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Ultrasonication and food technology: A review

Ishrat Majid[1], Gulzar Ahmad Nayik[1]* and Vikas Nanda[1]

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*Corresponding author: Gulzar Ahmad Nayik, Department of Food Engineering and Technology, Sant Longowal Institute of Engineering and Technology, Longowal, Punjab 148106, India
E-mail: gulzarnaik@gmail.com

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Abstract: With increasing consumers demand and tightening of food and environmental regulations, traditional food-processing techniques have lost their optimum performance which gave rise to new and powerful technologies. Ultrasonic is a one of the fast, versatile, emerging, and promising non-destructive green technology used in the food industry from last few years. The ultrasound is being carried out in various areas of food technology namely crystallization, freezing, bleaching, degassing, extraction, drying, filtration, emulsification, sterilization, cutting, etc. Ultrasound is being applied as an effective preservation tool in many food-processing fields viz. vegetables and fruits, cereal products, honey, gels, proteins, enzymes, microbial inactivation, cereal technology, water treatment, diary technology, etc. This review summarizes the latest knowledge on impact and application of ultrasound in food technology.

Subjects: Engineering & Technology; Food Engineering; Food Laws & Regulations

Keywords: ultrasonic; food industry; preservation; extraction; non-destructive

1. Introduction

From the past many years, food industry demand for minimal processed food leads to significant alterations in the processing methods as some processing techniques applied under critical conditions lower their nutrient level and bioavailability by inducing physical and chemical changes, thereby reducing

ABOUT THE AUTHORS

Ishrat Majid completed her master's degree in Food Technology from Jamia Hamdard, New Delhi. Currently, she is a doctoral research fellow at the Department of Food Engineering & Technology, SLIET, Longowal, Punjab, India, having four International publications to her credit.

Gulzar Ahmad Nayik is a doctoral research fellow at the Department of Food Engineering & Technology, SLIET, Longowal, Punjab, India. He has more than 14 International research papers to his credit.

Vikas Nanda received his PhD degree from PAU, Ludhiana in 2006. He is presently working as an associate professor at the Department of Food Engineering & Technology, SLIET, Longowal, Punjab, India. He has already attended various international conferences in Czech Republic, France (Apimondia, 2009), Greece and Argentina (Apimondia 2011), the Netherland (2014), and Thailand (2015). He is also the vice chairman of International Honey Commission. He has more than 25 International research papers to his credit and also published one book.

PUBLIC INTEREST STATEMENT

Ultrasonication is one of the new, fast, and emerging green technology in the field of food science and technology. The review focuses on various applications of ultrasound in food technology and its mode of action and effect on food constituents. The present review work collects informative knowledge that may be of interest to researchers, scientists, and industrialists.

organoleptic acceptability. Thus, in lieu of such techniques, newer mild processing methods in food industry have been devised in order to retain nutrient, non nutrient (bioactive) and sensory characteristics (Czechowska-Biskup, Rokita, Lotfy, Ulanski, & Rosiak, 2005). Ultrasonic method is one among those rapidly emerging techniques that were devised to minimize processing, enhance quality, and safeguard the safety of food products (Knorr et al., 2011). Ultrasound technology as a key area of research and development in the food industry (Ercan & Soysal, 2011) is based on mechanical waves at a frequency above the threshold of human hearing (>16 kHz), and can be categorized into two frequency ranges: low and high energy. Low-energy (low power, low intensity) ultrasound has frequencies higher than 100 kHz at intensities below 1 Wcm^{-2} while high-energy (high power, high-intensity) ultrasound uses intensities higher than 1 Wcm^{-2} at frequencies between 20 and 500 kHz (Mason, Chemat, & Vinatoru, 2011). The representative range for the frequency that is commonly applied in ultrasonic technology lies between 20 kHz and 500 MHz (Yusaf & Al-Juboori, 2014). High-frequency ultrasound as an analytical technique is used to obtain information on the physicochemical properties of food such as acidity, firmness, sugar content, ripeness, etc. While as, low-frequency ultrasound is used to change physical and chemical properties of food (Soria & Villamiel, 2010) by inducing pressure, shear, and temperature difference in the medium through which they propagate (Dolatowski, Stadnik, & Stasiak, 2007) and is capable of producing cavitations in order to inactivate microorganisms in foods (Piyasena, Mohareb, & McKellar, 2003). The typical limit for the frequency that is usually used in ultrasound applications ranges between 20 kHz and 500 MHz (Yusaf & Al-Juboori, 2014). Ultrasonication finds its application in quality control of fresh vegetables and fruits in both pre-harvest and post-harvest, cheese processing, commercial cooking oils, bread and cereal products, bulk and emulsified fat-based food products, food gels, aerated, and frozen foods. Other applications include the detection of honey adulteration and assessment of the aggregation state, size, and type of protein. Low power ultrasound (LPU): The frequency range of 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 (McClements, 1997).

