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Ultrasound applications for the preservation, extraction, processing and quality control of food

Ali Mohamadi Sani, Maryam Sardarodiyan
Young Researchers and Elite Club, Quchan Branch, Islamic Azad University, Quchan, (IRAN)
E-mail: Mohamadisani@yahoo.com

ABSTRACT

Ultrasound assisted extraction (UAE) process enhancement for food and allied industries are reported in this review. Ultrasonic processing is a novel and promising technology in food industry. The propagation of ultrasound in a medium generates various physical and chemical effects and these effects have been harnessed to improve the efficiency of various food processing operations. The advantages of using ultrasound for food processing, includes: more effective mixing and micro-mixing, faster energy and mass transfer, reduced thermal and concentration gradients, reduced temperature, selective extraction, reduced equipment size, faster response to process extraction control, faster start-up, increased production, and elimination of process steps. Low power (high frequency) ultrasound is used for monitoring the composition and physicochemical properties of food components and products during processing and storage, which is crucial for controlling the food properties and improving its quality. High power (low frequency) ultrasound, on the other hand, induces mechanical, physical and chemical/biochemical changes through cavitation, which supports many food processing operations such as extraction, freezing, drying, emulsification and inactivation of pathogenic bacteria on food contact surfaces. This review gives a brief presentation of the theory of UAE, discusses recent advances that influence its efficiency, advantages and the disadvantages of UAE and the possibility of coupling UAE with other analytical techniques.

KEYWORDS

Ultrasound;
Extraction;
Food quality;
Cavitation;
Preservation.

INTRODUCTION

Nowadays, consumers prefer and choose foods that not only provide them with essential nutrients but also contain substances which may have positive long-term effects[3]. In recent years, emerging technologies, such as high pressure, pulsed electric field electrolyzed water, irradiation, ozone and ultrasound treatments, have been widely studied for application in food industry. Studies evaluating the application of ultrasound in food science and technology have been expanded due to its promising effects in food processing and preservation[9, 10, 11,12]. The use of ultrasound energy in liquid and solid media has been extensive in food-processing applications and has created growing interest in sample treatment[1]. Ultrasound-assisted extraction (UAE) has found particular application as a procedure for the preparation and extraction of analytes. Ultrasound radiation, when transmitted through a medium, generates a disturbance that, if repeated periodically, creates expansion and compression cycles[2]. The application of ultrasound is a non-thermal technology which contributes to the increase of microbial safety and prolongs shelflife, especially in food with heat-sensitive, nutritional, sensory, and functional characteristics[36, 37, 38]. Ultrasound is increasingly being applied in food industry due to its promising effects in food processing and preservation[13]. The applied ultrasound range can be classified into two subclasses: low intensity diagnostic ultrasound (5–10 MHz) and high intensity power ultrasound (20–100 kHz range) (Figure 1)[14, 15]. Ultrasound irradiation[62, 63] is one of the upcoming extraction techniques that can offer high reproducibility in shorter time, lower temperature, reduced solvent consumption and less energy input[64]. Oscillatory particle motion produced by high-intensity ultrasonic waves can also induce secondary flows, known as acoustic streaming. Such an agitation should realize an internal convection motion of solute within the solvent inside holes of porous material. Moreover, cavitation produces micro-jets at the surface of the food material that may improve the exchange surfaces which has to be revealed globally through a high starting accessibility. Both effects can increase mass transfers of solvent within the solid and solute within the solvent[65, 66].

The application of power ultrasound in food industry for two reasons, namely replacing conventional processing technologies and assisting traditional food processes. In the latter case, the processing efficiency is enhanced and the disadvantages of traditional food processing technologies are improved[4, 5, 6]. Controlled application of ultrasound can be a promising food preservation approach that inactivates microorganisms without having harmful effects on the nutrition, quality, sensory and aesthetic attributes of food[23, 24].

Although commercial applications of ultrasound have been used in some industries (chemical, cosmetic, textile, polymer, and petrochemical) it has recently started to be used in the food industry for items such as ketchup, mayonnaise, and fruit juice production[7, 8].

