Review Paper

Ultrasonic Technology and Its Applications in Quality Control, Processing and Preservation of Food: A Review

Abstract

Ultrasound is one of the emerging technologies that were developed to minimize processing, maximize quality and ensure the safety of food products. In recent years, ultrasound technology has been used as an alternative processing option to conventional thermal approaches. Although ultrasonic have been used for years in research and diagnostics, major advances have been made in the last decade. The applications for which high power ultrasound can be used range from existing processes that are enhanced by the retrofitting of high power ultrasonic technology, to the development of processes up to now not possible with conventional energy sources. The present paper reviews the generation, principle mechanism, properties, process parameters, applications, merits and demerits and future trends of the ultrasound technology in the food processing.

Keywords: Ultrasound, Quality, Food processing, Preservation, Food safety.

1. Introduction

The trend of production of prolonged shelf-life foods which are fresh like is nowadays preference of consumers. Environmentally friendly, green novel technologies are nowadays interest of industry due to the expectations of consumers. Instead of traditional food spoilage control processes, the growing demand to prolong the shelf-life of fresh-like foods with mild preservation techniques such as refrigeration, mild heating, modified atmosphere packaging, irradiation, high pressure, pulsed electric fields, pulsed white light, ultrasound, ultraviolet radiation and the use of natural antimicrobial systems are preferred (Zeuthen, *et al.*, 2002). Ultrasound is one of the emerging technologies that were developed to minimize processing, maximize quality and ensure the safety of food products. In recent years, ultrasound technology has been used as an alternative processing option to conventional thermal approaches. Ultrasonication can pasteurize and preserve foods by inactivating many enzymes and microorganisms at mild temperature conditions, which can improve food quality in addition to guaranteeing stability and safety of foods. In addition, the changes to the physical properties of ultrasound, such as scattering and attenuation caused by food materials have been used in food quality assurance applications. Ultrasound is composed of sound waves with frequency beyond the limit of human hearing. By tuning frequency, ultrasound can be utilized in many industrial applications including food. Ultrasound techniques are relatively cheap, simple and energy saving, and thus became an emerging technology for probing and modifying food products.

The use of acoustic energy in food or bio-processing operations is relatively new when compared to other sources of energy, such as mechanical or thermal, which have been utilized for centuries in various applications. Two important factors make current ultrasound assisted processes possible: (a) the development in more scalable ultrasound generation technology in the last 20–30 years and (b) the better understanding of interactions between acoustic energy and food materials. In general, ultrasound refers to acoustic pressure waves with frequencies of 20 kHz or higher. Most effects of ultrasound at low and high frequencies are directly related to the cavitations occurring in the treated liquid, i.e., the growth of vapour bubbles, which violently collapse in low frequency applications (20 to100 kHz), generating locally high pressures (higher than 500 bar) and temperatures (up to 5000 °C) (Tiwari and Mason, 2012), resulting in high shear forces, which can enhance cleaning, homogenization or reduce fouling, among other effects. Cavitation also is more stable (less violent collapse of smaller bubbles) when applying high frequency ultrasound, while inducing more micro-streaming.

The use of high power low frequency ultrasound generating sonotrodes was initially suggested in the 1960s for bacterial lysing, emulsification, and cleaning (Mason*et al.,* 1996). Between1970 and 1995, high power ultrasound equipment was further developed for chemical processes with sonotrodes operating up to 6 kW. The concept of low frequency ultrasonic reactors made up of multiple transducers to deliver better uniformity is fairly recent with developments in the past 6 years. Nevertheless, only few companies manufacture high frequency transducer plates for industrial use, finding applications in recent years in the food industry. In the food industry, many applications appear at laboratory to pilot scale in diagnostics (e.g., non-destructive testing for flaw detection in material science), and processes such as cutting (e.g., frozen or soft foods through ultrasonic vibration on the edge of a cutting tool), homogenization (e.g., sauces and mayonnaise through turbulent mixing induced by cavitation), extraction (e.g., enhanced yields of flavourings and nutraceuticals from plants caused by the breakdown of cell walls), degassing (e.g., beverages before canning or bottling), anti-fouling (e.g., heat exchangers and membranes). In the past 10 years, ultrasonic applications have widened as a result of fairly recent developments of systems able to generate ultrasound in the air at reasonable power levels as well as systems able to generate ultrasound at higher megasonic frequencies (> 400 kHz) and various power levels (in the order of> 100 W). Latest developments include the use of airborne ultrasound for de-foaming and drying applications. Ultrasound at low frequencies has also been suggested to alter the casein micelles in dairy products (Liu*et al*., 2014), while low and high frequencies can alter the texture and modify the structure of foods. More recently, high frequency ultrasound standing wave fields have been implemented for enhanced palm oil separation at industrial scale (Juliano*et al*., 2017), while showing promising prospects for olive oil and coconut oil processing as well as for enhanced milk fat separation. Nevertheless, it has been reported that degradation of compounds may occur when exposing products to ultrasound.