2. Mechanism of action

Application of ultrasound to liquid systems causes acoustic cavitation which is the phenomenon of generation, growing and eventual collapse of the bubbles (Figure 1). As ultrasound waves propagate, the bubbles oscillate and collapse which causes the thermal, mechanical, and chemical effects. Mechanical effects include collapse pressure, turbulences, and shear stresses (Yusaf & Al-Juboori, 2014), while the chemical effects include generation of free radicals (Lateef, Oloke, & Prapulla, 2007). The effects in the cavitation zone generate extremely high temperatures (5,000 K) and pressures (1,000 atm) (Soria & Villamiel, 2010). Depending on the frequency of the ultrasound, locally produced alternating positive and negative pressures cause expansion or compression of the material, resulting in cell rupture. Ultrasound causes hydrolysis of water inside the oscillating bubbles leading to formation of H^+ and OH^- free radicals that can be captured in some chemical reactions e.g. free radicals can be scavenged by amino acids of the enzymes involved in structure stability, substrate binding, or catalytic functions. This disruption effect of sonication is significantly resisted by homogenous liquids (Ercan & Soysal, 2011). During sonication treatment, bubbles produced are divided into two types on the basis of their structure:

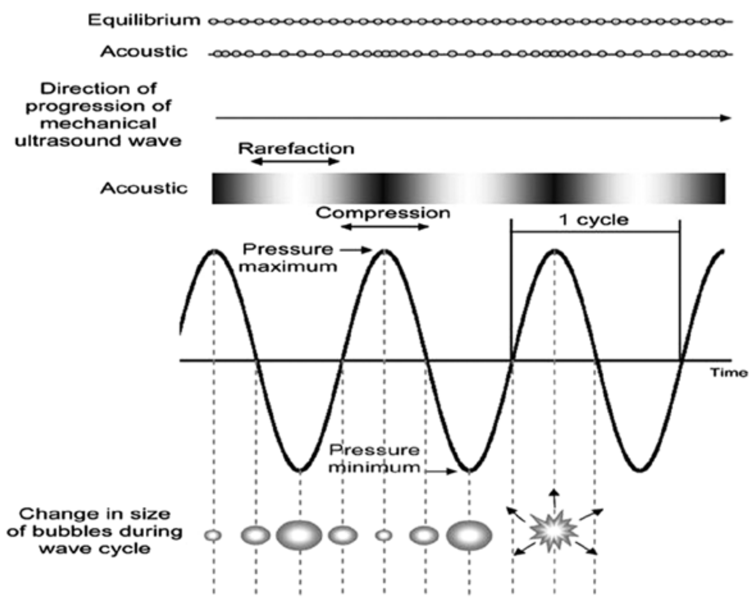
(1) Non-linear, forming large bubble clouds with equilibrium size during pressure cycles are known as stable cavitations bubbles.

(2) Non-stable, rapidly collapsing and disintegrating into smaller bubbles are known as internal (transient) cavitations bubbles.

These small bubbles quickly dissolve, but during bubble stretching, the mass-transfer boundary layer is thinner and the interfacial area is greater than during bubble collapse which implies that more air transfers into the bubble during the stretching phase than leaks out during the collapse phase (Tiwari & Mason, 2012).

Figure 1. Cavitation caused by ultrasonication.

Source: Soria and Villamiel (2010).