From the literature review, the use of ultrasound is increasingly employed as an alternative method over the traditional in extraction of natural products because they are shortening of processing and residence times (they can now be completed in minutes instead of hours

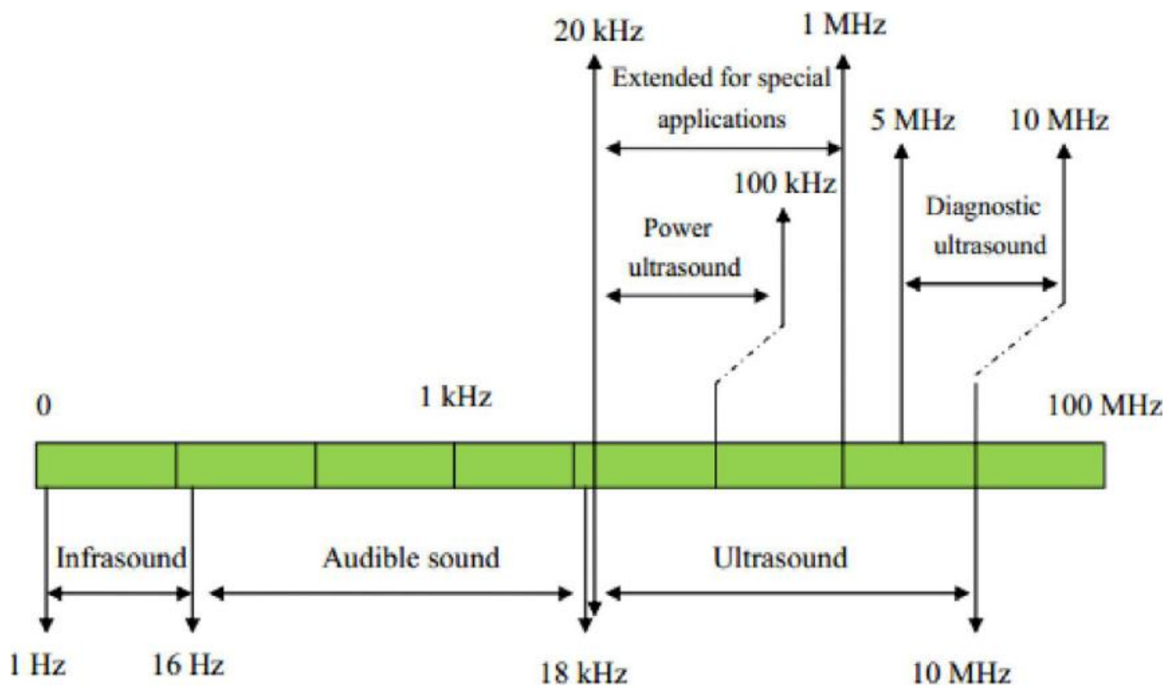

Figure 1 : Frequency range of sound waves

with high reproducibility) and accelerated heat and mass transfer, eco-friendly, with strongly decreased solvent consumption and quality of the extracts[18].

This paper aims to provide a detailed and critical review of the latest applications of US with regard to the improvement of some technological properties (preservation, extraction, processing and quality control of food, etc) and the bioactivity of food. Special emphasis has been placed on ultrasound assisted extraction as one of the most feasible and cost-effective large-scale applications of US in the food industry.

Principle of ultrasound technology in food

The history of scientific advances and the discovery of ultrasound are rooted in the study of sound, with Sir Isaac Newton first proposing his theory of sound waves in 1687[22]. Ultrasound energy accelerates Al/Si dissolution and strengthens the bonds at the solid particle/gel phase interface[35]. This increases the condensation process thus speeding up the zeolite crystallization process. Ageing of source of Al or Si, either from pure chemical precursors or CFA using US energy has been shown to reduce the crystallization time[34, 36].

The ability of ultrasound to cause cavitation depends on the characteristics of ultrasound (e.g., frequency and intensity), product properties (e.g., viscosity and surface tension) and ambient conditions (e.g., temperature and pressure). This technique requires a liquid medium, an energy generator and a transducer, which transforms the electric, magnetic or kinetic energy into acoustic energy[25].

Ultrasound is a form of energy generated by sound waves at frequencies that are too high to be detected by the human ear. These waves participate in a region of the sound spectrum that is divided into three main parts: infrasound ($v < 16$ Hz), band sound (16 Hz $< v <$ 16 kHz) and ultrasound ($v >$ 16 kHz). The ultrasound band is also divided into low frequency (16 kHz $< v <$ 1 MHz) and high frequency ($v >$ 1 MHz) bands. High-frequency ultrasound bands are typically used for medical and industrial imaging purposes[20, 21]. Low power ultrasound is mainly used in medical diagnostics whereas high power ultrasound is used to induce physical and chemical changes in biological matrices due to mechanical, cavitational and thermal effects. Implosion of cavitational bubbles, formation of microjets, microturbulence, high-velocity inter-particle collisions and perturbation in micro-porous particles[32] result in enhanced extraction yield and accelerated chemical reactions[33]. Ultrasound can drive processes (e.g., extraction, dissolution and digestion) when applied to finely powdered solids dis-

