify the ultrasonic effects through numerical stimulation.

Keywords Ultrasound, food processing, process enhancement, extraction, freezing, thawing, brining, oxidation, filtration, drying, dehydration

INTRODUCTION

Modern food industry is always on the way looking for innovative technologies which can produce high-quality and safe products, enhance the processing efficiency, and reduce the energy consumption. For this purpose, the feasibility of ultrasonic technology in food-processing area has been widely studied. Ultrasound is cyclic sound pressure with a frequency greater than 20 kHz. Normally, the application of ultrasound in the food industry can be classified into two distinct fields, depending on the ultrasonic frequency and intensity. The first field is low-frequency and high-energy power ultrasound, the frequency of which is approximately in the range of 20–800 kHz (Laborde et al., 2000). Several physical and chemical phenomena can be generated when power ultrasound passes through the medium. Power ultrasound can be used in various food processing areas, including freezing, thawing, extraction, drying, etc. The other field is high-frequency low-energy diagnostic ultrasound in the MHz range, which can be used as an analytical technique for providing information about the physicochemical properties of foods, such as composition, structure, particle size, and flow rate (McClements, 1995).

During food processing, ultrasonic treatment can be performed in different ways. Mostly, ultrasonic waves are introduced to liquid or liquid–solid systems. An ultrasonic probe can be inserted into the system, otherwise samples can be submerged in an ultrasonic bath to receive the acoustic irradiation (Li and Sun, 2002a; Adekunte et al., 2010; Guan et al., 2011). In certain cases, ultrasonic waves travel from gas to solid medium or foodstuffs contact the ultrasound equipment directly (García-Pérez et al., 2009). Furthermore, ultrasound machine can be coupled with other devices to finish the whole processing (Chemat et al., 2010). No matter how the ultrasonic treatment is carried out, the ultrasonic system always consists of three essential parts, namely, the generator, transducer, and delivery system. Among them, the generator transforms the electricity into desired alternating current at ultrasonic frequency to drive the transducer assembly. Afterwards, the transducer converts the current into mechanical vibrations. The transducer is the key device for the ultrasonic system. There are three different types of ultrasonic transducers available, namely liquid-driven transducers, magnetostrictive transducers, and piezoelectric transducers (Mason, 1998). Lastly, the delivery system conveys the vibration to the ultrasonic reactor.

In the applications of ultrasound to food processing, the main purpose of utilization of ultrasonic technology could be broadly

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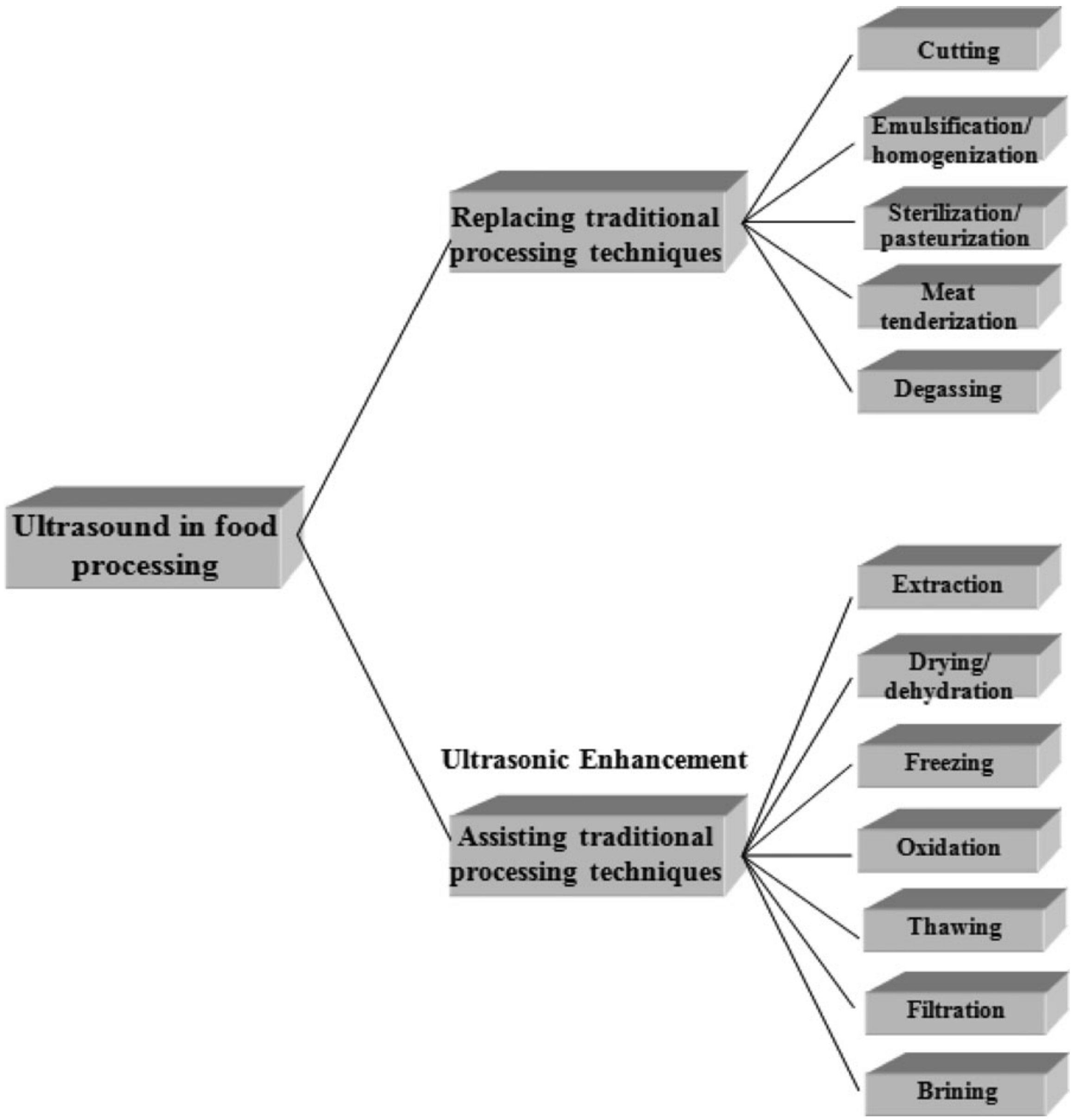


Figure 1 Classification of applications of ultrasound in food-processing area.

divided into two main categories (Fig. 1). The first one is to replace the traditional processing techniques by the ultrasonic one. The applications of ultrasound for food cutting, emulsification/homogenization, sterilization/pasteurization, meat tenderization, and degassing belong to this category. The other category is to assist or accelerate the traditional techniques so that processing can be completed more efficiently and rapidly. In this latter case, the whole process is enhanced by ultrasound, and disadvantages of traditional techniques during processing are overcome or improved. These ultrasonic effects can be defined as ultrasonic enhancement of food processes. These food processes include extraction, freezing, thawing, brining, oxidation, filtration, and drying/ dehydration.

In this review, ultrasonic enhancement of food extraction, freezing, thawing, brining, oxidation, filtration, and drying/ dehydration are highlighted, and the major functions of ultrasound and the factors that affect the ultrasonic enhancement during processing are elucidated. In addition, the modeling of the food processing enhanced by ultrasound is provided, and future trends in using this technique are proposed. At beginning, the summarization of ultrasonic enhancement of food processing is provided in Table 1 and the discussions below are carried out following the information inside.

ULTRASONIC MECHANISMS INVOLVED IN THE ENHANCEMENT OF FOOD PROCESSING

As a kind of mechanical wave, ultrasonic waves could cause a series of compression and rarefaction when they pass through a medium. In the case of their traveling across aqueous phase, the cavitation phenomenon occurs once the amplitude of the waves

Table 1 Summarization of ultrasonic enhancement of food processing

		Factor affecting ultrasonic enhancement		
Processing area	Major function	Nonultrasonic factors	Ultrasonic factors	Modeling strategy
Extraction	a. Extraction rate enhancement b. Extraction yield enhancement c. Reduction of solvent consumption d. Reduction of extraction cost e. Reduction of pollution to environment f. Reduction of extraction temperature g. Improvement of product quality in some cases	a. Solvent type b. Particle size c. Solvent/sample ratio d. Temperature e. Extraction container type	a. Ultrasound frequency b. Ultrasound duration c. Ultrasound power/intensity d. Treatment mode (continuously/ intermittently)	Nonparametric simulative models (response surface methodology and artificial neutral network)
Freezing	a. Initiation of ice nucleation b. Regulation of nucleation phenomenon c. Heat- and mass-transfer rate enhancement d. Control of ice crystal size and shape	a. Gas bubble concentration b. Supercooling degree c. Freezing phase	a. Ultrasound power/intensity b. Ultrasound duration	Physical models for freezing
Thawing	a. Thawing rate enhancement b. Reduction of drip loss c. Maintenance of product quality	a. Sample orientation b. Composition of thawed products	a. Ultrasound frequency b. Ultrasound power/intensity	Physical models for thawing
Brining	a. Mass-transfer rate enhancement b. Decrease of drying rate during ripening process for cheese products c. Control of the problems of enzymatic softening, bloating, and structural damage d. Reduction of NaCl consumption	a. Pressing time for cheese products b. Temperature c. Sample geometry	a. Ultrasound power/intensity	Physical models for brining
Oxidation (wine ageing)	a. Wine ageing rate enhancement b. Increase of the duration when wine quality stays at their peak level c. Reduction of cost and space for wine ageing d. Elimination of barrel contamination by undesirable microorganisms e. Reduction of wine loss due to evaporation	a. Temperature b. Wine type	a. Ultrasound frequency b. Ultrasound duration c. Ultrasound power/intensity d. Treatment mode	Non-parametric simulative models (response surface methodology and artificial neutral network)
Filtration	a. Increase of permeate flux b. Decrease of flow resistance c. Extension of filter life	a. Feed properties b. Membrane properties c. Applied pressure d. Temperature e. Cross-flow velocity f. Membrane position	a. Ultrasound frequency b. Ultrasound power/intensity c. Treatment mode d. Ultrasound propagation direction	Physical models for filtration
Drying/dehydration	a. Drying rate enhancement b. Reduction of drying cost and energy consumption c. Prevention of food quality damage d. Modification of food composition using ultrasound as a pretreatment	a. Characteristics of food materials b. Air velocity c. Temperature d. Mass load density	a. Ultrasound power/intensity b. Treatment mode	a. Physical models for drying/dehydration b. Empirical models

exceeds a threshold level. The acoustic cavitation is composed of the formation and subsequent dynamic life of microbubbles (Mason et al., 2005). There are two types of cavitation according to the dynamic experience of bubbles, namely stable cavitation and transient cavitation (Zheng and Sun, 2005). Stable cavitation, which usually occurs at low acoustic pressure, involves growth of microbubbles over every ultrasound cycle without collapse since they cannot reach the critical size for collapse. On the contrary, at high acoustic pressure, microbubbles grow rapidly followed by violent collapses when they reach a critical size. This process is named transient cavitation. In this case, the instantaneous implosion of these bubbles can locally generate extreme temperature (up to 5000 K) and pressure (up to 100 MPa) (Gong and Hart, 1998).

The acoustic effects accompanied by the cavitation phenomenon are of paramount importance for enhancing food processing. To start with, the extreme high temperature and pressure can break down water molecules into highly reactive free radicals, such as H^+ and OH^-. These chemical radicals could accelerate certain chemical reactions and modify other molecules (Riesz and Kondo, 1992). The high temperature and pressure can also facilitate the disruption of solid foodstuff surface. Secondly, strong eddies are produced when cavitation bubbles vibrate vigorously in liquid. As a result, microstreaming is created due to the attraction of other small bubbles into ultrasonic fields (Hughes and Nyborg, 1962). The microstreaming can generate violent agitation, which can facilitate the blend of reactants and enhance heat and mass transfer during processing (Simal et al., 1998; Tarleton and Wakeman, 1998). Microstreaming also provides a large force to accelerate the damage of solid material surface. Furthermore, during the compression and rarefaction, an unequal diffusion of vapor and gases from bulk liquid phase into bubbles, which is known as rectified diffusion, may occur (Thompson and Mascheroni, 1999). The rectified diffusion plays an important role during ultrasound-assisted drying process.

Besides the acoustic effects produced by cavitation, part of ultrasonic energies are absorbed and converted into heat. This thermal effect can benefit several processes, such as thawing, drying, and sterilization.

On the other hand, no cavitation phenomenon occurs when ultrasonic waves travel in gas and solid systems. In this circumstance, the alternative compression and rarefaction of ultrasonic waves can produce pressure variations at gas/solid interfaces (Fuente-Blanco et al., 2006; García-Pérez et al., 2007). At the same time, extreme turbulence at the interface is formed, which can benefit the reduction of diffusion boundary layer, thus promoting the mass transfer (Zheng and Sun, 2005). For solid materials, they also experience a series of contractions and expansions. All these mentioned effects are associated with the ultrasonic enhancement of food drying process.