2. Generation of power ultrasound

Ultrasound is a form of vibrational energy in the frequency range of 20e100 kHz with a sound intensity of 10e1000 W/cm^2. Generally, power ultrasound employed in food processing uses lower frequencies (20e100 kHz) and causes cavitation with sound intensities of 10e1000 W/cm^2 (Feng and Yang, 2005). The ultrasonic transducers convert electrical or mechanical energy to sound energy.

3. Principal of high power ultrasound

The fundamental effect of ultrasound on a continuum fluid is to impose an acoustic pressure (P_a) in addition to the hydrostatic pressure already acting on the medium. The acoustic pressure is a sinusoidal wave dependent on time (t), frequency (f) and the maximum pressure amplitude of the wave, $P_{a,max}$ (Muthukumaran *et al.,* 2006).

$$P_a = P_{a,max} \sin(2\pi ft)$$

The maximum pressure amplitude of the wave ($P_{a,\,max}$) is directly proportional to the power input of the transducer. At low intensity (amplitude), the pressure wave induces motion and mixing within the fluid, so called acoustic streaming (Leighton, 1994). At higher intensities, the local pressure in the expansion phase of the cycle falls below the vapour pressure of the liquid, causing tiny bubbles to grow (created from existing gas nuclei within the fluid).

4. Process parameters

4.1. Energy and intensity

Ultrasonic liquid processing can be described by the following parameters: amplitude, pressure, temperature, viscosity and concentration of solids. The result or outcome (e.g., % improved extraction yield and/or rate) is a function of:

1) Energy — the energy input per volume treated material (in kWh/L);

2) Intensity — the actual power output per surface area of the sonotrode (in W/cm2), where the energy input is the product of power output (kW) and the time of exposure. The time of exposure is directly related to the flow rate through the ultrasonic device (L/h).

4.2. Pressure

Increasing the external pressure (as controlled by the back pressure) increases the cavitation threshold and thus the number of cavitation bubbles is reduced (Muthukumaran *et al*., 2006). On the other hand, increasing the external pressure will increase the pressure in the bubble at the moment of collapse resulting in more rapid but violent collapse. Therefore, increasing the back pressure can be an effective tool in intensifying the process without having to increase the amplitude (Hielscher, 2005).

4.3. Temperature and viscosity

Temperature affects the vapour pressure, surface tension, and viscosity of the liquid medium (Muthukumaran *et al.,* 2006). While increased temperature increases the number of cavitation bubbles, the collapse is ‘cushioned' or ‘dampened' by the higher vapour pressure. Cavitation bubbles form less easily in a highly viscous environment. Increased temperature decreases the viscosity allowing for a more violent collapse.

5. PROPERTIES OF ULTRASONIC WAVES

The ultrasonic waves cannot travel through vacuum and can travel with the speed of sound in a given medium. Their velocity remains constant in homogeneous media. These waves can weld certain plastics, metals etc. These can produce vibrations in low viscosity liquids. The ultrasonic waves are reflected and refracted just like light waves. The speed of ultrasonic waves/acoustic waves is more in more dense media. Ultrasound travels through various media including gases, liquids and solids, but cannot travel through a vacuum. The speed of sound varies by the medium it travels through. Sound is likely to travel faster through solids, followed by liquids and gases.