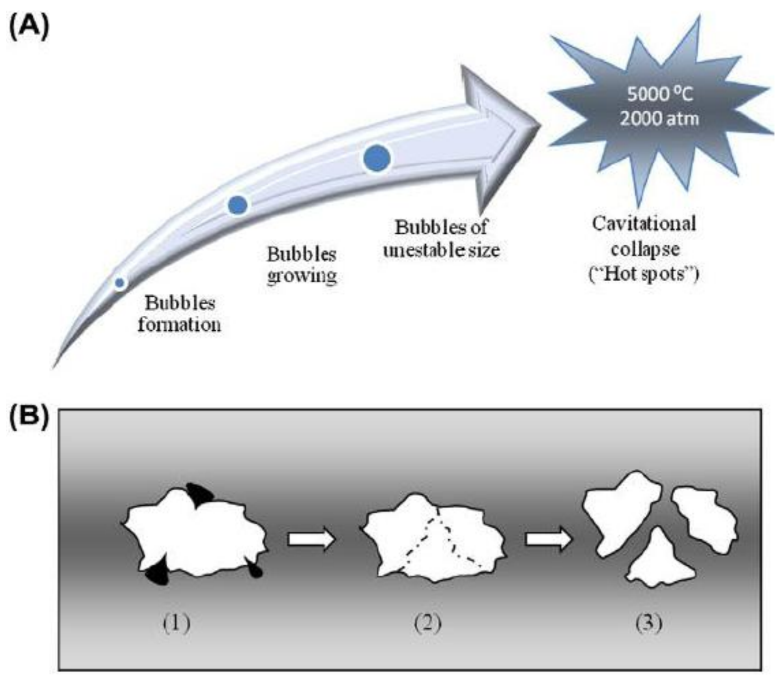

Figure 2 : Cavitation phenomenon. (A) Development and collapse of cavitation bubbles. (B) Cavitational collapse at a solid-liquid interface. The sequence (1), (2) and (3) shows a scheme of fragmentation or disruption due to gas trapped on the defects on the solid surface giving rise to particle-size reduction (increase in surface area)

persed in a liquid medium, as a result of the conditions derived from cavitation (Figure 2A). Thus, high local temperatures inside collapsing cavitation bubbles can cause an increase in analyte solubility and solvent diffusivity inside the solid particles. High pressure occurring during microbubble implosion improves solvent penetrability and transport. Surface renewal caused by particle fragmentation makes it possible for more analyte to come in contact with the solvent (Figure 2B)[67].

Ultrasound effects on liquid systems are mainly related to the cavitation phenomenon. Ultrasound is propagated via a series of compression and rarefaction waves induced on the molecules of the medium passed through (Figure 3)[19].

This type of cavitation, called "transient cavitation", can produce shearing forces and turbulence in the medium[40, 42]. Another important effect is that water molecules can be broken, generating highly reactive free radicals ($H2O \rightarrow H + \bullet OH$) that may react and consequently modify other molecules, such as proteins[41]. This wide range ofmechanisms involved in the HIU treatment induces physical and biochemical effects with several potential applications in the food industry.

Low power ultrasound

Low power ultrasound (LPU) along with spectroscopy and nuclear magnetic resonance (NMR) are currently the most popular, practical and widely used nondestructive analytical methods. For many years, LPU has been successfully utilized for studying the physicochemical and structural properties of fluid foods[75]. The changes in ultrasound properties enable to assess the properties of opaque fluids and to detect foreign bodies in foods through container walls (i.e., without contact), which allows to make measurements in the lab as well as on-line using a robust and reasonably cheap measurements apparatus[76].

Applications of low power ultrasound (LPU)

Meat products

In the beef industry, LPU has been a fast, reproducible and reliable technology to enhance genetic improvement programs for livestock[77, 78].

Fruits and vegetables

The application of ultrasound for the quality control of fresh vegetables and fruits in both pre- and postharvest applications was highlighted in a recent review[79]. Alexandre et al. (2012) treated strawberries with non-thermal technologies, such as ultrasound (35 kHz), and observed higher anthocyanin contents than in samples washed with chemical solutions when stored at room temperature for 6 days. Tiwari et al. (2010) observed the significant retention of anthocyanins in grape juices after treatment with ultrasound (at a constant frequency of 20 kHz and pulse durations of 5 s on and 5 s off): 97.5% AC (cyanidin), 48.2% MA (malvanidina) and 80.9% DA (delphinidin).