ULTRASONIC ENHANCEMENT OF EXTRACTION PROCESS

The un-eco-friendly defects of traditional extraction technique contribute to the emergence of novel extraction techniques. Ultrasound has been widely studied to enhance the extraction of various components, including herbal extracts, protein, oil, bioactives, etc. In the meantime, the scale up of ultrasonic extractor is attracting growing interest and several industrial scale reactors have already been successfully applied in the food industry.

Major Functions of Ultrasound in Enhancing Extraction Process

The extraction process can be simply described as the transfer of desired components from raw materials to solvent. Under ultrasonic irradiation, the mass transfer rate can be enhanced markedly. On one hand, the microstreaming produced by ultrasound has a mechanical effect on the surface of raw materials, which can destroy the surface and reduce the particle size. On the other hand, the high temperature and pressure can also facilitate the destruction of material surface. As a result, the area exposed to ultrasonic field increases and the compounds inside the raw materials tend to release into solvent. Table 2 compares the conventional extraction and ultrasound-enhanced extraction from three distinct aspects, namely extraction time, yield, and solid–liquid ratio. As can be seen, the application of ultrasound during extraction leads to a higher extraction yield within less extraction time compared to the conventional extraction technique. Besides, the solvent consumption can be reduced. Generally speaking, the advantages of using ultrasound to assist extraction process can be summarized as high extraction efficiency, high reproducibility, high yield, low solvent consumption, easy-operating, low cost, and low pollution to environment.

Together with the enhancement of mass transfer by ultrasound, several other benefits are obtained. The ultrasound-enhanced extraction is usually carried out at a relatively low temperature. Consequently, the evaporation of solvent can be prevented. As for the bioactive components and other components which may be thermally degraded, low temperature is beneficial to keep their bioactivity and value during extraction. Moreover, the utilization of ultrasound during extraction can improve the quality of final products. In the date syrup industry, the application of ultrasound not only can facilitate the extraction of date syrup, but can also give products a better physical quality and enhance the effectiveness of the antimicrobial components in date fruit (Entezari et al., 2004). When ultrasound was employed to assist extraction of lignins from wheat straw, it could promote the cleavage of α-ether bonds between hemicelluloses and lignin to lower the content of neutral sugar, thus increasing the purity of final products (Sun and Tomkinson, 2002). At the same time, it was found that the lignins extracted using ultrasound had a higher molecular weight than those extracted by conventional methods, which had a higher thermal stability (Sun and Tomkinson, 2002). In the study of Xia et al. (2006) about extraction of tea components from tea infusion, ultrasound was found not only to promote the extraction of desired components, including amino acid, tea polyphenols, and caffeine, but also to inhibit the extraction of undesired protein

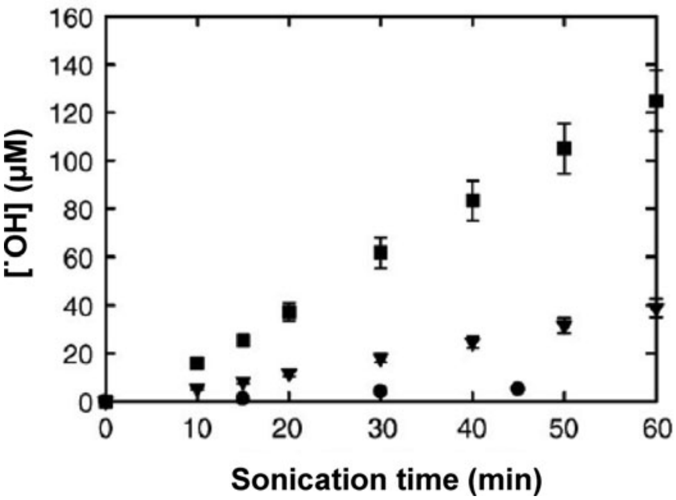


Figure 2 OH^- radical yield generated in water during sonication at different ultrasonic frequencies (0.90 W cm^{-2}). (■: 358 kHz, ▼: 1062 kHz, •: 20 kHz) (Ashokkumar *et al*., 2006).

and pectin. As a result, the sensory quality of final products was improved by ultrasound treatment.

Attention should be paid to the stability of extracted component after a long exposure to ultrasonic irradiation. It is generally agreed that ultrasound usually has very weak effects on the stability of extracted components and this is a major premise on the application of ultrasound on extraction area. However, in some cases, ultrasound may degrade several components after a long-time irradiation at a high temperature, such as phenolic acid and salvianolic acid B (Ma et al., 2008b; Dong et al., 2010). Therefore, the potential degradation of extracted components during sonication should be avoided. Free radicals, especially hydroxyl radicals, generated during the collapse of cavitation bubbles mainly contribute to the degradation. Ashokkumar et al. (2006) found that the amount of hydroxyl radials relied on the ultrasonic frequency and more radials were generated if a higher frequency was used (Fig. 2). The theoretical study of Arrojo and Benito (2008) also confirmed that high frequency ultrasound promoted the diffusion of hydroxyl radials to liquid and accelerated chemical reactions. Based on these findings, a low-frequency ultrasound is recommended to enhance extraction process. Another strategy to minimize the influence of free radicals during extraction is to add the chemicals which can quench these free radicals. Both ascorbic acid and volatile surface active solutes, such as ethanol can be used to achieve this goal (Ashokkumar et al., 2006; Vilkhu et al., 2008).

Factors Involved in Ultrasonic Enhancement of Extraction Process

The factors that affect the extraction efficiency are dependent on both the behavior of ultrasound in solvent and the physicochemical characteristics of extracted compounds and raw materials. In general, these factors can be divided into ultrasonic factors and nonultrasonic factors. Ultrasonic factors include ultrasonic frequency, the acoustic power/intensity, ultrasound duration, and treatment mode while the nonultrasonic factors involve solvent type, solvent/sample ratio, particle size, temperature, etc.

Nonultrasonic Factors

To fulfill the potential of ultrasound during extraction, the nonultrasonic parameters should be chosen properly. Solvent type is an important factor for ultrasound-enhanced extraction, since the physical properties of solvent, such as viscosity, polarity, surface tension, density, diffusivity, and vapor pressure can affect the extraction efficiency. To be specific, these properties of solvent are correlated with its molecular affinity with extracted components and its diffusion into raw materials (Annegowda et al., 2012; Sun et al., 2011). In the meantime, the boiling point of solvent should be low enough to make the removal of solvents from final products more easily (Albu et al., 2004). Moreover, some properties of solvent, including viscosity, surface tension, and vapor pressure can affect the behavior of ultrasonic cavitation in the medium. Low vapor pressure, low viscosity, and low surface tension of the solvent can benefit the formation of high-intensity cavitation (Hemwimol et al., 2006). Among current studies, ethanol, methanol, acetone, and their mixtures with water have been widely used during ultrasound-assisted extraction of various compounds including antioxidants while hexane and its mix with isopropanol show their priority for oil extraction (Li et al., 2004; Zhang et al., 2009b). On the other hand, the toxicity of the organic solvents should not be ignored as these solvents are potentially used in food processing area. Recently, the β-cyclodextrin water solution was used as a green alternative to organic solvents during ultrasonic extraction of two kinds of polyphenols, resveratrol and polydatin from *Polygonum cuspidatum* (Mantegna et al., 2012). β-cyclodextrin can encapsulate extracted compounds and enhance their stability, solubility, and bioavailability. As regarded to the problem of degradation of extracted compounds induced by the generation of free radicals in solvent, the degradation can be minimized if methanol is used. It was reported that no hydrogen peroxide was formed during sonication in methanol. At the same time, the amount of free radicals inside was low (Jerman et al., 2010).

During ultrasonic extraction, the influences of particle size and solvent/sample ratio on extraction should be taken into account. The particle size was regarded as an important factor during extraction of polyphenol from orange peels (Cuoco et al., 2009; Khan et al., 2010). For a constant quantity of raw material, a small particle size means a large surface area, which can benefit the penetration of ultrasonic wave into raw materials and the subsequent release of inner components (Sun et al., 2011). A simple equation below can be employed to describe the relationship between the particle size and the extraction yield:

$$K = \pi r^2 E \quad (1)$$

where K is a constant, r is the particle radius, and E is the extraction yield (Sun et al., 2011). However, if the particle size is too small, solid particles may float on the surface of solvent, which can reduce the ultrasonic effects (Khan et al., 2010). On the other hand, solvent/sample ratio is another parameter which affects the mass transfer rate during extraction. The concentration gradient between the solid raw material and the bulky solvent is the driving force during mass transfer. Therefore, in a proper range, either a high solvent/sample ratio or sample/solvent ration can facilitate the ultrasonic extraction process due to a high concentration gradient (Herodež et al., 2003; Pinelo et al., 2005; Gribova et al., 2008). If the sample/solvent ratio is too high, the extraction yield may remain stable or decreases (Virot et al., 2010; Sun et al., 2011). The reason for this phenomenon is that the quantity of solvent is not high enough to permit the mass transfer from raw material to solvents (Sun et al., 2011). In the meantime, a high quantity of solid raw material in the liquid system can hinder the transmission of ultrasonic energy into solvent (Gribova et al., 2008). Furthermore, a high solvent/sample ratio also cannot lead to the increase of extraction yield if it grows to a too high level (Zhao et al., 2007; Zhang et al., 2009b; Sun et al., 2011). Generally, an optimized solvent/sample ratio not only benefits the ultrasound-assisted extraction, a waste of solvent and excess work in the subsequent concentration process can also be avoided.

The applied temperature during ultrasonic extraction should be chosen carefully. In many cases of ultrasound-enhanced extraction, the extraction yield first increases to a peak level and then decreases gradually along with the increase of extraction temperature (Zhao et al., 2007; Zhang et al., 2009a; Ying et al., 2011). The rising of temperature can accelerate the softening and swelling of the raw materials, increase the solubility of extracted compounds and decrease the viscosity of solvent. Consequently, the mass transfer is improved when the temperature gradually increases (Zhang et al., 2009a). However, if the temperature continues increasing, the surface tension may decrease and the vapor pressure of cavitation bubbles may increase, which can result in the decrease of cavitation intensity (Raso et al., 1999). At the same time, the thermal labile components may be degraded at a high temperature. As can be seen, both the low-intensity cavitation and thermal effects result in the decrease of extraction yield at high temperatures. Furthermore, a high temperature may promote the evaporation of solvent and lead to a high consumption of energy input and the impurity extraction (Zhang et al., 2009b).

In some cases, the type of container used for ultrasound-assisted extraction can somewhat impact the final yield. During the ultrasound-assisted extraction of hesperidin from Penggan, the hesperidin yield in a rotary beaker was higher than that in a fixed beaker (Ma et al., 2008a).

Ultrasonic Factors

The ultrasonic frequency used for extraction is mainly in the range from 20–100 kHz. Higher frequency is not recommended since there is an inverse relationship between the acoustic power and the square of frequency (Mason, 1998). Thus, the increase of frequency can reduce the ultrasound intensity for extraction and consequently reduce the extraction efficiency. Moreover, it has been mentioned above that more free radicals can be generated using high frequency ultrasound.

The extraction yield is always time-dependent during ultrasonic extraction. Therefore, the ultrasound duration should be optimized. At the first stage of ultrasonic extraction (around 10–20 minutes), ultrasound may not improve the extraction efficiency significantly since more time is needed for ultrasound to disrupt the structure of raw materials and promote the release of inner components (Ma et al., 2008a; Jerman et al., 2010). A longer ultrasound duration can markedly improve the extraction efficiency and increase the extraction yield (Ma et al., 2008a; Jerman et al., 2010; Sun et al., 2011). In this period, the structure of raw material is already disrupted by ultrasound and a large amount of inner components can be transferred into exterior solvent through osmosis and diffusion (Wei et al., 2008). After this stage, prolonged ultrasonic treatment is not beneficial to the extraction of desired components. On one hand, since the inner components are released outside gradually, the diffusion front is moving towards the interior of raw materials, the diffusion area is reducing, as well as the diffusion rate is decreasing (Zhao et al., 2007). Moreover, the osmotic pressure between the inside and outside of raw materials may arrive at equilibrium when the diffusion rate decreases (Sun et al., 2011). As a result, the extraction yield cannot enhance after a long-time ultrasound treatment. On the other hand, long ultrasound duration may be detrimental to extracted components because of the potential degradation. In most studies, the extraction yield can reach the peak level with the assistance of ultrasound within one hour. However, when it comes to extract xyloglucan from apple pomace, Fu et al. (2006) found that the optimum extraction time was 2.5 hours, which was much longer than conventional ultrasound duration.