6. Applications

Presently, ultrasound technology has gained wider applications in almost all fields including medical scanning ultrasonic therapy, mineral processing, nanotechnology, food and beverage technology, non-destructive testing, industrial welding, surface cleaning, and environmental decontamination applications (Nithila *et al*., 2014). Over the past few decades, microbial inactivation, foaming/de-foaming, degassing/deaeration, cooking, freezing and crystallization, meat tenderization, drying, brining, pickling and marinating, filtration, extraction, homogenization/emulsifying, cleaning, enzyme inactivation and cutting processes, assisted with ultrasound are some of the most studied and applied processes in the food industry.

Ultrasound is applied by three different methods

- Applying directly to the product.
- Coupling with the device.
- Submerging in an ultrasonic bath.

6.1. Microbial Inactivation

The effectiveness of thermal processing depends on temperature and time. By the way, the magnitude of treatment, time and process temperature are also proportional to the amount of nutrient loss, development of undesirable flavours and deterioration of the functional properties of food products. Ultrasonic power of around 100 W was found to be optimal for maximum microbial inactivation (Yusaf and Al-Juboori, 2014). It has been demonstrated that micro-organisms with "soft" and thicker capsule are extremely resistant to ultrasonic treatment.

6.2. Foaming/De-foaming

When the sonication horn is fixed at the air-fluid interface, foam formation becomes possible. By this method, aerated gelatin and β-lactoglobulin gels were obtained (Zuniga *et al*., 2011). The use of a powerful ultrasonic transducer, directly fixed above a foaming solution, is effective in destroying the foam. It may be due to a partial vacuum on the foam bubble surface (Kentish and Feng, 2014).

6.3. Degassing/De-aeration

Removal of the air in the solution is possible by ultrasound treatment. Reduction of pressure and boiling are common degassing methods. The agglomeration of the bubbles in the sonicated medium makes easier the rise up of the bigger bubbles through the surface (Tervo, *et al*., 2006). Degassing with ultrasound is applied to carbonated drinks, beer (de-fobbing) and wine (Boistier-Marquis, *et al*., 1999). The effectiveness of degassing is reduced by the increase of the viscosity of the applied liquid medium (Chemat, *et al*., 2011).

6.4. Cooking

Sonication in cooking led to homogeneous cooking of the food due to improved heat transfer in the medium. Also, reduction of energy consumption is an outcome for ultrasound assisted cooking application. McClements (1995) reported the assist of ultrasound in cooking provides better quality in cooked meats.

6.5. Freezing and Crystallization

A nucleus is a point where crystallization starts. The cavitation bubbles act as the nuclei as a start point of crystals. Ultrasound maintains more rapid cooling as its ability to increase heat transfer (Li and Sun, 2002). By the help of nuclei formation and rapid cooling ability of ultrasound, the desired types of smaller crystals, not to damage cells, form.

6.6. Meat Tenderization

Ultrasound is generally applied successfully in sanitary application to increase the effect of sanitary agents. The sanitary purpose of the application has also a side effect on tenderization. Ultrasonic tenderization applied on poultry meat, veal and beef. A large number of applications of ultrasonic treatment are reported in meat technology like, reduction of meat toughness due to large proportion of connective tissue (Jayasooriya *et al*., 2007), examining the composition of fish, poultry, raw, and fermented meat products by supporting genetic enhancement programs in case of livestock and in the tenderization of meat products.

6.7. Brining, Pickling and Marinating

Brining, pickling and marinating are used for preservation of foods and also the products are preferred for their desired taste. Salt, commonly around 10 % in brine, is used as a barrier for the growth of bacteria except for Lactic acid bacteria. Sonication increases the transfer of salt and water in tissues so helps to reduce the pickling time and a uniform salting (Hatloe, J. 1995).