Cereal products

Skaf et al. (2009) developed a low frequency acoustic technique with two large sensors (through transmission) to overcome the continuous physical and chemical evolution of dough medium during fermentation, which allowed to evaluate the physical properties of dough and determine the critical time as well as the influence of several technological parameters in the process of dough development[82]. More recent work utilized a low cost and rapid through transmission ultrasound velocity technique to monitor changes in wheat flour dough consistency induced by proteins and gelatinization of the starch[83].

High power ultrasound

There have been numerous studies about various applications of high power (low frequency) ultrasound in food science and technology. All of these applications and principles were reviewed by Awad et al. (2012), Carcel et al. (2012) and Chandrapala et al. (2012).

Several novel and interesting HIU applications for improving the technological properties and bioactivity of food have emerged during the last years[84, 85]. Due to the physical, chemical andmechanical effects inducedmainly by cavitation, HIU has been used to provokemodifications in the structure of both animal and plant proteins[92, 86]. High-frequency ultrasound has been used to provide information on the physicochemical properties of food such as the salt and fat content in meat products[87, 88, 93] or firmness, ripeness, sugar content and acidity in fruit and vegetable products[79].

Review

Ultrasound in food preservation

Ultrasound is one of the new preservation techniques that could eliminate microbial activity. High power ultrasound alone is known to disrupt biological cells. When combined with heat treatment, it can accelerate the rate of sterilization of foods. Therefore it reduces both the duration and intensity of the thermal treatment and the resultant damages. At sufficiently high acoustic power inputs, ultrasound is known to rupture cells[44, 45, 46]. Ultrasonic techniques are finding increasing use in the food industry. Ultrasound (US) is used to alter, physically or chemically, the properties of foods, for example pasteurisation, sterilisation, generation of emulsions, disruption of cells, promotion of chemical reactions, inhibition of enzymes, tenderising meat and modification of crystallization[56, 57].

Ultrasound-assisted extraction

The principal objective of an extraction process is to maximize the target-compound yield with no or minimal impact on properties of the target compound whilst minimizing the extraction of undesirable compounds. Conventional solid-liquid extraction (SLE) techniques, including maceration, infusion and "Soxhlet" extraction, are time consuming and use large amounts of solvents[31]. Plant extraction applied to food domain is usually done by solvents, representing high cost, pollutant and fastidious techniques. In the case of vegetable oils extraction, most of matrixes are seeds and kernels, which constitute barriers for the penetration of the solvent with consequent low yield. Also, the most common oil extraction is done by normalized Soxhlet extraction. The advantages of the use of low frequency ultrasound have been extensively extraction, such as Jatropha curcas L.[27] and soybean oil[28].

The use of ultrasound to accelerate extractive processes is a well established technique in analytical chemistry demonstrated by several recent reviews[48, 49, 50].

The frequency of the applied ultrasound is a very important parameter, with lower frequencies leading to more rapid agitation and cell damage. For instance, when a frequency of 20 kHz is applied, instable cavitation is induced into the system, where violent collapse of the cavitation bubbles generates locally high temperatures and pressures (up to 50 MPa or in instances even higher) (Figure 4). By increasing the frequency, cavitation goes through a transient zone, until stable cavitation can be reached at frequencies in the order of several hundred kilohertz. At these frequencies, cavitation bubbles do not collapse, or at least not violently, and effects on food products are largely caused by sonochemical effects or gentle physical effects such as microstreaming. Some plants and their by-products should in fact be treated with ultrasound at frequencies exceeding several hundred kilohertz to protect sensitive bioactive compounds. Applied amplitude (power), frequency and geometry of the sonotrodes are also very important parameters. For some products, the directly immersed sonotrodes, generally operating at high powers and low frequencies, should not be used to avoid negative effects on the food product caused by cavitational activity or contamination with particles from horn erosion[47]. Extraction enhancement by ultrasound has been attributed to the propagation of ultrasound pressure waves, and resulting cavitation phenomena. High shear forces cause increased mass transfer of extractants[26].