The amount of ultrasonic energy transmitted to the solvent is of great importance in most cases of extraction. The ultrasound power (W), ultrasound intensity (W/cm^2), and the acoustic energy density (W/ml) can be used to express the ultrasonic energy dissipated in the system (O'Donnell et al., 2010). Similar to the influence of ultrasound duration and temperature, the extraction yield also follow the trends of first increasing gradually to a peak level and then decreasing or keeping stable along with the increasing of ultrasound power/intensity in many studies (Wei et al., 2008; Lou et al., 2010; Ying et al., 2011). The increase of ultrasound power can promote the formation and collapse of more cavitation bubbles (Hemwimol et al., 2006). Thus, the violent shock and high-speed microstreaming are generated, which can accelerate the disruption of raw material surface and the release of extracted components. However, if the ultrasound power keeps increasing, the efficiency of ultrasonic energy transmitted to solvent may decrease since too many cavitation bubbles are generated (Filqueiras et al., 2000). Furthermore, a high ultrasound power may result in a chemical decomposition of extracted compounds (Ying et al., 2011).

The last ultrasonic factor involved in ultrasonic extraction is the treatment mode. Despite that the ultrasonic extraction is usually carried out continuously without any intervals, the pulse mode also has its own advantages. The study of Sivakumar et al. (2007) indicated that during myrobalan extraction, the extraction yield in a pulse mode of 0.5 seconds on and 0.5 seconds off was as high as 70% of the yield in a continuous mode while the electrical energy consumed in the former mode was only half of the energy consumed in the latter mode. As can be seen, the pulse mode can be regarded as an energy-saving mode. For the pulse mode, the applied pulse duration and interval are critical for obtaining the highest extraction yield within less treatment time (Zhu et al., 2009; Pan et al., 2011). In the case of long-time ultrasonic extraction, the pulse mode may be superior to the continuous mode not only due to low energy consumption, but also due to the potential decrease of bioactivity of extracted compounds after long-time ultrasound irradiation (Pan et al., 2011).

Mathematical Modeling of Ultrasonic Enhancement of Extraction Process

Mostly, the models developed to describe the ultrasonic enhancement of extraction are nonparametric simulative models, which do not need to express the physical meaning of the process (Marchitan et al., 2010). Response surface methodology (RSM) is the most popular tool for modeling. In RSM, a second-order polynomial equation below is always employed to build the relationship between the response variables and independent variables (Tiwari et al., 2009; Zhang et al., 2009b):

$$Y = \beta_0 + \sum_{i=1} \beta_i X_i + \sum_{i=1} \beta_{ii} X_i^2 + \sum_{i=1} \sum_{j=i+1} \beta_{ij} X_i X_j \tag{2}$$

where X_i and X_j are the independent variables, Y is the response variable, β_0, β_i, β_{ii}, and β_{ij} are the constant, linear, quadratic, and cross-product coefficients, respectively. According to the developed models, both the optimization of each response and the simultaneous optimization of multiple responses can be carried out numerically or graphically.

Normally before modeling, the extraction process using RSM, single factor studies are helpful to eliminate the factors which do not affect the extraction significantly and shorten the range of those factors which are important for the extraction. RSM has been successfully used to model various extraction process assisted by ultrasound. Through RSM modeling, not only the extraction process is optimized, the interaction effects between different independent variables on the response can also be elucidated.

On the other hand, artificial neutral network (ANN) is another choice to model the extraction process enhanced by ultrasound. Unlike the RSM modeling that the input and output data will be fitted into a second-order polynomial equation, ANN does not require a prior knowledge about the relationship between the input and output parameters (Plumb et al., 2005). Instead, it can train and learn itself to recognize the patterns in a systematic way. Several studies were performed to compare the RSM and ANN modeling effects on sterilization and extraction processes (Lou and Nakai, 2000; Marchitan et al., 2010). The results showed that ANN models had a higher accuracy than RSM models to build the relationship between processing parameters and response variables. Although few studies about ANN modeling of ultrasonic extraction are published, it is confident that this modeling tool is effective to model the extraction process enhanced by ultrasound.

Novel Ultrasonic Strategies to Enhance Extraction Process

Since the application of ultrasound during extraction has been widely studied, several novel strategies have been developed, which extend the use of ultrasound in extraction area.

The first strategy is called dynamic ultrasound-assisted extraction, which induces a solvent circulation through pumping while raw materials are put in an extraction cylinder and the extraction process occurs inside. Two main kinds of dynamic approaches can be used, namely, open systems in which fresh solvents continuously flow through the samples and closed systems where a preset volume of solvent always passes through the samples (Ruiz-Jiménez et al., 2003). Considering the disadvantage of extract dilution, the latter approach is more popular in actual application. Furthermore, the direction of solvent can be changed occasionally to avoid undesired pressure increasing in the system and sample compactness (Japón-Luján et al., 2006). The comparison between dynamic and conventional ultrasound-assisted extraction of oil from chickpea was carried out by Lou et al. (2010). They found that the dynamic extraction not only exhibited a higher extraction yield and a lower solvent consumption, the extraction rate in the dynamic way was also higher than that in a static way. Therefore, the continuous flowing of solvent can promote the contact between raw materials and solvent and enhance the mass transfer process. Future studies about ultrasonic extraction can pay more attention to the dynamic way, so as to further enhance the ultrasonic efficiency.

Secondly, the ultrasonic technique can be used during the supercritical fluid extraction to enhance the extraction efficiency of supercritical solvent. Different from the traditional liquid extraction, supercritical fluid extraction is based on the contact of extractable compounds with CO_2 in supercritical conditions. Supercritical fluid extraction is an eco-friendly technology and can improve product recovery and quality (Lang and Wai, 2001). However, the required long extraction time and high pressure, as well as the low solubility of extracted compounds in CO_2 have badly hindered the application of this green technology. Ultrasound is promising to improve the supercritical fluid extraction. During the supercritical fluid extraction of coixenolide and oil from adlay seeds, the extraction pressure and temperature could be reduced by 5 MPa and 5°C, respectively, when ultrasound technology was introduced (Hu et al., 2007). At the same time, the selectivity of supercritical CO_2 fluid to extracted compounds did not change and no significant quality differences in final products were detected in the extraction of oil from adlay seeds (Hu et al., 2012). Furthermore, ultrasound has been proven to increase both the supercritical fluid extraction yield and extraction rate significantly in the cases of oil extraction from almonds and lutein esters extraction from marigold (Riera et al., 2004; Gao et al., 2009). In addition, the ultrasonic transducer is a good tool to monitor the phase behavior of supercritical fluids since it is sensitive to the big change in flow density and rate (Riera et al., 2004). It should be noticed that when ultrasound is used to enhance the supercritical fluid extraction, more operational parameters need to be considered, including the ultrasonic factors, extraction temperature, CO_2 flow rate, pressure, etc.

Furthermore, it is a good idea to incubate raw materials with immobilized enzymes prior to ultrasound treatment to avoid the use of organic solvent. This strategy has been used in the ultrasonic extraction of oil from flaxseed (Long et al., 2011). A reasonable oil recovery was attained when the flaxseed was first incubated with the mixture of cellulose, pectinase, and hemicellulase and subsequently immersed in distilled water. The oil quality from enzyme-assisted ultrasonic extraction was higher than that from organic solvent extraction since the products had less free fatty acids and more unsaturated fatty acid.

Overall, the dynamic strategy can benefit the enhancement of ultrasonic extraction efficiency and the other two strategies favor the development of the environmental-friendly extraction technology. Together with the conventional ultrasound treatment, all these options can satisfy the different requirements of extraction.

ULTRASONIC ENHANCEMENT OF FREEZING PROCESS

As a means of preservation, freezing plays an important role in extending the shelf life of food products. The freezing process can be simplified to initial ice nucleation followed by crystal growth within the unfrozen aqueous phase. The quality of frozen foods is tightly related to the location and size of ice crystals (Li and Sun, 2002a). It is believed that the generation of ice crystals within frozen foodstuffs depends on the freezing rate. Rapid freezing produces small intracellular ice crystals, which are desired for high-quality products (Delgado and Sun, 2001). Therefore, increasing the freezing rate can greatly improve the whole freezing process and maintain the original quality of foodstuffs. Furthermore, freezing can be used for drying and concentration. Ultrasound is promising in either enhancing the freezing rate or controlling the formation and distribution of ice crystals.

Major Functions of Ultrasound in Enhancing Freezing Process

To facilitate the whole freezing process, latent heat generated by water nucleation and crystallization should be removed immediately. Moreover, nonwater components need to be taken away from the freezing interface while water molecules should move to the freezing front. Therefore, besides the water crystallization phenomenon, heat and mass transfer phenomenon occurs simultaneously during freezing. Ultrasound can mainly enhance the freezing process through initiating nucleation, increasing the heat- and mass-transfer rate and controlling the crystal shape and size distribution in frozen foodstuffs.

Initiation of Ice Nucleation

Nucleation is composed of two different processes, namely, primary nucleation and secondary nucleation. Primary nucleation refers to the emergence of crystals in a solution without any existing crystals while secondary nucleation occurs in a solution with pre-existing crystals and refers to the formation of new crystals (Chow et al., 2005). Both the primary nucleation and secondary nucleation of ice can be initiated by ultrasound (Chow et al., 2003; Delgado et al., 2009). Furthermore, compared to conventional immersion freezing, ultrasound can increase the nucleation temperature (Kiani et al., 2011a).

The gas bubbles produced by cavitation can act as nuclei for ice nucleation once they reach the critical nucleus size (Mason et al., 1996). In the meantime, the flow streams and pressure gradient generated by cavitation bubbles can also be the driving force for nucleation (Chow et al., 2005; Kiani et al., 2011a). It has been reported that the application of ultrasound in a concentrated sucrose solution can result in a significant increase of nucleus number (Suslick, 1988). As for the solid food, ultrasound was successfully applied to promote the ice nucleation in agar gel samples (Kiani et al., 2011a).

Together with the initiation of ice nucleation, ultrasound is an effective tool to regulate the nucleation and improve the repeatability of this phenomenon (Kiani and Sun, 2011b). It is well-known that nucleation is a stochastic phenomenon, thus, it is difficult to control this process. However, in the case of ultrasound-assisted freezing of both water-based solutions and agar gel samples, a linear relationship between ultrasound application temperature and nucleation temperature was detected within the studied range (Kiani et al., 2011a). As can be seen, ultrasound can regulate the ice nucleation process by controlling the nucleation temperature.

Increasing the Heat- and Mass-Transfer Rate

Heat and mass transfer (Hu and Sun, 2000; Sun and Hu, 2003; Sun and Deng, 1989; Sun and Woods, 1997) takes place in many processes and normally enhancing the heat and mass transfer rate can significantly speed up these processes. The heat- and mass-transfer rate during freezing process is closely related to the freezing rate. The violent agitation provided by ultrasonic microstreaming can enhance the heat and mass transfer process during food freezing (Li and Sun, 2002a). During immersion freezing of potatoes samples, the application of power ultrasound, whose power was 15.85 and 25.89 W, significantly

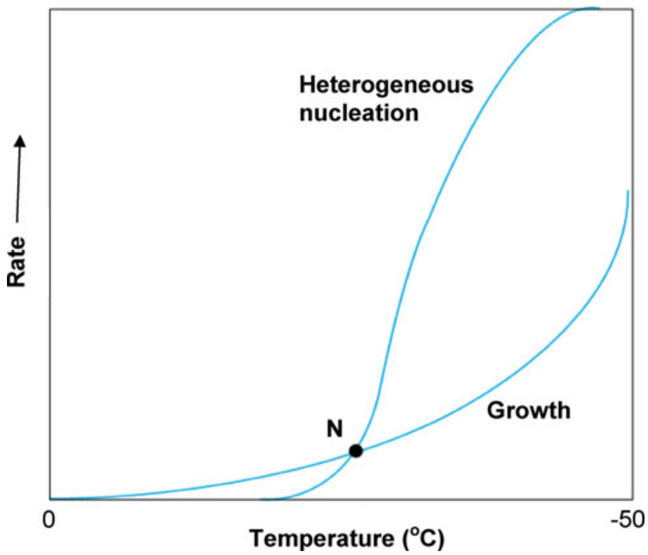


Figure 3 Comparative rates of nucleation and crystal growth of water as influenced by supercooling. (Fennema, 1973).

increased the freezing rate compared to those without ultrasound treatment. Less time was required for ultrasound treated samples to transverse the product temperature from −1 to −7°C, when the maximum ice crystals were formed (Li and Sun, 2002a).