6.8. Drying

In literature ultrasound assisted drying is called acoustic drying and has potentially great commercial importance. Ultrasound creates microscopic channels in the material and these channels allow the easy transportation of the vapour from centre to surface. Gallego-Juarez (1998) noted that heat transfer is increased approximately between 30-60 % in liquid systems. Sonication treatment permits the application of lower temperatures than conventional methodology in the drying process. Heat sensitive foods may be dried with the ultrasound assisted drying applications to avoid alterations of flavour, colour and nutritional values. The treatment produced a reduction also in rehydration properties (Chemat, *et al*., 2011).

6.9. Filtration

The membranes used in conventional filtration have a wide range from the simplest to the osmotic types. The clogging is the main problem in filtration. By the time, the cake formation in front of the surface of the filter resists the transfer of the material through the filter. Ultrasound maintains the suspension of the particles in the system that prevent the congestion of the channels of the solvent to elute (Grossner, *et al*., 2005).

6.10. Extraction

Ultrasound is mentioned as a green technique for applications in extraction. By the assistance of ultrasound, the amount of solvent used, total extraction time and the energy consumed reduces. The aid of ultrasound in extraction the process may be completed in minutes instead of hours with high reproducibility. It increases the purity of the target substances. Ultrasound is applicable in all matrices. It increases the contact of the solvent molecules with the target material. Extraction of plant components using ultrasound with its lower operating temperatures successfully dodged the limitations of degradation and loss of thermos labile constituents in conventional extraction methods.

6.11. Homogenization / Emulsifying

Particle size is one of the main important parameters for the success and stability of both homogenization and emulsifying processes. In some cases, the existence of microparticles avoids the need of addition of surfactants. The existence of microparticles makes the emulsions more stable. In-line applications are possible in production lines (Behrend and Schubert, 2001). Fruit juices, mayonnaise and tomato ketchup, homogenization of milk (Wu, *et al*, 2000) and aroma encapsulation are some of the applications in industry.

6.12. Cutting

The ultrasonic knife is a blade attached through a shaft to an ultrasonic source. Ultrasound improves the performance of food cutting or slicing. Ultrasound provides the minimization of waste and energy requirement (Schneider, *et al*., 2009).

6.13. Cleaning

The amount of solvent and the time spent for cleaning are the important parameters to focus when cleaning procedure discussed. Ultrasonic energy is now used extensively in critical cleaning applications to both speeds and enhance the cleaning effect. Ultrasonic cleaning devices generally operate between 20-50 kHz. Ultrasonic cleaning is the oldest industrial application of power ultrasound (Chemat, *et al*., 2011). Surface cleaning is applicable to a wide range of disciplines and applications (sensors, filters, substrates, reactors, catalysers and heat exchangers). It is effective on relatively hard materials such as metals, glass, ceramics, and plastics, which reflect rather than absorb sound. Cavitation is responsible for cleaning effect of ultrasound.

6.14. Water treatment

Ultrasound treatment in combination with other water treatment methods (chlorination, ozonation) is considered an efficient and economically feasible technique as in ultrasound equipment, the energy requirement is huge (Nithila *et al.,* 2014). Ultrasonication is reported to remove all impurities such as worms, sludge, mold, fungi, bacteria, and agrochemicals (Cao *et al*., 2010).

6.15. Enzyme inactivation

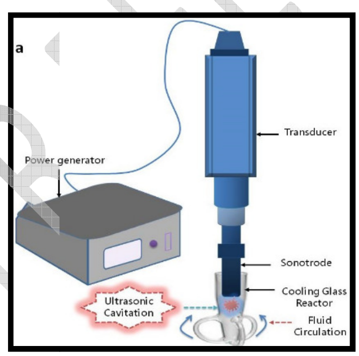
Enzyme inactivation may be a need for prolonged shelf-life of some foods and enzyme inactivation can be easily achieved by heat treatment. Ultrasonication has been used to influence enzyme activity and to obtain intracellular enzymes from microbial cells. Ultrasound treatment helps in the release of glucose oxidase from *Aspergillus niger*, galactosidases from Lactobacillus strains and *E. coli*, and invertase from *A. niger*.