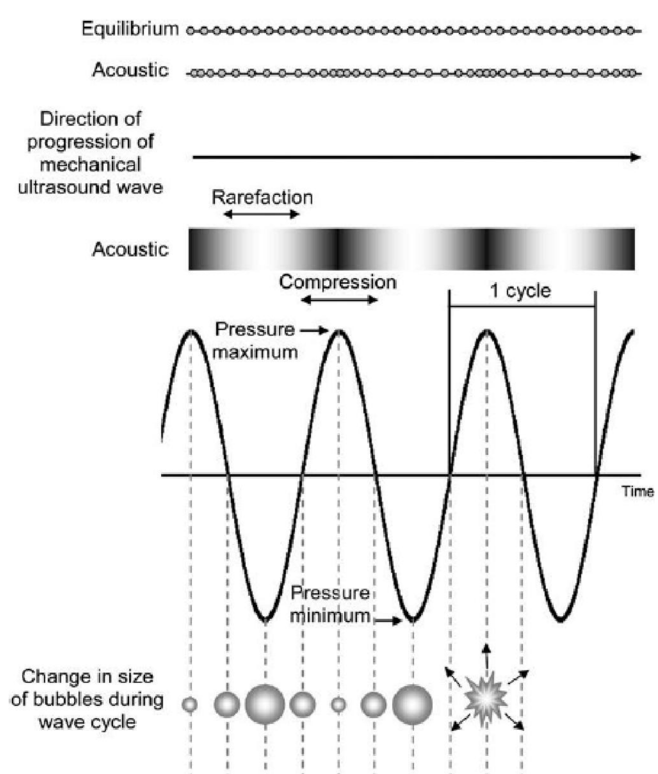

Figure 3 : Ultrasonic cavitation

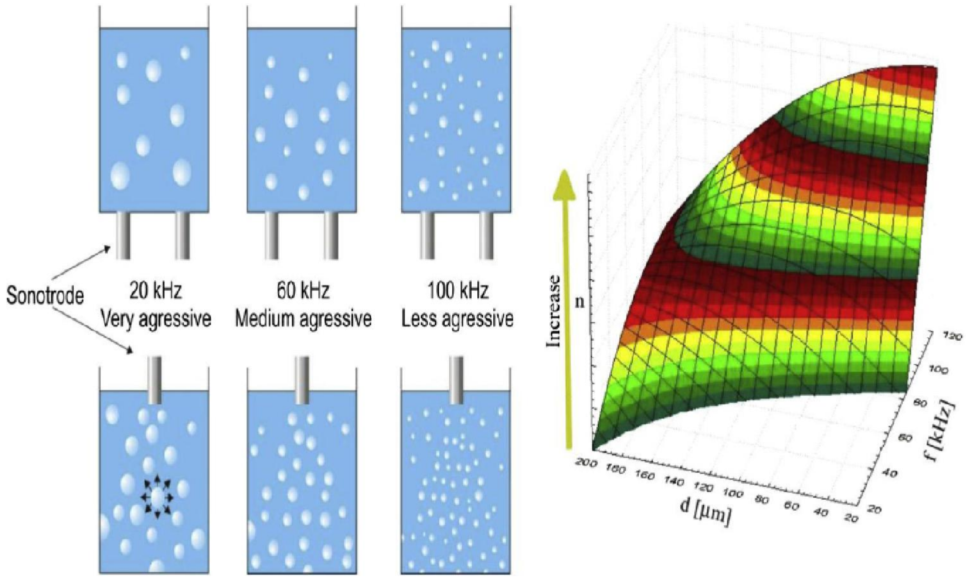

Figure 4 : Size of the cavitational bubbles in dependence of ultrasounds frequency

In the study on supercritical fluid extraction enhancement by ultrasound Balachandran et al. (2006) they were able to demonstrate that the effectiveness of ultrasound was gained by the increase in the superficial mass transfer and that effectiveness declined sharply after the readily accessible surface solute had been removed. However, by reducing the substrate particle size major gains in extraction efficiency and extraction time reduction could be achieved.

Ultrasound in food processing

One of the major issues in using ultrasound in food processing is the controlled modification of the functionality of food ingredients without chemical modification[58].

Filtration

In the food industry, the separation of solids from liquids is an important procedure either for the production of solid-free liquid or to produce a solid isolated from its mother liquor. But the deposition of solid materials on the surface of filtration membrane is one of the main problems. The application of ultrasonic energy can increase the flux by breaking the concentration polarization and cake layer at the membrane surface without affecting the intrinsic permeability of membrane (Figure 5). The liquid jet serves as the basis for cleaning, and some other cavitational mechanisms lead to particle release from the blocked membrane[43].

Microbial growth

Alternative methods of food processing that have an almost zero influence on the quality of food have become more important due to increased consumer demand for minimally-processed foods. Ultrasound processing is an alternative technology that has shown promise in this field. With ultrasound technology, high pressure, shear, and a temperature gradient are generated by high power ultrasound (20 to 100 kHz), which can destroy cell membranes and DNA, thus leading to cell death[51]. A relatively new concept in antimicrobial treatment has been proposed involving the combined effect of pressure and ultrasound (manosonication), ultrasound and heat (thermosonication) or the combination of ultrasound, heat and pressure (manothermosonication)[52].