Control of Ice Crystal Size and Shape in Frozen Foodstuffs

During freezing, a tool to control the size and shape of ice crystal is highly valuable. The purpose of freezing is crucial to decide what size is preferable for processing. For food preservation and ice cream manufacturing, smaller size of ice crystals is always desired since it can benefit the final product quality (Zheng and Sun, 2005). On the contrary, for freeze drying and freeze concentration, large and vertical ice crystals formed during freezing can shorten the subsequent sublimation time since this kind of crystal enhances the permeability of frozen products (Saclier et al., 2010a). Both the size and morphology of ice crystal are dependent on the nucleation temperature (Saclier et al., 2010a). Since the nucleation temperature could be controlled by ultrasound, this effect can be employed to control the crystal size and shape in frozen products. To be specific, despite that both the nucleation and crystal growth depend on the supercooling levels, nucleation, and crystal growth rates behave differently with the increase of supercooling level (Fennema, 1973) and there is a point of intersection (Fig. 3). If ultrasound is introduced when the system temperature stays in the range from freezing point to point N, crystal growth is dominant in the whole freezing process and the nuclei will grow extensively. Reversely, in the case of application of ultrasound when the system temperature is below point N, a large amount of nuclei will be generated and they will only grow to a limited size (Zheng and Sun, 2005).

Factors Involved in Ultrasonic Enhancement of Freezing Process

Since several phenomena are involved in freezing process, such as nucleation, crystal growth, and heat- and mass-transfer, the factors affects these phenomena are discussed respectively, as detailed below.

Factors Affecting the Ultrasonic Enhancement of Ice Nucleation

For enhancing ice nucleation during freezing, the gas bubble concentration within the solution, supercooling degree, the ultrasound power, and ultrasound duration should be strictly controlled.

To start with, a high gas bubble concentration can favor ice nucleation. Zhang et al. (2003) found that during exposure to the 39 kHz ultrasonic irradiation, supercooled water had a higher probability of ice nucleation when the number of air bubble was 27 cm^{-3} than the number of air bubble was 8 cm^{-3}. However, it should be noticed that high gas bubble concentration may also produce a time delay between the commencement of ultrasound treatment and the commencement of ice nucleation (Zhang et al., 2003).

Secondly, high supercooling level is beneficial to initiate ice nucleation. In the study of Kiani et al. (2011a) about the nucleation of water and sucrose solutions, the time delay from the commencement of ultrasound treatment, and the commencement of ice nucleation was shorter at a lower ultrasound treatment temperature. This result confirms that the materials tend to be nucleated at a high supercooling degree.

Furthermore, a high ultrasound power or intensity in a proper range is desired for ice nucleation while a low acoustic power is not strong enough to initiate the nucleation (Inada et al., 2001; Chow et al., 2003; Kiani et al., 2011c). The study of Chow et al. (2003) indicated that as the acoustic power increased, the nucleation temperature increased simultaneously (Fig. 4). Attention should be paid that increasing the acoustic power may result in a production of a great amount of heat, which is undesired for food freezing. Kiani et al. (2011c) found that due to the thermal effect at applied high ultrasound intensities, the water nucleation during freezing of agar samples only occurred occasionally when the ultrasound duration was 5 or 15 seconds. Therefore, the thermal effect of ultrasound should be taken into account when choosing the ultrasound power for freezing.

As for the ultrasound duration, long duration cannot favor the nucleation due to the heat generation while too short time is not able to cause the commencement of nucleation. In fluid samples, 1 second of ultrasound irradiation was enough to initiate the nucleation (Chow et al., 2003; Inada et al., 2001). As regarded to agar gel samples, Kiani et al. (2011a) found that the ultrasound duration of 3 seconds could trigger repeatable nucleation. However, there was an interesting result in the study of Kiani et al. (2011c), who found that the nucleation occurred again in a repeated way when samples were treated for 15 seconds at the

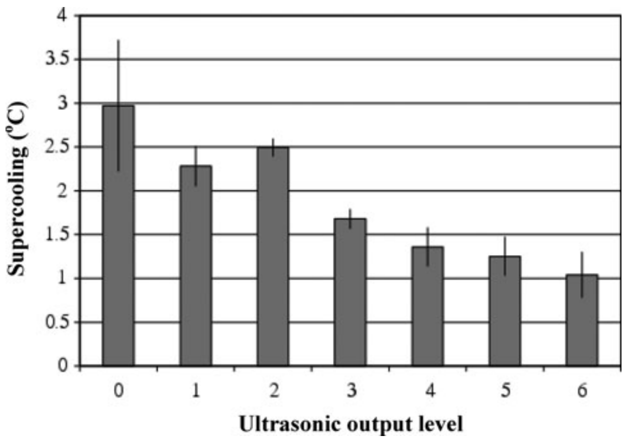


Figure 4 The primary nucleation temperatures of ice in a 15 wt.% sucrose solution at different ultrasonic output levels. (Chow *et al*., 2003).

ultrasonic intensity of 0.25 W/cm^{-2}. Considering that too many unknown factors can affect the ultrasound-assisted nucleation of water in solid samples, it is difficult to explain the mechanism of this phenomenon. More studies should be performed to elucidate the exact nucleation mechanism in solid samples.

Factors Affecting the Ultrasonic Enhancement of Heat and Mass Transfer

The factors that affect the ultrasonic enhancement of heat- and mass-transfer process during freezing include the ultrasound power, ultrasound duration, and the freezing phase.

Since high level of ultrasound power can create a strong ultrasound vibration, it can lead to an increase of the heat and mass transfer rate during freezing (Sastry et al., 1989). Li and Sun (2002a) confirmed that the use of ultrasound at a higher power level induced a more rapid decrease of potato sample temperature from 0 to −7°C, which was the phase changing period. However, after this phase changing period, Li and Sun (2002a) found the sample temperature treated with a higher power level decreased more slowly. This phenomenon is probably due to that the accumulated thermal effect of ultrasound and the absorption of ultrasonic waves by the freezing system are proportional to the acoustic power (Zheng and Sun, 2005).

Ultrasound duration is another important parameter to affect the heat and mass transfer process during freezing. In the study of Li and Sun (2002a), ultrasound treatment for more than 1 minute increased the freezing rate significantly during immersion freezing of potato samples while the negative thermal effect should be considered when the exposure time exceeded 2 minutes.

Moreover, the heat and mass transfer process behaves differently when ultrasound is applied in different freezing phases. The freezing process is composed of three phases, including a precooling or chilling phase, a phase change period, and a tempering phase (Delgado and Sun, 2001). Li and Sun (2002a) found that the most effective phase, when ultrasound was applied, was the phase change period. In this phase, a great deal of latent heat is produced due to water crystallization (Fennema, 1973). Thus, the heat- and mass-transfer process can be improved markedly by ultrasonic waves in this period.

Factors Affecting the Crystal Shape and Size

In theory, small ice crystals are formed during rapid freezing (Fennema, 1973). It has already been discussed that high level of ultrasound power can increase the freezing rate (Li and Sun, 2002a). Consequently, the size of ice crystals decreases with the increase of acoustic power (Saclier et al., 2010a). By comparing the microstructures of frozen potato tissues treated with 15.85 and 7.34 W ultrasound, Sun and Li (2003) found that smaller ice crystals were formed inside and outside the cells at the higher level of acoustic power, which resulted in a better structural integrity. Furthermore, the violent agitation provided by high levels of acoustic power can fragment the preexisting crystals, which also contributes to the formation of small ice crystals. As for the influence of acoustic power on the morphology of ice crystal, Saclier et al. (2010a) found that the increase of acoustic power could increase the mean circularity of ice crystal.

On the other hand, it is known that the increase of supercooling degree can benefit the formation of small ice crystals. After examining the characteristics of ice crystals in 10% mannitol frozen solutions, Nakagawa et al. (2006) found that large and directional ice crystals were formed at lower supercooling degree, while higher supercooling degree resulted in the appearance of a great number of small heterogeneous ice crystals. Furthermore, the study of Saclier et al. (2010a) revealed that the mean circularity of ice crystal increased with the increase of supercooling degree.

Mathematical Modeling of Ultrasonic Enhancement of Freezing Process

It is a difficult task to use mathematics to describe the whole freezing process enhanced by ultrasound. To our best knowledge, only Saclier et al. (2010b) developed a theoretical model for ice primary nucleation induced by ultrasound. This model was based on the theory that high pressures formed during the collapse of cavitation bubbles increase the equilibrium freezing temperature of water, and subsequently increase the supercooling level to promote ice nucleation. The correlations between the operational parameters, including ultrasonic wave amplitude and supercooling degree and the number of nuclei were built. More specifically, the number of nuclei generated by a single bubble can be expressed as:

$$N_B = \int_t \int_v J(r, t) \mathrm{d}V \mathrm{d}t \tag{3}$$

where $J(r, t)$ is the nucleation rate distribution as a function of liquid pressure and temperature, V is the liquid volume surrounding the bubble, and t is time.

To specify the relationship between the nucleation rate and ultrasound-generated pressure and temperature, J (T) can be written as:

$$J(T) = \left(\frac{\mathrm{RT}\rho_{\mathrm{sol}}}{M_{\mathrm{sol}}\mathrm{h}}\right) \exp\left(\frac{-\Delta G_D(T)}{\mathrm{RT}}\right) \exp\left(\frac{-\Delta G(T)}{\mathrm{RT}}\right) \quad (4)$$

where J is the nucleation rate, h is the Planck constant, R is the perfect gas constant, ΔG is the critical free energy at the point of formation of a nucleus of critical size, ΔG_D is the activation energy for the water molecules diffusion across the water/ice interface, M_{sol} is the molar weight of the solution, and ρ_{sol} is its density. Considering the high pressure produced during the collapse of cavitation bubble, ΔG can be expressed as:

$$\Delta G(T, p) = \frac{16\pi}{3} \frac{\sigma_{sl}^3(T, p)}{\rho_s^2(T, p) L^2(p) \left(\frac{T_m(p)-T}{T_m(p)}\right)^2} \quad (5)$$

where L is the latent heat of melting, σ_{sl} is the crystal-solution interface energy, T_m is the solidification temperature, T is temperature, ρ_s is the solid phase density, and p is the liquid pressure.

Furthermore, the same authors (Saclier et al., 2010b) validated this model qualitatively through the finding that the size of ice crystal was negatively correlated with acoustic power and supercooling level.

However, more mathematical models are expected to be developed to simulate not only the ultrasonic initiation of ice nucleation, but also the ultrasonic enhancement of heat and mass transfer and the ultrasonic control of crystal size and shape during freezing.

ULTRASONIC ENHANCEMENT OF THAWING PROCESS

Thawing is the reverse process of food freezing. The final quality of frozen products is also dependent on the thawing process. The thawing of bulky frozen foodstuffs is a time-consuming process, which is usually slower than freezing process. In the meantime, food products are subject to damage by microorganism and physical and chemical changes (Li and Sun, 2002b). Therefore, several technologies are employed to promote heat generation within food to enhance the thawing rate. Ultrasound has shown some potential to benefit the thawing process.

Major Functions of Ultrasound in Enhancing Thawing Process

Despite the negative aspects of localized heating, poor penetration and high power requirement that block the utilization of ultrasonic technology during thawing, the acoustic energy can still be absorbed by frozen foods to accelerate the thawing process. Kissam et al. (1981) successfully shortened the thawing time of blocks of cod using low frequency acoustic energies. Furthermore, the thawing process of frozen meat and fish samples was accelerated under appropriate ultrasonic irradiation without surface overheating problems (Miles et al., 1999). Generally speaking, the application of ultrasound in a proper way can enhance the thawing rate without the problems of surface overheating and excessive dehydration of food products. As a result, the drip loss in thawing can be reduced and the product quality is assured.

During thawing, ultrasound treatment can be carried out together with water immersion. Otherwise, ultrasound can provide all the energies required. In this case, ultrasound transducer can be mounted on a coupling disc and the frozen samples contacted the coupling disc directly (Miles et al., 1999).

Factors Involved in Ultrasonic Enhancement of Thawing Process

The ultrasound frequency is a critical factor for ultrasound to enhance thawing process. Kissam et al. (1981) recommended the application of a frequency in the relaxation frequency range of ice crystals in foodstuffs for thawing, since more acoustic energies can be absorbed at this frequency. However, ice mainly responds to frequencies in the low kilohertz range during a relaxation process whereas ultrasound usually works at a frequency greater than 20 kHz. Therefore, the applicability of relaxation mechanism during ultrasound-assisted thawing needs to be verified. The study of Miles et al. (1999) found that low frequencies ($\leq$ 430 kHz) resulted in low ultrasonic penetration and surface over-heating due to cavitation. In the meantime, the heating rate in the thawed region of samples increased as the frequency increases when the frequency was above 430 kHz. Moreover, the surface overheating happened again at high frequencies ($\geq$ 740 kHz) because of the high ultrasound attenuation. To obtain an acceptable surface temperature and prevent poor energy penetration, the applied frequency of 500 kHz was proper for this kind of experimental setup and thawed samples.