3. Application

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) and in food industry, it has gained enormous attention (Jambrak, Lelas, Mason, Krešić, & Badanjak, 2009). Wide spread applicability of ultrasonication as a non-thermal technology in heat-sensitive foods is because it retains sensory, nutritional, and functional characteristics along with enhanced shelf life, microbial safety (Alegria et al., 2009), and carrying away of bacterial biofilms (Baumann, Martin, & Hao, 2009). Over the past few decades, ultrasonic applications were optimized for processing or testing with the result ultrasonic applications for emulsification, defoaming, decontamination, extraction, wastewater treatment, extrusion, and tenderization of meat existed commercially (Anonymous, 2012). In addition, ultrasonic radiation, a type of low-frequency energy (20 kHz–1 MHz), has been enormously utilized for enhancing pretreatment processes like, degassing, crystallization, precipitation, leaching, cleaning, extraction, digestion sample preparation (Jiao & Zuo, 2009), changing functional characteristics of food proteins, textural properties of fat products (sonocrystallization), and promoting the extraction of bioactive constituents (Gallego-Juárez, Rodriguez, Acosta, & Riera, 2010). Favorable effects of ultrasound in food processing involves enhancement in food preservation, aid in thermal treatments, improved mass transfer, and alteration of food texture and analysis (Knorr et al., 2011). Ultrasound technology has achieved significant importance due to advancement of novel ultrasound-based and ultrasound-aided detection systems assisted by modern developments in ultrasound electronic/transducer designs (Jerman Klen & Mozetič Vodopivec, 2012).

Ultrasound is applied by three different methods

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

3.1. Effect of ultrasonication on protein

Application of ultrasound in protein modification has received ample attention in recent years either as pretreatment in order to enhance modification or chemical reaction of protein by changing its physical and functional attributes such as, gelation, foamability, emulsification, and solubility.

Ultrasonication has proved as an efficient method in producing protein conjugates and to improve the hydrolysis of proteins enzymatically (Chen, Chen, Ren, & Zhao, 2011).

3.2. Effect of ultrasonication on microbial inactivation

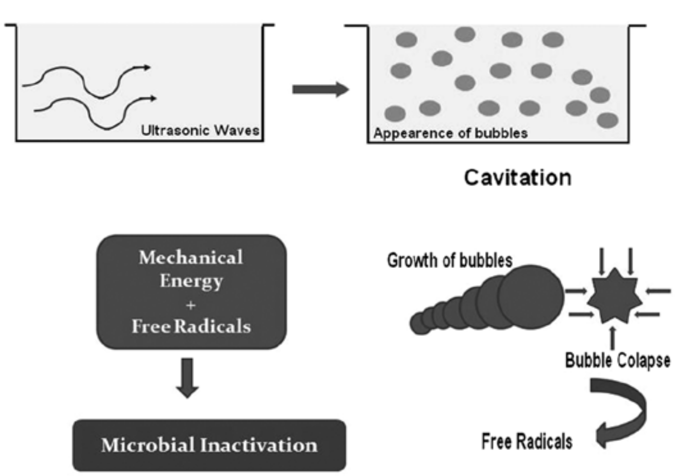
Combined effect of power ultrasound and heat (thermosonication) has proved to be more efficient method of microbial in cativation than either of the two methods alone (Raviyan, Zhang, & Feng, 2005). Microbial inactivation of ultrasound treatment accounts for generation of acoustic cavitations, resulting in increased permeability of membranes, selectivity loss, cell membrane thinning (Sams & Feria, 1991), confined heating (Suslick, 1998), singlet electron transfer in cooling phase (Lee & Feng, 2011), and hydroxyl radical formation (Kadkhodaee & Povey, 2008) (Figure 2). High-frequency ultrasound method, patented as sonoxide, has more than 600 applications and provided best results in inhibiting bacterial and algal growth in industrial waters (Broekman, Pohlmann, Beardwood, & de Meulenaer, 2010). Ultrasonic-treated cells were found to lack internal content when viewed under transmission electron microscopy, but disintegration was not affirmed to be main reason of cell death (Cameron, McMaster, & Britz, 2008). Ultrasonication has achieved the FDA requirement of a 5-log reduction in microbial population (Salleh-Mack & Roberts, 2007). Earlier, ultrasound as disinfection treatment was used by the electronics industry but now is used as substitute sanitization process in food industry (Sagong et al., 2011). Exploitation of ultrasound as means of inhibiting and killing micro-organisms came from the observation that sonar used for anti-submarine warfare resulted in killing of fishes (Scherba, Weigel, & Obrien, 1991). Ultrasound frequency of 20 kHz and power of 12.8 W was used on 50 cm^3 water contaminated with Streptococcus mutans for a period of 15 min and 97% microbial reduction was achieved (Koda, Miyamoto, Toma, Matsuoka, & Maebayashi, 2009). Ultrasonic power of around 100 W was found to be optimal for maximum microbial inactivation (Yusaf & Al-Juboori, 2014) and ultrasonication has been found to be effective method for microbial inactivation in *Escherichia coli* (Furuta et al., 2004), *Listeria monocytogenes*, and other pathogens. Efficiency of ultrasonic treatment as antimicrobial tool depends on the physical (size, hydrophobicity) and biological (gram-status, growth phase) characteristics of the micro-organisms. It has been demonstrated that micro-organisms with "soft" and thicker capsule are extremely resistant to ultrasonic treatment (Gao, Lewis, Ashokkumar, & Hemar, 2014).