Freezing

Ultrasound aids crystallization by controlling nucleation and crystal growth in frozen foods[54]. It also affects texture and the release of thawed cell liquid[55], which are of major importance for consumer acceptance of meat products, fruits and vegetables, as well as for the conservation of both nutrient and bioactive ingredients.

Laboratory investigation indicates that power ultrasound is able to accelerate the freezing process of fresh food products, mainly through its ability in

Review

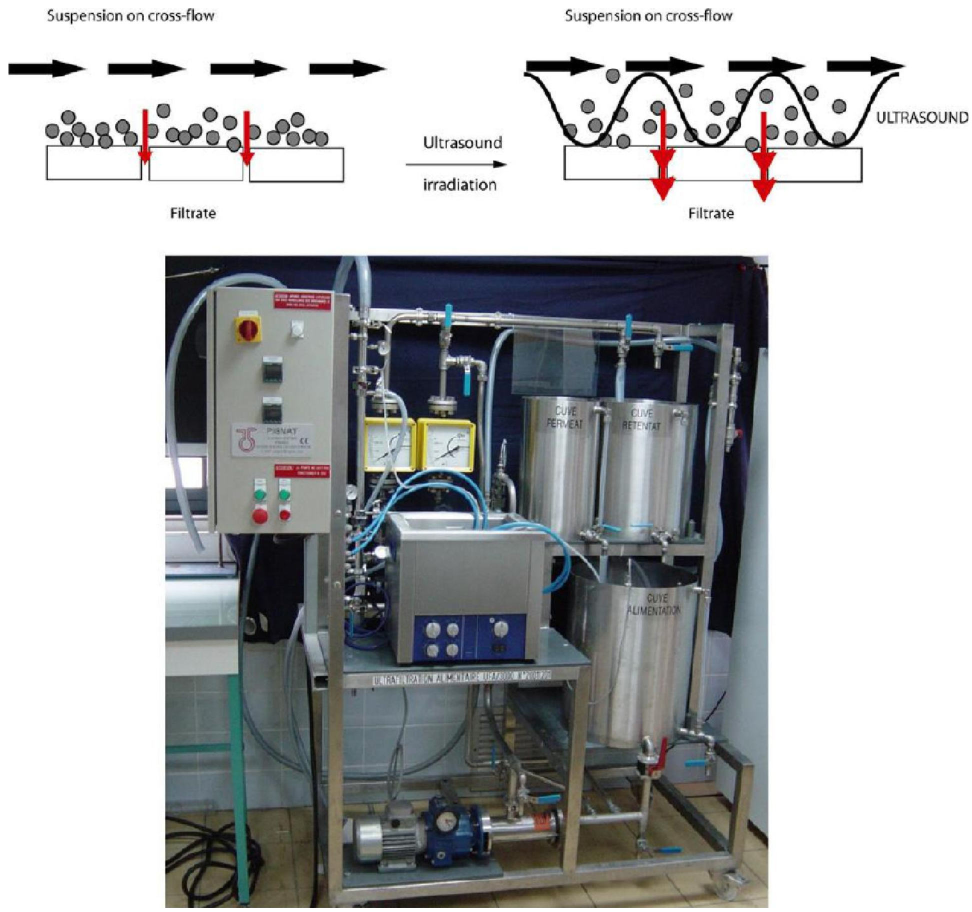

Figure 5 : Enhancement of permeability using ultrasound

enhancing the heat and mass transfer process[53]. During immersion freezing of potatoes slices, Li and Sun (2002) applied power ultrasound intermittently when potatoes temperature was reduced from 0 to K7 8C. The purpose of the intermittent treatment is to avoid the rise of refrigerant temperature, since continuous application of power ultrasound can lead to prolonged thermal effect upon the refrigerant. Their results (Li & Sun, 2002) indicate that power ultrasound can lead to noticeable increase of freezing rate. As an example, the freezing curves for potato samples treated with an acoustic power level of 15.85 Wand without acoustic treatment are compared in Figure 6.

Thawing

Thawing is a time consuming process and an suboptimal thawing can accelerate the physiochemical changes and microbial growth both of which can lead to the deterioration of quality of frozen foods[68, 69]. Recently, studies were being carried out to explore the possibility of using various ultrasound frequencies and power levels during thawing[70, 71].