The heating rate of thawed region increases with the increase of ultrasound intensity (Miles et al., 1999). For ultrasound-assisted thawing coupled with cold water immersion, a higher acoustic intensity should be used than that of thawing with all energy supplied by ultrasound due to the additional heat dissipation (Miles et al., 1999).

Sample orientation during ultrasound treatment can also affect the thawing rate. During ultrasonic thawing of meat and fish samples at a frequency of 520 kHz, it took 39% more time for thawing to take place at a depth of 76 mm when transmission was parallel to samples than when perpendicular (Miles et al., 1999). This phenomenon was probably related to the attenuation coefficients at different orientations. The attenuation coefficient when transmission was parallel was higher than that when transmission was perpendicular (Shore et al., 1986). As a result, more heat was accumulated near the surface when samples were parallel to ultrasonic waves.

Furthermore, the composition of thawed products can affect the ultrasonic transmission coefficient, thus affecting the overall thawing time. Take fat and lean for example, the ultrasonic transmission coefficient is low when ultrasonic waves travel from warmed fat to frozen lean (Miles et al., 1999).

Although the feasibility of ultrasonic technology during thawing process was investigated around 60 years ago, there are not many researches in this area. More studies are expected to fully understand the influence of ultrasound on food thawing.

Mathematical Modeling of Ultrasonic Enhancement of Thawing Process

Through simulating the thawing process under ultrasound irradiation, the thawing time and temperature of thawed tissue can be predicted. When ultrasonic waves travel through the frozen samples, the temperature of thawed region rises since the acoustic energy is absorbed and dissipated as heat. A differential equation below can be employed to describe the heat conduction in unfrozen region for slab geometry (Miles et al., 1999):

$$\lambda \frac{\partial^2 \theta}{\partial \mathrm{x}^2} + 2\mu I_0 e^{-2\mu x} = \rho c \frac{\partial \theta}{\partial t} \tag{6}$$

where λ is the thermal conductivity, θ is the increased temperature, μ is the amplitude attenuation coefficient, x is unfrozen region, I_0 is intensity per unit area at $x = 0$, c is the specific heat capacity of sample, and ρ is the density of the sample.

Furthermore, the thermal conduction and absorption of ultrasound at the position of frozen/thawed boundary can be described by:

$$\rho L \frac{\mathrm{d}X}{\mathrm{d}t} = I_0 e^{-2\mu x} - \lambda \left(\frac{\partial \theta}{\partial x} \right) x = X \tag{7}$$

where L is the absorption of latent heat of fusion of ice. By solving Equations (6) and (7), the ultrasonic thawing time and temperature in the thawed region can be calculated. This model was successful in predicting the ultrasonic thawing time of meat and fish (Miles et al., 1999).

ULTRASONIC ENHANCEMENT OF BRINING PROCESS

Brining process is a common step during the manufacturing of food products, particularly for meat and cheese products. It is an efficient method for food preservation. As for cheese products, the brining process directly determines their final quality. In this operation, samples are salted by immersion in a brine solution, inside which the counter-current mass transport of salt and water takes place. Either external or internal mass transfer during brining process can be accelerated by ultrasound.

Major Functions of Ultrasound in Enhancing Brining Process

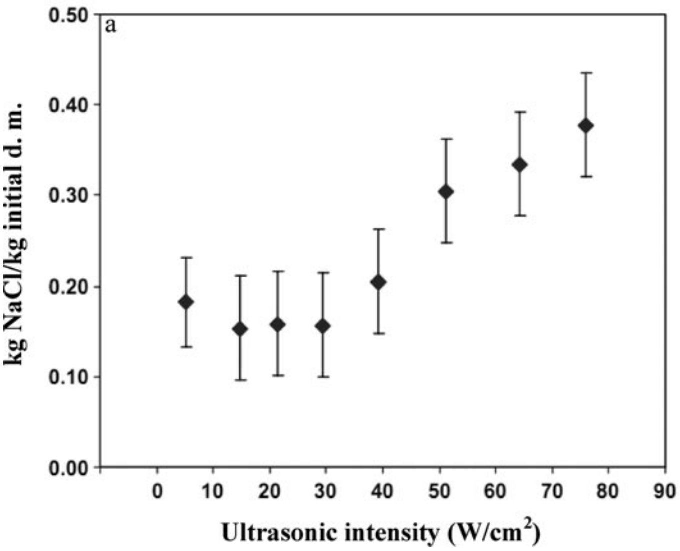
When ultrasound was employed during cheese brining in the study of Sánchez et al. (1999), the magnitude of the improvement in NaCl gains and water losses in ultrasound-treated samples was clearly higher than that in non-ultrasound treated ones. Acoustic cavitation mainly contributes to the mass transfer enhancement rather than the mechanical effects of ultrasound (Sánchez et al., 1999). For brined cheeses, most of the absorbed salt accumulates in their outer position. Therefore, a subsequent ripening process is required to achieve uniform salt distribution (Sánchez et al., 2000). The study of Sánchez et al. (2000) indicated that salt equilibrium in ultrasound-treated cheeses could not be attained at an earlier ripening stage than that in conventionally brined cheeses. However, ultrasonically brined cheeses exhibited a lower effective water diffusivity, which meant that these samples had a lower drying rate. As for acoustical brining of meat product, Cárcel et al. (2007) found that ultrasound significantly enhanced the mass transfer rate once the acoustic intensity reached a threshold value.

On the other hand, a rapid brining technology can bring several other benefits. The problems of enzymatic softening, bloating, and structural damage of brined foodstuffs can be controlled. Additionally, high salt gain rate allows the reduction of NaCl content in the brine solution, thus decreasing the desalting possibility after processing (Chemat et al., 2013).

Factors Involved in Ultrasonic Enhancement of Brining Process

The factors that affect the ultrasonic enhancement of brining vary during cheese and meat processing.

During ultrasonic brining of cheeses, the pressing time prior to brining can markedly affect the salt and water diffusion. The salt absorption increased with the increase of pressing time (Sánchez et al., 2000). The study of Sánchez et al. (2000) exhibited that among the ultrasound-treated cheeses, the NaCl concentration in the most external position of cheeses pressed for 145 minutes was 7.1 g NaCl/100 g, which was 2.3 g NaCl/100 g higher than that in samples pressed for 60 min. The differences in pH of unsalted samples probably contributed to the differences in salt transfer rate, since the pH of unsalted samples decreased with the increase of pressing time (Sánchez et al., 2000). A low pH can promote the resistance to sample shrinkage during brining. Thus, a higher porosity is attained in the long-time pressed cheeses, which is beneficial to mass transfer. Furthermore, the water and salt transfer during brining are influenced by ultrasound treatment temperature. Higher water losses and salt gains



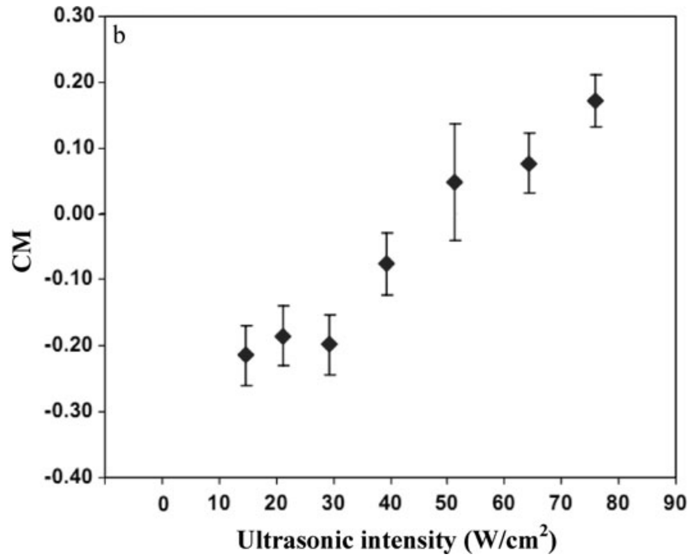


Figure 5 NaCl (a) and moisture (b) content in meat samples treated in 800 mL of saturated NaCl brine at 2°C and at different ultrasonic intensities. (Cárcel *et al.*, 2007).

were detected during acoustic brining of cheeses at 20°C than that at 5°C (Sánchez et al., 1999).

When it comes to use ultrasound to enhance brining process of meat, the enhancement of mass transfer depends on the applied ultrasound intensity. Both the moisture and NaCl transport can only be affected by ultrasound when the acoustic intensity exceeds a threshold (Cárcel et al., 2007). Once the applied intensity was over the threshold value, the moisture and NaCl contents in meat increased as the intensity increased (Fig. 5). Furthermore, although the sample geometry had no marked effect on the global mass-transfer process in the experimental setup of Cárcel et al. (2007), this factor should be taken into account when large samples are treated ultrasonically. There is a general agreement that mass transfer from liquid is proportional to the external surface (Bird et al., 2002).

Mathematical Modeling of Ultrasonic Enhancement of Brining Process

To model the cheese bringing process under ultrasonic irradiation, the equations based on the combination of microscopic mass transfer balance with Fick's law can be employed (Sánchez et al., 1999). For parallelepiped shapes, the equation can be written as follows:

$$\frac{\partial X}{\partial \mathrm{t}} = D\left(\frac{\partial^2 X}{\partial x^2} + \frac{\partial^2 X}{\partial y^2} + \frac{\partial^2 X}{\partial z^2}\right) \tag{8}$$

where X is the local concentration of either moisture or NaCl in the cheese, D is the effective diffusional coefficients for either water or salt, t is the time, and x,y,z are the characteristic coordinates of each geometry. By solving Equation (8), the influence of ultrasound on mass transfer during brining process can be elucidated. Furthermore, Sánchez et al. (1999) found that the identified effective diffusivity coefficients for both NaCl and water transfer could be fitted to the following Arrhenius equation well:

$$D = D_0 \exp\left(\frac{-E_a}{R(T + 273)}\right) \tag{9}$$

where T is the osmotic solution temperature and R is the gas constant. Thus, the influence of brine temperature during sonication on mass transfer can be elucidated.

For meat brining, the diffusion equation based on the Fick's second law of diffusion can also be used for modeling (Barat et al., 2011). However, the feasibility of the model for ultrasonic brining needs to be verified.

ULTRASONIC ENHANCEMENT OF OXIDATION PROCESS

It is well-known that the collapse of cavitation bubbles can generate extreme high temperature and pressure. At the same time, free radicals are produced. There is a general agreement that the rate of oxidation reaction can be enhanced in the presence of free radicals. The wine ageing process is regarded as a mild oxidation process (Bozalongo et al., 2007). Therefore, the sonochemical effect can be used to enhance the reactions during wine ageing. The following discussion is focused on wine ageing instead of the general oxidation.

Major Functions of Ultrasound in Enhancing Oxidation Process

Wine ageing is an essential operation to produce high-quality wines. However, the traditional barrel ageing process is time-consuming, which normally takes from 3–5 months to 3–5 years. Several novel technologies have been developed to shorten the ageing time, such as additions of wood fragments, small amounts of pure oxygen and lees to wine. As a physical method, ultrasonic irradiation shows some potential to reduce the ageing time drastically. The studies of Chang and Chen (2002) showed that after 1-week ultrasound treatment at a frequency of 20 kHz, the quality of rice wine was regarded to be identical to that of market wine, which was naturally aged for 1 year. Furthermore, the quality of ultrasound-treated red wines can not only arrive at their peak level rapidly, wine quality can stay at peak level for a much longer time than that of naturally aged wines (Leonhardt and Morabito, 2007).

Together with the ultrasonic enhancement of wine ageing rate, other benefits can be obtained. Both the cost and space for wine ageing can be reduced greatly when traditional ageing process is replaced by ultrasonic ageing. The contamination of barrels by undesirable microorganisms is also eliminated. Moreover, the great wine loss due to evaporation during barrel ageing can be avoided (Tao et al., 2013).

Factors Involved in Ultrasonic Enhancement of Oxidation Process

To ensure that the wine ageing process can be enhanced successfully, the ultrasonic frequency should be chosen properly. Chang (2005) found that the taste of rice wines treated with 20 kHz ultrasonic waves within one week could be equivalent to that of market rice wines whereas the taste of rice wines treated with 1.6 MHz ultrasonic waves was not appreciated by the sensory panelists. Combined with the report of Lindley and Mason (1987), it could be concluded that the suitable ultrasonic frequency used for accelerating wine ageing reactions is probably in the range from 20 to 100 kHz.

The ultrasound duration also needs to be controlled well. Chang's study (2005) indicated that more ultrasonic modifications of wine composition were detected when wine was treated for longer time. Particularly for the compounds which were responsible for unpleasant offensive flavor such as acetaldehyde and high alcohols, their contents in rice wine all decreased with the increase of overall treatment time. In this study, the quality of rice wine treated by 20 kHz ultrasound for the longest time was regarded best. However, this result does not mean that a long ultrasound duration can always benefit the improvement of wine quality. It has been discussed that ultrasound treatment could result in a degradation of phenolic compounds, which contribute to wine's organolectic characteristics (Ashokkumar et al., 2006). Furthermore, despite a lack of scientific data, it is believed that a long ultrasound duration is detrimental to wine's aromatic properties. During the application of ultrasound for wine ageing, the treatment time should be decided cautiously since the wine quality is sensitive to the processing conditions.