Table.1: Applications of ultrasound in food processing

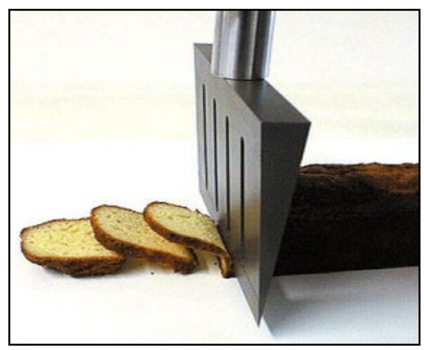
Product	Frequency	Power	Time	Purpose
Meat				
Steers meat	24 kHz	12Wcm^{-2}	240 s	Impact on the ageing of meat and characteristics quality
Beef	45 kHz	2Wcm^{-2}	2 min	Influence of ultrasound in pH of meat, its colour, and shear force
Beef	40 kHz,	1500W	10-60 min	Effects on meat quality and connective tissue collagen
Poultry	24 kHz	12Wcm^{-2}	4 min after 7 d of storage	Influence of ultrasound together with either a protease inhibitors cocktail
Holstein bulls	20 kHz	100 and 300W	10, 20, and 30 min	To develop a novel process for improving meat tenderness
Alfalfa seeds	US 40 kHz		+ $Ca(OH)_2$ 1%	Reduction of *E. coli* and *Salmonella*

Strawberries	US 40 kHz	350 W/L	10 min	Reduction of mesophilic microorganisms, molds, and yeasts
Lettuce	32–40 kHz	10 W/L	10 min + chlorinated water (25 ppm)	Reduction of *S. typhimurium*
Cherry tomato	45 kHz		10 min, 25^{0}C + peracetic acid (40mg/L)	Reduction of *S. enterica* Typhimurium
Spinach		200 W/L	2 min + various sanitizers	Reduction of *E. coli* O157:H7
Lettuce	37 kHz		30 min	Reduction of *E. coli, S. aureus, S. enteritidis*, and *L. innocua*
Cabbage, lettuce and spinach	40 kHz		3 min, 23^{0}C + electrolyzed water + washing with water	Reduction of *E. coli* O157: H7
Lychee		120W	10min	Reduction in the degradation of anthocyanins and delayed browning
Plum	40 kHz	100W	10 min	Inhibition of respiratory rate (greater firmness), preservation of flavonoids, ascorbic acid, reducing sugars, and titratable acids

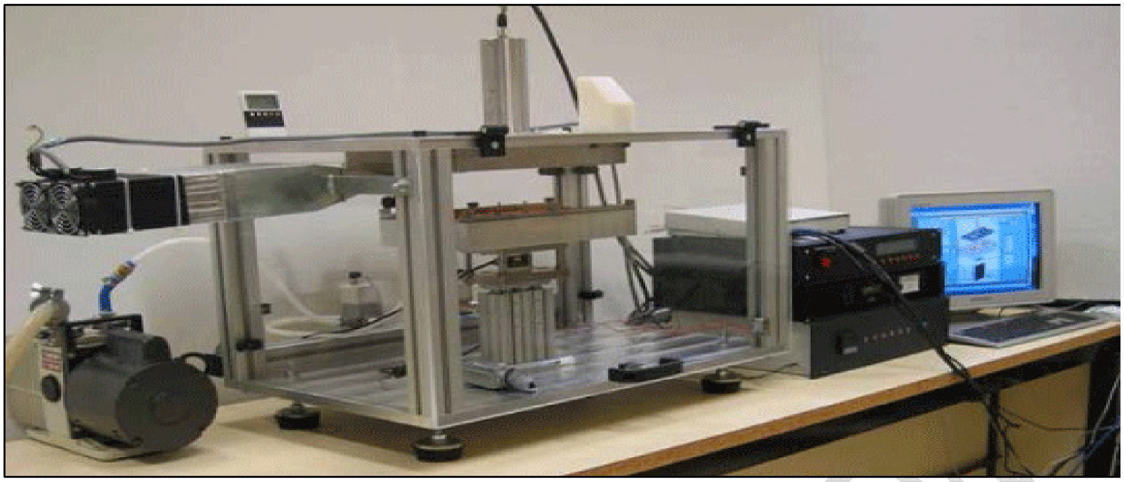
Ultrasonic Extraction



Ultrasonic Emulsion



Ultrasonic Cutting



Ultrasonic Assisted Drying

Figure.1: Equipment's used for ultrasound application in different food processing unit operations