Dairy

The use of ultrasound is increasingly being developed for a range of applications in dairy systems, due to the improved processing effectiveness, the ability to manufacture products with 'tailored' functionality, the ability to preserve food and modulate enzyme activity, and the capability of improving the microstructure through component interactions. The ultrasound-induced physical effects are used in applications such as

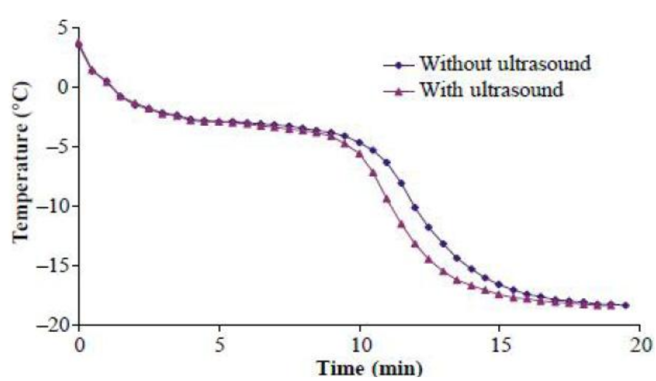

Figure 6 : Influence of power ultrasound on the freezing rate during immersion freezing of potato slices[53]

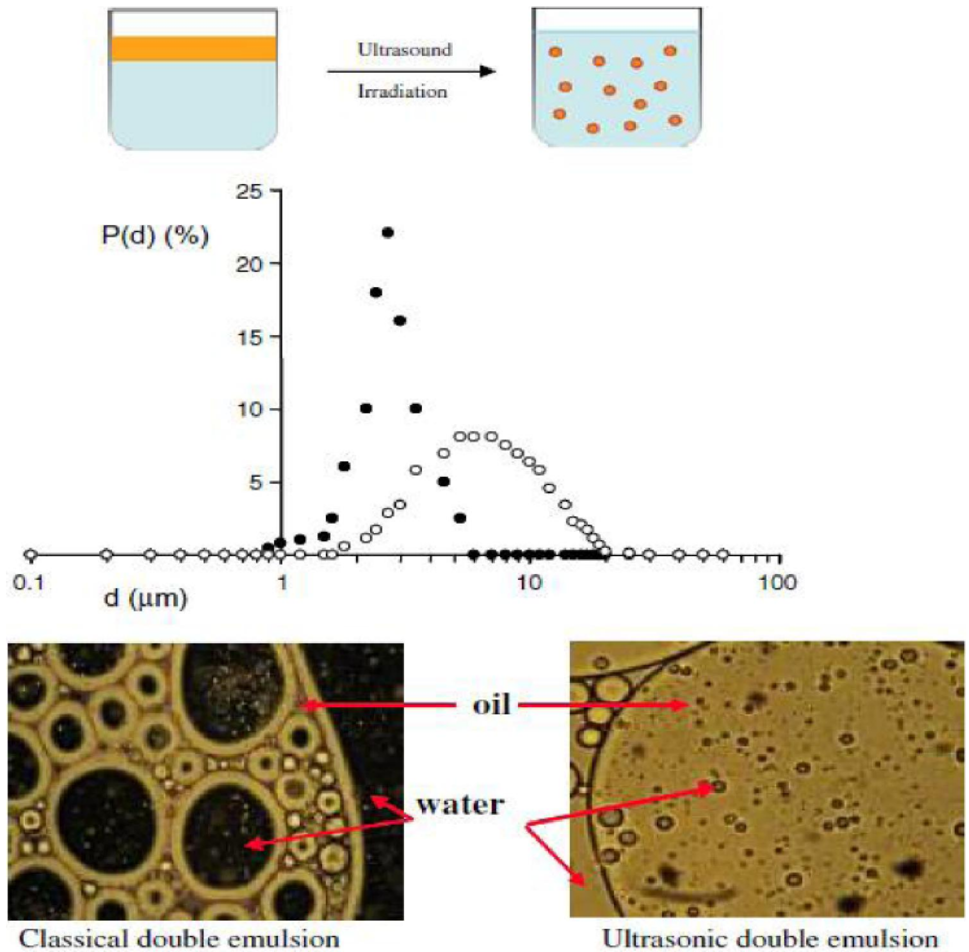

Figure 7 : Phase dispersion of two immiscible solvent and drop size distribution by power ultrasound (•) mechanical agitation (o)

the enhancement of whey ultrafiltration, extraction of functional foods, reduction of product viscosity, homogenization of milk fat globules, crystallization of ice and lactose, manufacturing yogurts with superior rheological properties, reduction of yogurt's total fermentation time and cutting of cheese blocks[59, 60].