The processing temperature is an important parameter for wine quality. Although chemical reaction rate is enhanced at high temperature, it can sharply reduce the contents of aromatic compounds in wine (D'Auria et al., 2009). Therefore, the influence of temperature on wine quality should be taken into account when deciding the ultrasound treatment temperature.

Furthermore, the feasibility of ultrasonic technology for enhancing wine ageing is dependent on the wine type. The study of Chang and Chen (2002) exhibited that ultrasound improved the quality of rice wine whereas the quality of maize wine got worse after treatment. When it comes to use ultrasound to enhance wine ageing, a preliminary study should be performed to verify whether the wine quality of each specific type can be improved by ultrasound or not.

Other factors, such as ultrasound intensity, the treatment mode (continuously or intermittently), etc., can also affect the ultrasonic enhancement of wine ageing. More studies should be carried out in the future to elucidate the influence of these factors on wine quality.

Mathematical Modeling of Ultrasonic Enhancement of Oxidation Process

Wine ageing is a complicated process involving numerous chemical reactions. Since it is difficult to confirm how these reactions occur exactly during ageing, the easiest way to model these reactions is using empirical equations or non-parametric simulative models, such as RSM and ANN. In this way, the influence of each factor related to ultrasonic enhancement of wine ageing on wine quality can be predicted.

Chang and Hsu (2006) used the following general polynomial model to build the relationship between the wine parameters and the ultrasound treatment times:

$$Y=\beta_0+\beta_1 X+\beta_2 X^2+\cdots+\beta_k X^{\mathrm{k}}+\varepsilon \tag{10}$$

where ε is a normal random variable and β_i ($i = 0, 1, \ldots\ldots k$) are the adjustable parameters. Equation (10) has a limitation due to that it only considers one independent variable. RSM and ANN can perform well during modeling if more than one independent variable is involved.

ULTRASONIC ENHANCEMENT OF FILTRATION PROCESS

Filtration is a common procedure to separate the solid particles from bulky liquids. During filtration, the problems of membrane fouling and concentration polarization severely reduce the filtration efficiency. Membrane fouling is generally characterized as the marked decline of permeate flux through membrane, which is caused by cake formation and pore blocking (Muthukumaran et al., 2007). In the meantime, the formation of concentration gradient of retained components near or on the membrane surface contributes to the emergence of concentration polarization (Muthukumaran et al., 2005). The application of ultrasound during filtration can eliminate the negative effects of membrane fouling and concentration polarization, thus enhancing the filtration efficiency.

Major Functions of Ultrasound in Enhancing Filtration Process

When ultrasound is introduced during filtration, cake layer and concentration polarization on the membrane surface can be disrupted whereas the intrinsic permeability of membrane is not affected by ultrasound. As a consequence, the flow resistance decreases and the flux increases (Chemat et al., 2010). The cavitation bubbles, liquid jet, microstreaming and turbulence generated by cavitation phenomenon are responsible for the detachment and transport of particles away from membrane surface (Kyllönen et al., 2005). Furthermore, the utilization of ultrasound during filtration can prolong the life of filter due to the elimination of cake and clog on its surface (Chemat et al., 2010). In food processing area, ultrasound has been successfully employed to enhance the dairy whey filtration and juice extraction from apple pulp (Mason et al., 1996; Muthukumaran et al., 2005).

Factors Involved in Ultrasonic Enhancement of Filtration Process

During ultrasonic filtration, the ultrasonic factors that affect the ultrasonic enhancement of filtration involve ultrasound frequency, ultrasound intensity, treatment mode, and ultrasound propagation direction. The nonultrasonic factors include feed properties, membrane properties, cross-flow velocity, temperature, pressure, and membrane position.

Nonultrasonic Factors

The feed properties are important parameters which are closely associated with the ultrasonic enhancement of permeate flux, and include feed concentration, viscosity, and particle size. At a high feed concentration, the permeate flux probably shows a small value without ultrasonic assistance whereas ultrasound can significantly enhance the flux (Kobayashi et al., 1999). However, an extreme high feed concentration can reduce the ultrasonic effect on permeate flux, since a high particle concentration generate a high degree of ultrasound attenuation when ultrasonic waves travel through the cross-flow suspension (Kyllönen et al., 2005). As for the feed viscosity, the ultrasonic effect on flux is weak in a suspension with a high viscosity because it is difficult to generate cavitation in viscous liquid. Furthermore, the magnitude of the ultrasonic enhancement of permeate flux in a suspension can be high if big particles with high rejection by membrane are suspended (Kyllönen et al., 2005).

The ultrasonic enhancement of filtration process is also affected by the membrane properties, such as the membrane pore size and material. Too big pore size and small size can hinder the ultrasonic enhancement of permeate flux. In the case of utilization of big-pore size membrane, the pores may be plugged severely with particles and ultrasound is not effective enough to take away these particles. When the membrane with a small pore size is applied, there is not too much cake formed under ultrasonic irradiation (Matsumoto et al., 1996). On the other hand, the ultrasonic erosion of membrane varied on membranes with different materials. However, the influence of membrane material on the acoustic enhancement of permeate flux has not been elucidated.

The permeate flux decreases with the increase of applied pressure. A high pressure compresses the cake layer strongly. Thus, the efficiency of ultrasonic removal of cake layer is reduced (Kyllönen et al., 2005). On the other hand, the increase of pressure can lead to an increase of cavitation threshold and a simultaneous decrease of the effects caused by cavitation (Muthukumaran et al., 2005). There is an interesting result in the study of Muthukumaran et al. (2005), who found that the ultrasonic enhancement of flux compared to non-ultrasonic filtration increased slightly as the pressure increased. This result indicated that the liquid jet and microstreaming contribute more to the ultrasonic enhancement of permeate flux rather than ultrasonic cavitation.

Furthermore, the permeate flux can be changed when the sonication temperature varies. Muthukumaran et al. (2005) found that the permeate flux increased slightly as the temperature increased during ultrasonic filtration of dairy whey. This phenomenon can be explained by the decrease of liquid viscosity at high temperatures.

As regard to the cross-flow velocity, the cleaning effect of ultrasound on the cake layer is not affected by a high-speed flow rate while the high-speed flow can help ultrasound carry away the particles continuously. Both the studies of Muthukumaran et al. (2005) and Kobayashi et al. (1999) found that the highest permeate flux during sonication was obtained at the highest cross-flow velocity.

In addition, the ultrasonic effects on filtration vary when the membrane is placed at different positions. During the filtration of milk solution, the membrane was placed at 4, 8, and 12 cm distance, respectively, from the ultrasonic transducer (Latt and Kobayashi, 2006). It was observed that the permeate flux was the highest at the 8-cm distance. The result of morphology also confirmed that ultrasound was most effective for membrane cleaning at the 8-cm distance.

Ultrasonic Factors

Normally, the low-frequency ultrasound performs better than the high-frequency ultrasound in terms of the enhancement of filtration. Kobayashi et al. (1999) applied ultrasound of 28, 45, and 100 kHz frequencies to assist dextran filtration. They found that the permeate flux reached its highest value more rapidly when a 28 kHz ultrasound was used (Fig. 6). In the meantime,

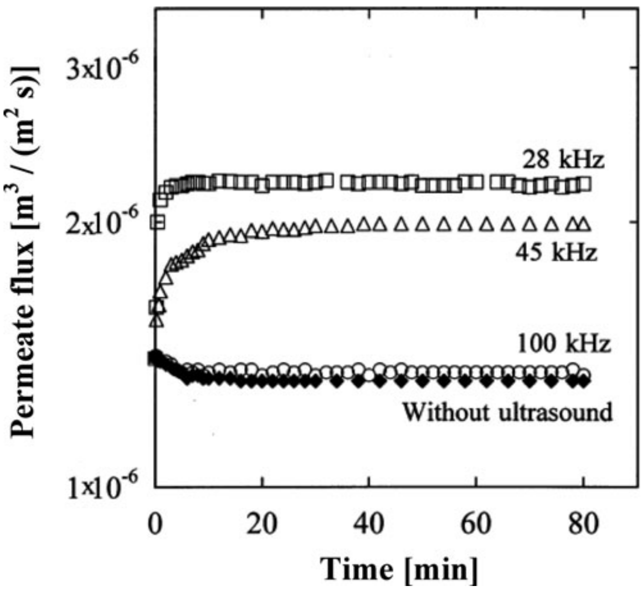


Figure 6 Permeate flux change with time for 1 wt.% dextran aqueous solution during ultrasonic irradiation at different frequencies. (♦: without ultrasound, □: 28 kHz, △: 45 kHz, ○: 100 kHz) (Kobayashi *et al*., 1999).

the value of flux using the 28 kHz frequency ultrasound was always higher than that when the solution was treated by 45 and 100 kHz ultrasound. Moreover, the 100 kHz ultrasound had no positive effect on the permeate flux compared with nonultrasound assisted filtration. Similar results were obtained in the study of Muthukumaran et al. (2007), who found that the 50 kHz ultrasound was more effective than 1 MHz ultrasound to enhance the whey permeate flux. Despite that ultrasonic cavitation is not the only contributor to the enhancement of filtration, cavitation bubbles behave more energetically at low frequency, which can promote the removal of cake layer. Therefore, a low-frequency ultrasound is recommended to enhance the filtration process.

During filtration, high ultrasound intensity is beneficial to membrane cleaning and permeate flux enhancement. During the ultrasonic filtration of dextran solution, the permeate flux increased with the increase of acoustic intensity (Kobayashi et al., 1999). Furthermore, the flux increased more rapidly as acoustic intensity increased when 45 kHz ultrasound was used than the 28 kHz ultrasound was used. However, it should be noticed that the higher the acoustic intensity is, the easier the membrane is damaged by ultrasound. Based on this reason, a gentle ultrasound treatment with high filtration efficiency is expected.

From an energy saving point of view, an intermittent ultrasound treatment can be considered. In this case, the influence of pulse mode on filtration should be taken into account. In the study of Muthukumaran et al. (2007), a pulse mode of five minutes on and five minutes off was applied. These authors found that within short-time treatment, the intermittent ultrasound significantly enhanced the permeate flux. However, the intermittent ultrasound performed less effectively or even had negative effect on the filtration process for long-time treatment. To enhance the filtration in a proper way, the pulse mode of ultrasound should be controlled well.

In the meantime, the factor of ultrasound propagation direction should be taken into account. During filtration, ultrasound can be irradiated perpendicularly either from the feed side or the permeate side of membrane. Moreover, the ultrasonic transducer can be placed vertically against the membrane. The influence of ultrasound propagation direction was studied during the filtration of industrial wastewater (Kyllönen et al., 2006). It was found that with the ultrafiltration membrane, ultrasound was much more effective to increase permeate flux when the ultrasonic irradiation was from the feed side than from the permeate side of membrane. On the other hand, when the microfiltration membrane was used, ultrasonic irradiation from the feed side of membrane led to the fouling of membrane whereas sonication from the permeate side enhanced the permeate flux to a steady level. As can be seen, in the case of filtration using open membrane, ultrasound behaves less effectively to enhance the filtration process when the ultrasound propagation direction is from the feed side of membrane.

Mathematical Modeling of Ultrasonic Enhancement of Filtration Process

The film theory and resistance in series model can be employed to model the ultrasound-enhanced filtration process. In this case, the flux through the membrane (J) can be expressed as:

$$J = \frac{\Delta p}{\mu R_t} \tag{11}$$

where R_t is the total flow resistance, Δp is the trans-membrane pressure, and μ is the liquid viscosity. The total flow resistance is composed of the membrane resistance (R_m), the fouling resistance due to the irreversible deposits (R_f) and the reversible resistance due to both concentration polarization and cake layer (R_r) (Kyllönen et al., 2005). Moreover, R_m can be calculated from the Equation (11) with the data from pure water filtration.

In the next step, the following two equations developed by Ho and Zydney (2000) can be used to describe the flux decay as a function of time (t) when both cake filtration and pore blockage mechanisms are available:

$$\frac{J}{J_0} = \exp\left(-\frac{\alpha \Delta p C_b}{\mu R_m} t\right) + \frac{R_m}{R_m + R_p}\left[1 - \exp\left(\frac{\alpha \Delta p C_b}{\mu R_m} t\right)\right] \tag{12}$$

$$R_p = (R_m + R_{p0})\sqrt{1 + \frac{2 f' R' \Delta p C_b t}{\mu (Rm + R_{p0})^2}} - R_m \tag{13}$$

where J_0 is the initial flux, C_b is the particle concentration in unfiltered solution, α is the pore blockage parameter, R_{p0} is the initial resistance of the deposit, and $f'R'$ is the cake growth factor. In this way, the three adjustable parameters, namely, α, R_{p0}, and $f'R'$ can be used to characterize the permeate flux. The model has been successfully employed for the ultrasonic enhancement of dairy whey ultrafiltration (Muthukumaran et al., 2005). Their results indicated that the value of R_{p0} and $f'R'$ decreased when ultrasound was introduced whereas the value of α only decreased slightly.