3.3. Ultrasonication in meat technology

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, Torley, D'Arcy, & Bhandari, 2007), examining the composition of fish, poultry, raw, and fermented meat products by supporting genetic enhancement programs in case of livestock (Gallego-Juárez et al., 2010) and in the tenderization of meat products.

Figure 2. Cavitation phenomenon and microbial inactivation by ultrasonic waves.

Source: de Sao Jose et al. (2014).



3.4. Ultrasonication in fruit and vegetable processing

Ultrasonication is used to maintain both pre- and post-harvest quality attributes in fresh fruits and vegetables(Gallego-Juárez et al., 2010) and is considered a substitute for washing of fruit and vegetable in food industry (Alexandre, Brandao, & Silva, 2013). In an attempt to meet the consumers needs of not only maintaining but also improving the nutritional value of fruit juices (Bhat, Ameran, Voon, Karim, & Tze, 2011; Bhat, Kamaruddin, Min-Tze, & Karim, 2011), ultrasonication has proved to be one such technique (Abid et al., 2013) and is reported to retain fresh quality, nutritional value, and microbiological safety in guava juice (Cheng, Soh, Liew, & Teh, 2007), orange juice (Valero et al., 2007), and tomato juice (Wu, Gamage, Vilkhu, Simons, & Mawson, 2008). Ultrasound treatment can also be used to recover the nutrient loss occurred during blanching, resulting in achieving the collaborative benefit of both the techniques (Jabbar et al., 2014). Ultrasonication cleaners (20–400 kHz) have been efficiently used to produce fruits and vegetables free of contamination (Lin & Erel, 1992) and at 40 kHz, it has been applied on strawberry fruits in which decay and infection was considerably reduced along with quality maintenance (Cao et al., 2010).

3.5. Ultrasonication in dairy technology

Ultrasound treatment is applied in dairy industry for removal of fat from dairy wastewater using enzyme (Lipase z) as a catalyst (Adulkar & Rathod, 2014), improvement in whey ultrafiltration, cutting of cheese blocks, crystallization of ice and lactose, alter the functionality of dairy proteins (Ashokkumar et al., 2010), cleaning of equipment, pasteurization, and homogenization which involve minimum loss of flavor, and increased homogeneity and considerable savings in energy (Chouliara, Georgogianni, Kanellopoulou, & Kontominas, 2010).

3.6. Ultrasonication in extraction of plant materials or ultrasound-assisted hydrolysis

Extraction of plant components using ultrasound with its lower operating temperatures successfully dodged the limitations of degradation and loss of thermolabile constituents in conventional extraction methods (Jadhav, Rekha, Gogate, & Rathod, 2009). Ultrasound extraction involves lower running cost, considerable reduction in time and temperature of extraction with almost same yields (Yang, Zhao, Shi, Yang, & Jiang, 2008), and has been employed in extracting various intracellular components such as soybean oil (Hu, Zhao, Liang, Qiu, & Chen, 2006; Li, Li, & Guo, 2006), isoflavones from oregano (Rostagno, Palma, & Barroso, 2007), xyloglucan (Caili, Haijun, Quanhong, Tongyi, & Wengjuan, 2005), and cellulose nanofibers from wood. Ultrasonication is reported to induce some secondary plant metabolites such as ginsenoside saponins by 75% in ginseng cell (Lin, Wu, Ho, & Qi, 2001), taxol by three times in *Taxus baccata* cell culture (Rezaei, Ghanati, & Dehaghi, 2011), and resveratrol by 8–143 times in whole or sliced peanut kernel (Rudolf & Resurreccion, 2005). Ultrasound hydrolysis with higher polyphenol amounts in extracts (Teh & Birch, 2014) has gained much popularity in phenolic compound analysis in various plant matrices because of its faster extraction, efficiency, and low consumption of solvent in strawberries, red raspberries, grape seeds, olive fruits, and leaves (Jerman Klen & Mozetič Vodopivec, 2012) and it was reported that to extract naringenin, ellagic acid, naringin, rutin, quercetin, and kaempferol in three cycles of 30 s compared to 2–20 h of traditional methods (maceration/stirring) in case of strawberries and conjugated phenolics of cranberry in less than 1.5 h as compared to 16 h by traditional hydrolysis methods. Ultrasonication is used to extract lycopene (Eh & Teoh, 2012), to improve the separation of protein-starch in the wet-milling industry (Zhang, Niu, Eckhoff, & Feng, 2005), and to reduce particle size of milled corn for sugar release in corn dry-milling (Khanal, Montalbo, van Leeuwen, Srinivasan, & Grewell, 2007).