Emulsification/homogenization

Emulsification is an important mean to deliver the hydrophobic bioactive compounds into a range of food products (Figure 7). Acoustic emulsification offers the following improvements over conventional methods[61]:

- The emulsion produced has particles in the submicron range with an extremely narrow particle size distribution.
- The emulsions are more stable.
- Addition of a surfactant to produce and stabilize the emulsion is not necessary.
- The energy needed to produce an emulsion by acoustic waves is less than that needed in conventional methods.

Changes in viscosity and texture

Depending on the ultrasound intensity, food viscosity can either increase or decrease, the effect being temporary or permanent. Cavitation causes shear, which in the case of thixotropic fluids causes a temporary decrease in viscosity. If enough energy is applied, the molecular weight may be decreased giving rise to a permanent viscosity diminution[72, 73]. A study by Iida et al.[73] evaluated the effectiveness of the ultrasonic process for the depolymerization and viscosity control of starch and polysaccharide solutions after gelatinization. Figure 8 shows the typical changes in viscosity observed by sonicating 5% and 10% of waxy maize starch solution after gelatinization. A drastic decrease in the viscosity of the ultrasonicated solutions is observed: about two orders of magnitude. For example, the viscosity of

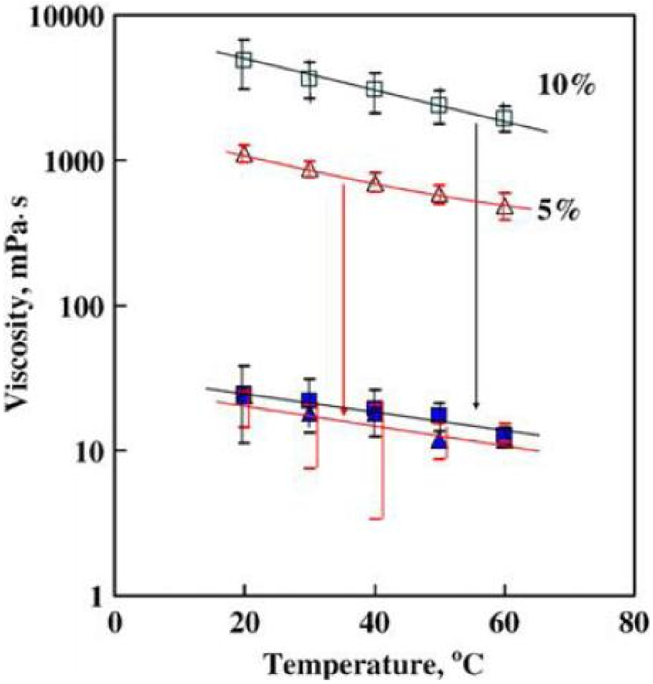

Figure 8 : Viscosity of 5 and 10 wt.% waxy maize starch solution by sonication for 30 min at 60 C using a horn: (□) 10% unsonicated, (■) 10% sonicated, (Δ) 5% unsonicated, (▲) 5% sonicated. The viscosity was measured continuously at 10 C intervals. The experiments were repeated 3 times and the error bars indicate 2X standard error[73]

10% starch solution decreased from 2000 to 20 mPa/s after 30 min sonication. The low viscosity was maintained even after cooling down to room temperature. Higher amounts of starch, i.e., 15–20% starch slurries seemed to limit the depression of viscosity because the firm gel formed at this starch content range is affected to lesses extent by sonication.

CONCLUSION

The use of ultrasound on food products has proved to be advantageous in numerous processes. However, some modifications in the physicochemical parameters or structures of components and the degradation of some compounds have been increasingly reported. Ultrasonic energy has a special place in meeting the challenges of processing recalcitrant, multicomponent and heterogeneous biomass materials. The introduction of an ultrasonic field can provide an extremely severe physicochemical environment that is difficult to realize with other engineering methods. Sonication does not remarkably change the chemical mechanism of biomass pretreatment and reactions, but the reaction kinetics is remarkably accelerated as the result of ultrasonic cavitation and the secondary effects, and therefore enhances the efficiency and economics of the biomass conversion process. Potential exists for applying UAE for enhancement of aqueous extraction and also where organic solvents can be replaced with generally recognised as safe (GRAS) solvents. UAE can also provide the opportunity for enhanced extraction of heat sensitive bioactive and food components at lower processing temperatures. There is also a potential for achieving simultaneous extraction and encapsulation of extracted components to provide protection through the use of ultrasonics.

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