On the other hand, the following gel polarization model can also be employed, which assumed that there is a concentration-polarized boundary layer above the precipitated cake (Muthukumaran et al., 2005):

$$J(C - C_p) = -D\frac{\mathrm{d}C}{\mathrm{d}x} \tag{14}$$

where C_p is the permeate concentration, C is the feed concentration, and D is the diffusion coefficient of solute molecules. Through integrating Equation (14) across the concentration polarization layer, the permeate flux can be expressed as:

$$J = k\ln\frac{C_w - C_p}{C_f - C_p} \tag{15}$$

where C_f is the bulk feed concentration and C_w is the concentration at the membrane surface. C_p could be ignored if the solute rejection is high. k is the mass transfer coefficient, which can be expressed as $k = D/\delta$. Here, δ is the thickness of the concentration polarization layer.

ULTRASONIC ENHANCEMENT OF DRYING/DEHYDRATION PROCESS

Together with the freezing and brining process, drying is a useful method for preserving agricultural and food products (Sun and Woods, 1994a; Sun and Woods, 1994b; Cui et al, 2004; Sun 1999; sun and Byrne, 1998) reducing postharvest loss, and prolonging their shelf-life. In addition, this process can be used to manufacture the dehydrated food, the consumption of which is growing rapidly in the last decades (Fuente-Blanco et al., 2006). The traditional drying technology is based on the convective hot-air drying, which is a simultaneous mass and heat-transfer process including phase change. However, this kind of technology has several disadvantages. First of all, the drying rate is low, especially during the falling rate period when the internal mass transfer resistance is in charge of the drying process (García-Pérez et al., 2007). Secondly, the hot-air drying can result in severe food quality damage, such as product shrinkage with tough texture, generation of undesired food flavor, low rehydration rate, product browning, etc. (Hu et al., 2006; Jayaraman and Gupta, 1992). Furthermore, this treatment is energy-consuming and expensive. Based on these reasons, novel technologies including microwave, infrared radiation, and ultrasound have been introduced during air drying while freeze drying and spray drying have been developed to replace air drying. Among them, ultrasound is promising to enhance air drying process in different ways.

On the other hand, ultrasonic irradiation is a useful pretreatment for air drying. To be specific, samples can be either immersed in hypertonic solutions which is known as osmotic dehydration or in distilled water, and then submitted to ultrasound treatment (Fernandes et al., 2009; Fernandes et al., 2011). Although ultrasonic waves behave somewhat differently on the product structure in different liquid mediums and the soluble solids may be incorporated into samples when the hypertonic solutions are used, both treatments are effective to enhance the subsequent air drying rate (Fernandes et al., 2009).

Major Functions of Ultrasound in Enhancing Drying/Dehydration Process

The main purpose of drying is to remove water or other solvents from products through evaporation for air drying and osmotic pressure difference for osmotic dehydration. The mass-transfer process during drying can be significantly accelerated by ultrasound. Several ultrasonic effects are responsible for the enhancement of drying rate. To start with, ultrasonic waves, which behave similarly to the sponge, produce a rapid series of alternative compression and expansion when they travel through the solid medium. This alternating force promotes the formation of microscopic channels inside the material, which can reduce the diffusion boundary layer and benefit the moisture removal (Fuente-Blanco et al., 2006). Secondly, no matter when ultrasound is applied during air drying or as a pretreatment, cavitation of water molecules inside solid materials can be generated, which makes the removal of strongly attached moisture easier (Mulet et al., 2003). Furthermore, the microstreaming, the variations of pressure, viscosity and surface tension introduced by ultrasonic waves, as well as the deformation of porous solid materials, also contribute to the drying process enhancement (Gallego-Juárez et al., 1999; García-Pérez et al., 2006b).

The ultrasonic technology has been introduced during air drying of several fruits and vegetables. Under the same experimental setup, the drying time of eggplant cylinders, carrot cubes, and lemon peel slabs could be reduced by 72%, 32%, and 53%, respectively, in comparison with untreated samples (García-Pérez et al., 2009, 2011). The main difficulty for the application of ultrasound during air drying is because of the solid/gas system. Both the high acoustic energy absorption of air and the acoustic impedance mismatch between air and application systems result in low transfer efficiency of acoustic energy from air into solid materials (García-Pérez et al., 2006b). Air-borne ultrasound and the prototype which allow samples to direct contact with a piezoelectric vibrating transducer have been developed to satisfy the processing requirements (Fuente-Blanco et al., 2006; Cárcel et al., 2011). Recently, a drying screen with aperture of 500 μm, which served as both the sound transmitting and sample supporting surface was successfully used during ultrasound-assisted air drying (Schössler et al., 2012). However, more efforts are needed to scale up the ultrasound-enhanced drying machines to industrialize this novel technology.

Furthermore, ultrasonic pretreatment can increase the effective water diffusivity in banana and pineapple during subsequent air drying process. As a result, the time required to remove the same amount of water from fresh fruit are reduced compared to nonultrasonic pretreated fruit (Fernandes and Rodrigues, 2007; Fernandes et al., 2008; Fernandes et al., 2009). The formation of microscopic channels in foodstuffs caused by ultrasound contributes to the enhancement of water diffusivity. However, ultrasound pre-treatment cannot always benefit the drying process. When mushrooms were treated using a 20 kHz ultrasound probe for three minutes before air drying, Jambrak et al. (2007) found that the drying time was prolonged. This phenomenon could be explained by the degassing effect of ultrasound, which made the pores at the food surface filled. Besides the enhancement of drying rate, ultrasound pretreatment can affect food composition, structure, and rehydration ability. More specifically, ultrasonic pretreatment resulted in a water loss in pineapple (Fernandes and Rodrigues, 2007). Ultrasound pre-treatment could also cause sugar loss in fruit when they were immersed in distilled water whereas a sugar gain was found when they were immersed in osmotic solution (Fernandes et al., 2009). As for the rehydration properties of ultrasound pretreated food, Jambrak et al. (2006) found that the rehydration rate was faster than untreated samples due to a greater internal stress and formation of pores in these samples. Moreover, ultrasound pretreatment leads to a reduction of money and energy required for drying. The study of Fernandes and Rodrigues (2007) indicated that the use of ultrasound reduced the cost of drying from US$ 3.54/kg to US$ 3.19/kg.

Factors Involved in Ultrasonic Enhancement of Drying Process

The factors which affect the ultrasonic enhancement of drying involve both ultrasonic factors and nonultrasonic factors.

Nonultrasonic Factors

The first nonultrasonic factor is the characteristics of food materials. The acoustic efficiency in foodstuffs during air drying is dependent on the porosity. In the study of García-Pérez et al. (2011), it was found that airborne ultrasound could affect the effective moisture diffusivity in carrot only when the acoustic power density exceeded a threshold between 8 and 12 kW/m^3. However, no acoustic power density threshold was observed during the ultrasound-enhanced drying of lemon peel. The more porous structure of lemon peel contributes to this difference of ultrasonic behavior. The ultrasonic compression and expansion is more intense in high-porosity materials due to the larger intercellular space inside and greater acoustic energy absorption. On the other hand, low-porosity materials have higher resistance to internal water transfer. Therefore, the analysis of foodstuff structure is the first step when using ultrasound to enhance the drying process. Furthermore, other characteristics of materials, including the size and shape also need to be taken into account.

Air velocity is another important factor for ultrasonic drying. Ultrasound can significantly enhance the drying rate at low air velocity whereas the high air velocity can weaken the ultrasonic

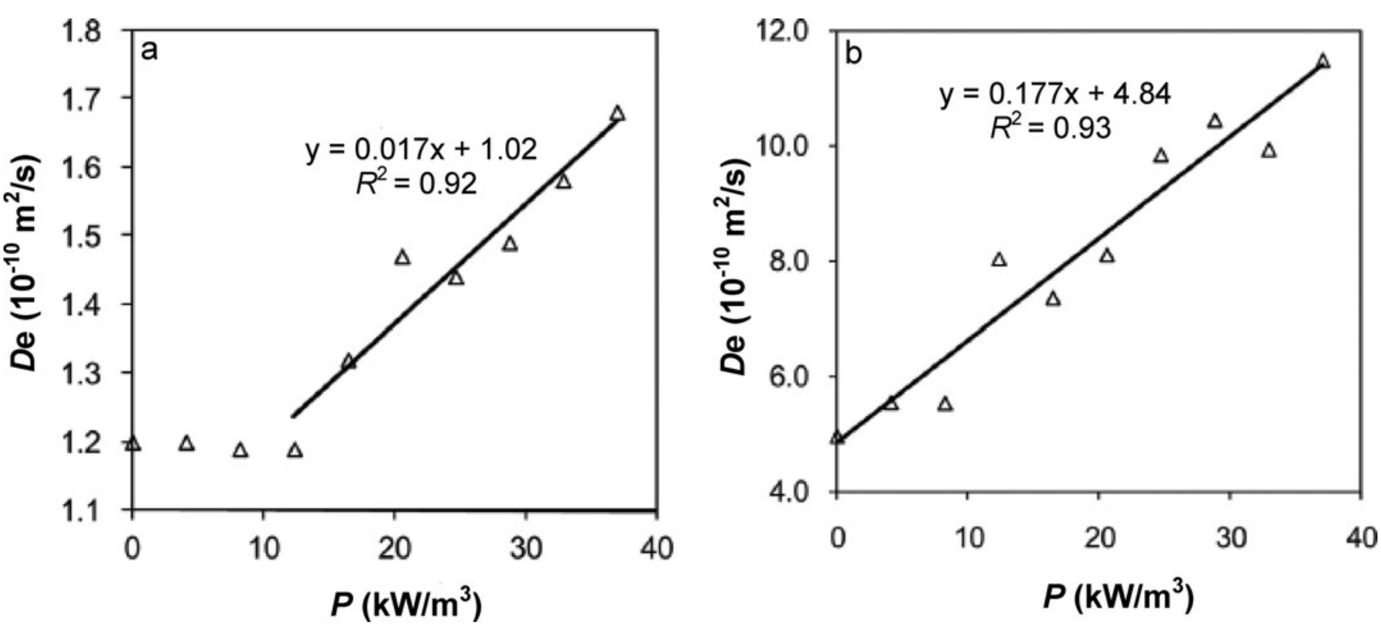


Figure 7 Influence of the acoustic power density on the average effective moisture diffusivity for carrot (a) and lemon peel (b) drying. (García-Pérez *et al.*, 2009).

effect on drying kinetics (García-Pérez et al., 2007). The explanation of this phenomenon is that high air velocity may disturb the ultrasonic field and reduce the acoustic intensity. Moreover, at a high air velocity, the ultrasonic efficiency during drying is higher when smaller size samples are used (García-Pérez et al., 2006b).

Temperature can also affect the ultrasonic efficiency during drying. When ultrasound was used during the drying of mushroom, apple, and carrot, the drying rate at 55°C was always higher than that at 20°C (Riera et al., 2002). However, a high temperature cannot always benefit the ultrasonic enhancement of drying kinetics. García-Pérez et al. (2006a) found little ultrasonic improvement of drying rate at 70°C. Considering that a high temperature is not only energy-consuming and useless for ultrasound-assisted drying, but also can reduce the product quality, the applied temperature during ultrasound-assisted drying should not be too high.

The influence of mass load density, which means the initial sample mass per unit of volume of drying chamber, on drying rate cannot be neglected. A low mass load density can contribute to a high drying rate (Cárcel et al., 2011). The increase of sample amount in the drying chamber can cause the fluctuations in air flow and subsequently increase the external resistance to mass transfer.

Ultrasonic Factors

Acoustic intensity plays an important role during the drying process. It has been mentioned above that a threshold of acoustic intensity exists in the drying of several foodstuffs. Little ultrasonic enhancement of drying can be expected when the applied acoustic intensity is below the threshold. On the contrary, the drying kinetics increases along with the increase of acoustic intensity when it exceeds the threshold (Fuente-Blanco et al., 2006; García-Pérez et al., 2006b). In the case of ultrasonic drying of carrot and lemon peel (Fig. 7), a linear relationship was observed between the applied acoustic intensity and the effective moisture diffusivity when ultrasound started to accelerate the drying process (García-Pérez et al., 2009). Thus, the acoustic intensity threshold should be identified in the case of using ultrasound to enhance drying.