3.7. Ultrasonication in equipment design and analytical operations

Application of ultrasound in food science and technology for improving food quality has widened due to the probable recent advancement in electronics that designed ultrasound instruments and probes with greater convenience and resolution either as sensors (LPU) or as modifiers (high power ultrasound). However, ultrasound equipment are designed for use in a particular application as they cannot be postulated to suit all different applications e.g. in studying functional and physicochemical characteristics of a particular food item selection of suitable processing or sensing system (probe design, frequency, geometry) and operation variables that give optimum outputs in a particular

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application should be considered (Knorr et al., 2011). LPU in conjugation with spectroscopy and NMR are extensively used in non-destructive analytical techniques for studying the characteristics of fluid foods (McClements, 1997) and any deviation in ultrasound characteristics helps to evaluate the properties of fluids and to assess foreign gents in foods through container walls thus, allowing measurements using relatively cheap and robust instrument in the lab as well as online (Coupland, 2004).

3.8. Ultrasonication in emulsification

Ultrasonication is relatively cheaper technique for emulsion formation with significant effect on emulsion droplet size and structure. In ultrasonic emulsification application of high energy reported viscosity decrease and lesser particle size distribution in sub-micron oil-droplets emulsions. However, change in sonication parameters caused remarkable change in stability and oil droplet size of the emulsion formed (Kaltsa, Michon, Yanniotis, & Mandala, 2013). Ultrasonically produced W/O emulsions are used by emulsion liquid membrane for the separation and recapture of cationic dyes, and the stability is governed by operating variables such as emulsification time, carrier, ultrasonic power, surfactant and internal phase concentrations, volume ratios of internal phase to organic phase and of external phase to W/O emulsions, stirring speed, contact time, and diluents (Djenouhat, Hamdaoui, Chiha, & Samar, 2008).

3.9. Ultrasonication in oil technology

Ultrasonication stimulates the mixing and required reaction for conversion of soyabean oil to biodiesel, and can achieve optimum yield using 9:1 oil to methanol ratio (Santos, Rodrigues, & Fernandes, 2009). Ultrasonic irradiation is also used to increase the rate of transesterification (Deshmane, Gogate, & Pandit, 2009).

3.10. Ultrasonication in water treatment

Ultrasound treatment in combination with other water treatment methods (chlorination, ozonation) is considered efficient and economically feasible technique as in ultrasound equipment, 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). Ultrasonication does not use chemicals for mineralization and destruction of recalcitrant organic compounds in water (Gogate, 2007). In anaerobic digestion process, ultrasonication is used to increase the process efficiency, leading to more methane production and significant decrease in digestion time. Anaerobic digestion process uses ultrasound treatment either as high or as low strength depending on the irradiation location. High-strength ultrasonication (HS-ultrasonication) is irradiated as a pretreatment to feedstock and low-strength ultrasonication (LS ultrasonication) is irradiated in the aerobic digestion process to the micro-organisms involved (Cho et al., 2013).

3.11. Ultrasonication in enzyme technology

Ultrasonication has been used to influence enzyme activity (Fahmi, Khodaiyan, Pourahmad, & Emam-Djomeh, 2011) 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*. Despite positive implications on enzymatic activity, high-intensity ultrasonication leads to denaturation and hence making ultrasound treatment enzyme-specific and sonication parameter-specific (Lateef et al., 2007). Thermosonication a combination treatment of incorporating high static pressure in an ultrasound treatment chamber is used as a means for enzyme inactivation such as lipoxygenase, peroxidase, lipase, and protease, and tomato or orange pectinmethylesterase (Raviyan et al., 2005). In cellulose preparation, the cellulolytic activity was found to increase with the ultrasonic intensity because of some minor changes in spatial structure of enzyme molecules that helped in the formation of enzyme–substrate complex and increased the adsorption of cellulase on insoluble cellulose (Nguyen & Le, 2013).