7. Advantages and limitations of ultrasonication

Ultrasound applications offer numerous advantages in the food industry. Ultrasound waves are non-toxic, safe, and environmentally friendly. Ultrasonication in combination with other non-thermal methods is considered an effective means of microbial inactivation. Ultrasonication involves lower running cost, ease of operation, and efficient power output. It does not need sophisticated machinery and a wide range of technologies. Use of ultrasound provides more yield and rate of extraction as compared to other conventional methods of extraction. Ultrasonication involves a minimum loss in flavour, superior consistency (viscosity, homogenization), and significant savings in energy expenditure. Ultrasound has gained huge applications in the food industry such as processing, extraction, emulsification, preservation, homogenization, etc.

Despite having a lot of advantages, use of ultrasonication has also many disadvantages such as: Ultrasound due to shear stress developed by swirls from the shock waves (mechanical effects) cause inactivation of the released products. Ultrasound application needs more input of energy which makes industrialists to think over while using this technique on a commercial scale. Ultrasound induces physicochemical effects which may be responsible for the quality impairment of food products by the development of off-flavours, alterations in physical properties, and the degradation of components. Ultrasonication leads to the formation of radicals as a result of critical temperature and pressure conditions that are responsible for changes in food compounds. Ultrasonic power is considered to be responsible for the change in materials based on characteristics of the medium.

8. HAACP for ultrasound food processing operation

The hazard analysis critical control point (HACCP) system is a process that identifies and assesses the hazards and risks associated with the manufacture, storage and distribution of foods and implement the appropriate controls aiming at the elimination or reduction of these hazards at specific points of the production line. For each hazard, preventive measures are set up with procedures that indicate who will do it, how, when and where. Preventive measures aimed primarily at avoiding the occurrence of the hazard. For example, a good maintenance plan decreases the risk of metal contamination from US horn (Table). The effectiveness of

US in food processing depends on the quality of the US equipment, the parameters used and the initial microorganism rate of growth in the product.

Table 2: Possible CCP limits and associated corrective actions in a US food processing operation/system.

Critical control point	Danger	Target	Deviation	Corrective actions
Processing operation	Temperature	Adequate	Does not conform to the requirements	Adjust temperature Reject or reprocess the product
	US frequency	Adequate	Does not conform to the requirements	Adjust frequency Laboratory controls Reprocess the product
	US power	Adequate	Does not conform to the requirements	Adjust the power Laboratory controls Reprocess the product
	Flow rate	Below specifications	Does not conform to the requirements	Adjust flow Laboratory controls Reprocess the product
	Probe spoilage	Absence	Detected	Reject

9. Future trends

Many traditional food processing techniques are reaching their optimum performance while consumers demand's stretch and food and environmental regulations tighten. Research shows ultrasound can play an important role in food technology: processing, preservation and extraction. Although conventional cutting, emulsification and cleaning are often bottlenecks, lack of knowledge keeps industry from implementing ultrasound in their processes. A recent survey and market study of the possible future applications of new process technologies (like microwave, ultrasound) in the food industry has revealed that many companies are reluctant to apply these new technologies. The main reason is a poor understanding of these new techniques by food professionals and the reason or weight of tradition.

Conclusions

Ultrasound being non-toxic and eco-friendly is an emerging technology which is considered as green technology as it saves a lot of energy and maximizes production. Ultrasound finds a diverse application in science and food technology which has been employed in studying food composition (fruits, vegetables, and dairy products) and detecting contamination by foreign extraneous materials in canned and dairy foods. A lot of research has been conducted on ultrasound technologies in food technology, but still, a great deal of future research is necessary in order to produce industrial-automated ultrasound systems that will help in reduction of labour, cost, energy, and should ensure the maximum production of high value and safe food products.

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