Moreover, although ultrasound is usually carried out during air drying in a continuous way, a proper pulse mode is helpful to reduce the energy consumption without significant reduction of ultrasonic efficiency on drying. Schössler et al. (2012) used an intermittent ultrasound to assist the drying of apple cubes. They found that the drying curve of samples treated by ultrasound in a pulse mode of 10 seconds on and 10 seconds off was almost identical to that of sample submitted to continuous ultrasound.

Mathematical Modeling of Ultrasonic Enhancement of Drying Process

The air drying process is mainly composed of constant-rate period and falling-rate period (Sanjuán et al., 2003). Most of the studies indicate that the constant-rate period rarely appears during the whole ultrasound-enhanced drying process, thus, the constant-rate period is usually not taken into account in the current developed models. To model the water transfer during ultrasound-enhanced drying, both the diffusional models based on the Fick's law with different degrees of complexity and several empirical models can be considered. Although these models do not involve any ultrasonic factors, the ultrasonic influence on drying can be reflected on the kinetic parameters.

For the diffusion models, the temperature is considered to be uniform and both the sample volume and effective moisture diffusivity are constant during drying (Cárcel et al., 2011). Therefore, the governing equation for cube geometry is shown below:

$$\frac{\partial W_p(x,y,z,t)}{\partial t} = De\left(\frac{\partial^2 W_p(x,y,z,t)}{\partial x^2} + \frac{\partial^2 W_p(x,y,z,t)}{\partial y^2} + \frac{\partial^2 W_p(x,y,z,t)}{\partial z^2}\right) \tag{16}$$

where De is the average effective moisture diffusivity, W_p is the local moisture content, t is the time, and x,y,z are the characteristic coordinates of each geometry.

To solve Equation (16), the strategies of either neglecting or considering the external resistance can be taken into account. Neglecting the external resistance is the simplest way for modeling. In this case, only water diffusion controls the water transfer during drying (García-Pérez et al., 2011). The governing equation can be solved by the following equations (García-Pérez et al., 2007):

$$W(t) = W_e + (W_0 - W_e)\left[\sum_{n=0}^{\infty} \frac{8}{(2n+1)^2\pi^2} \times \exp\left(-\frac{De(2n+1)^2\pi^2 t}{4L^2}\right)\right] \tag{17}$$

$$W(t) = W_e + (W_0 - W_e)\left[\sum_{n=0}^{\infty} \frac{8}{(2n+1)^2\pi^2} \times \exp\left(-\frac{De(2n+1)^2\pi^2 t}{4L^2}\right)\right] \times \left[\sum_{n=1}^{\infty} \frac{8}{\alpha_n^2} \exp\left(-\frac{De\alpha_n^2 t}{R^2}\right)\right] \tag{18}$$

Table 2 Comparison between conventional liquid extraction and ultrasound-enhanced extraction

Extraction	Extraction time		Extraction yield		Solid–liquid ratio (g/mL)		Reference
	Conventional extraction	Ultrasonic extraction	Conventional extraction	Ultrasonic extraction	Conventional extraction	Ultrasonic extraction	
Hesperidin from Penggan peel	160 minutes	20 minutes	Around 36 mg/g	> 38 mg/g	1:40	1:40	Ma et al., 2008a
Polysacchar-ides from mulberry leaves	85 minutes	20 minutes	4.67%	10.79%	1:17	1: 15	Ying et al., 2011
Phenolic contents from *Potentilla atrosanguinea* Lodd.	20 hours	60 minutes	17.2%	18.8%	1:10	1:10	Kalia et al., 2008
Epimedin C from fresh leaves of *Epimedium*	45 minutes	15 minutes	37%	86%	1:100	1:30	Zhang et al., 2009a
Oil from oilseed rape	5 hours	1 hour	39.06%	46.55%	1:250	–	Wei et al., 2008
Salvianolic acid B from *Salvia miltiorrhiza* root	60 minutes	20 minutes	28.76 mg/g	33.93 mg/g	1:20	1:20	Dong et al., 2010
Saikosaponins from *Radix Bupleuri*	3 hours	30 minutes	Around 54%	Around 56%	–	–	Zhao et al., 2007
Steroid and triterpenoids from *Chresta scapigera* flowers	24 hours	30 minutes	10 mg/g	65 mg/g	1:20	1:20	Schinor et al., 2004
Lipid from ground flaxseed	24 hours	20 minutes	9.25 mg	9.98 mg	1:120	1:120	Metherel et al., 2009

$$W(t) = W_e + (W_0 - W_e)\left[\sum_{n=0}^{\infty} \frac{8}{(2n+1)^2\pi^2} \times \exp\left(-\frac{De(2n+1)^2\pi^2 t}{4L^2}\right)\right]^3 \tag{19}$$

where W is the average moisture content, W_e is the equilibrium moisture content, and W_0 is the initial moisture content, which can be regarded as the critical moisture content when the constant rate period is neglected (García-Pérez et al., 2007). L is the half of the sample thickness, α_n is the eigenvalue. Equations (17–19) represent the solutions for slab, cylinder and cube geometries, respectively.

On the other hand, the external resistance to mass transfer should be considered when the air velocity is low (Cárcel et al., 2011). In this case, an implicit finite difference method can be employed to solve the governing equations with proper boundary conditions. However, there are disadvantages about using these diffusion models including external resistance to mass transfer. For example, the values of *De* in these models may be overestimated if the shrinkage is not considered (García-Pérez et al., 2011). A more precise diffusion model should include both the external resistance and shrinkage. The main difficulty in finishing this modeling is that the boundary condition is moving due to the shrinkage whereas the dry matters are not affected (García-Pérez et al., 2011). The implicit finite difference method and the same boundary equations as models only considering external resistance can be used to solve the governing equations (García-Pérez et al., 2011). In the study of García-Pérez et al. (2011), it was indicated that during modeling ultrasound-assisted drying of eggplant, the model considering both shrinkage and external resistance were more precise than those models that did not include the shrinkage effect. In addition, there is another way to correct models that ignore product shrinkage by multiplying a volume changing factor with *De* in Equations (17–19) (Schössler et al., 2012). The relationship between the rectified *De* and *De* without shrinkage effect is shown below (Gekas and Lamberg, 1991):

$$\frac{De - \text{unrectified}}{De - \text{rectified}} = \left(\frac{V_0}{V_f}\right)^{2/d} \tag{20}$$

where V_0 and V_f are the initial and final sample volumes and d is the power exponent. The value of d can be determined through the following relationship between the changes of sample volume and thickness during drying process:

$$\frac{V_0}{V_f} = \left(\frac{\lambda_0}{\lambda_f}\right)^d \tag{21}$$

where, λ_0 and λ_f are the sample thicknesses at the beginning and the end of drying process (Gekas and Lamberg, 1991).

Another modeling strategy is to use the empirical models. The empirical models which can be considered for modeling are shown in Table 3. Among these empirical models, the Page model was successful in modeling the drying process of banana that was pre-treated by ultrasound while the Weibull model was able to model the ultrasound-enhanced air drying of eggplant (Azoubel et al., 2010; García-Pérez et al., 2011). Furthermore, the drying kinetics of red bell pepper and apple enhanced by ultrasound can be simulated using the model developed by Midilli et al. (Schössler et al. 2012). Compared to the diffusion models, the computation of empirical models is much easier. In some cases, the results from empirical models are even better than that from diffusion models (Azoubel et al., 2010). However, the use of empirical models to simulate the ultrasound-enhanced drying has some disadvantages. These models do not provide any information about mechanism of mass transfer during drying. Moreover, the modeling results cannot be used for other product geometries or working conditions. Overall, both empirical

Table 3 Potential empirical models used for modeling the ultrasound-enhanced drying process

Model	Equation	Reference
Page	$\frac{W-W_e}{W_0-W_e} = \exp(-kt^n)$	Azoubel et al., 2010
Modified page	$\frac{W-W_e}{W_0-W_e} = \exp[-(kt)^n]$	Schössler et al., 2012
Midilli et al.	$\frac{W-W_e}{W_0-W_e} = a\exp(-kt^n) + bt$	Schössler et al., 2012
Weibull	$W = W_e + (W_c - W_e) * \exp(-(\frac{t}{\beta}))^\alpha$	García-Pérez et al., 2011
Newton	$\frac{W-W_e}{W_0-W_e} = \exp(-kt)$	Schössler et al., 2012
Henderson and Pabis	$\frac{W-W_e}{W_0-W_e} = a\exp(-kt)$	Schössler et al., 2012
Two term	$\frac{W-W_e}{W_0-W_e} = a\exp(-kt) + b\exp(-k_0t)$	Schössler et al., 2012
Two term exponential	$\frac{W-W_e}{W_0-W_e} = a\exp(-kt) + (1-a)\exp(-kat)$	Schössler et al., 2012
Logarithmic	$\frac{W-W_e}{W_0-W_e} = a\exp(-kt) + c$	Schössler et al., 2012

Where W is the moisture content at the give time, W_e is the equilibrium moisture content, W_c is the critical moisture content, W_0 is the initial moisture content, t is the treatment time, and other parameters are specific coefficients for each model.

and diffusion models should be taken into account to model the ultrasound-enhanced drying process.

FUTURE DEVELOPMENTS

Despite that a number of studies have been performed about using ultrasound to enhance the food processing in various areas, more efforts are still expected to fulfill all the potential of ultrasound during processing and scale up the ultrasound equipment for industrial adoption. Therefore, future researches can be carried out mainly in the following two aspects.

On one hand, more researches should be performed to fully understand the ultrasonic mechanism in every processing area. Although the ultrasonic effects during extraction and drying process have been widely investigated, the applications of ultrasound in food oxidation, filtration, brining, freezing, and thawing areas attract less attention. Particularly in food oxidation area, the utilization of ultrasound just commences. In each processing area, all the intrinsic factors which can affect the ultrasonic enhancement should be identified, so that ultrasonic processing can be controlled well and all the potential of ultrasound can be utilized to enhance the food processing.

On the other hand, it is necessary to scale up the ultrasound equipment, so as to widespreadly employ the ultrasonic technology in the food industry. To design the optimized sono-reactors on industrial scale, all the ultrasonic effects associated with the enhancement of processing, such as cavitation bubbles, microstreaming, free radicals, etc., should be taken into account. The main difficulty for scaling up the sono-reactor lies in the complexity of the interactions between the cavitation, sound field, and the generated temperature and flow distributions. The best way is to quantify the ultrasonic effects through numerical simulation. Computational fluid dynamics (CFD) is an efficient tool to model the fluid dynamics phenomena related with ultrasound. By using CFD code, the distribution of cavitation bubbles and the intensity of these bubbles as a function of acoustic and geometric factors can be predicted (Laborde et al., 2000). In the meantime, the information of the temperature, velocity and pressure fields in the sono-reactor can be provided by CFD modeling (Laborde et al., 2000; Servant et al., 2001; Trujillo and Knoerzer, 2011). Moreover, there is a link between bubble dynamics and the formation of free radicals. Thus, the free radical concentration in a collapsing bubble can be calculated by using the information provided by the bubble dynamic model (Sochard et al., 1997). As can be seen, numerical stimulation is a promising tool to model the phenomena induced by ultrasound. Future studies should pay more attention to quantify the ultrasonic effects in sono-reactors with the assistance of numerical stimulation. In this way, the desired ultrasound equipment on industrial scale can be developed to enhance the food processing.

CONCLUSIONS

The utilization of ultrasound can benefit various food processing areas. On one hand, ultrasonic technology is a promising alternative to traditional technologies for food cutting, emulsification, sterilization, meat tenderization, and degassing. On the other hand, ultrasound can enhance the processes of extraction, freezing, thawing, brining, oxidation, filtration, and drying/dehydration. This paper outlines the major functions of ultrasound in enhancing these processes and the factors that affect the ultrasonic enhancement.

The ultrasonic enhancement of food processing is mainly characterized as the enhancement of processing rate or efficiency. In the meantime, the disadvantages of traditional technologies during processing are improved. The factors which affect the ultrasonic enhancement of food processing can be divided into two distinct groups, namely, ultrasonic factors and nonultrasonic factors. Ultrasonic factors usually involve the ultrasound frequency, power/intensity, ultrasound duration, and treatment mode. The nonultrasonic factors are dependent on each specific processing area.

As for modeling the processes enhanced by ultrasound, nonparametric simulative models can be employed for the extraction and oxidation processes. For other processes, it is better to use the models which can express the physical meaning of the process. In the meantime, several empirical models can be considered to model the drying process in the presence of ultrasound.

Finally, more researches are expected to elucidate the ultrasonic effects in oxidation, filtration, brining, freezing, and thawing areas. For designing the ultrasound equipment at an industrial scale, it is better to model the ultrasonic effects through numerical stimulation.

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