3.12. Applications in membrane filtration

Use of ultrasound in conventional membrane filtration has proved to improve process efficiency and utilized in membrane cleaning (Masselin et al., 2001). Both cross-flow (Li, Sanderson, & Jacobs, 2002) and dead-end filtration (Simon, Gondrexon, Taha, Cabon, & Dorange, 2000) uses online ultrasonication. Most commonly ultrasonic water baths are used as ultrasound devices which are associated with high loss of acoustic power of about 90% (Cai, Wang, Zheng, & Liang, 2009). In an attempt to improve ultrasound equipment, several workers (Juang & Lin, 2004; Mirzaie & Mohammadi, 2012; Simon et al., 2000) have developed an ultrasonic probe system that in a dead-end filtration process passes ultrasonic waves directly to the feed medium. Also a membrane module fitted with many packed in type ultrasonic transducers are used to apply cross-flow filtration and involve minor loss of ultrasonic energy (Kyllönen, Pirkonen, Nyström, Nuortila-Jokinen, & Grönroos, 2006). Filtration performance is measured as the rate of release of permeate flux but is not correlated with processes involved in irreversible fouling and reversible concentration polarization layer in the feed. However, mass-transfer coefficients and concentration of filtrate at the membrane surface have been predicted by modeling and hypothetical methods (Muthukumaran, Kentish, Ashokkumar, & Stevens, 2005).

3.13. Ultrasonication in honey

Ultrasound applications in honey include use of velocity of ultrasonic wave propagation as a means to differentiate between different types of honey determination of adulteration in honey and evaluation of the type of protein, aggregation state, and size (Gallego-Juárez et al., 2010).

3.14. Other applications

Ultrasonication singly or in combination with other preservation methods have been used to decrease the required processing temperature and time, or both, in pasteurization of liquid foods like milk, wine, and juices. It is used as a substitute or additional process to traditional thermal methods (Valero et al., 2007). Numerous other applications of ultrasound are reported in several foods including, cooking oils, bread, cereal products, and emulsified fat-based food products, food gels, aerated foods, and frozen foods (Gallego-Juárez et al., 2010). Ultrasound has also been used to determine the interaction of powder with solvent in order to evaluate the reconstitution of powders (Richard et al., 2012) and is dependent on product porosity (García-Pérez, Ozuna, Ortuño, Cárcel, & Mulet, 2011).

4. Advantages and limitations of ultrasonication

Ultrasound applications offer numerous advantages in the food industry some of which are enlisted as follows:

- Ultrasound waves are non-toxic, safe, and environmentally friendly (Kentish & Ashokkumar, 2011).
- Ultrasonication in combination with other non-thermal methods is considered an effective means of microbial inactivation (Vercet, Sánchez, Burgos, Montañés, & Lopez Buesa, 2002).
- Ultrasonication involves lower running cost, ease of operation, and efficient power output.
- Ultrasonication does not need sophisticated machinery and wide range of technologies (Gallego-Juárez et al., 2010).
- Use of ultrasound provides more yield and rate of extraction as compared to other conventional methods of extraction (Balachandran, Kentish, Mawson, & Ashokkumar, 2006).
- Ultrasonication involves minimum loss in flavor, superior consistency (viscosity, homogenization), and significant savings in energy expenditure (Chouliara et al., 2010).
- Ultrasound has gained huge applications in the food industry such as processing, extraction, emulsification, preservation, homogenization, etc. (Chemat, Zill-e-Huma, & Khan, 2011).

Despite having 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 (Lateef et al., 2007).

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- Ultrasound application needs more input of energy which makes industrialists to think over while using this technique on commercial scale (Yusaf & Al-Juboori, 2014).
- Ultrasound induces physicochemical effects which may be responsible for quality impairment of food products by development of off-flavors, alterations in physical properties, and 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. The radicals (OH and H) produced in the medium deposit at the surface of cavitation bubble that stimulates the radical chain reactions which involve formation of degradation products and thus lead to considerable quality defects in product (Czechowska-Biskup et al., 2005).
- Frequency of ultrasound waves can impose resistance to mass transfer (Esclapez, García-Pérez, Mulet, & Cárcel, 2011).
- Ultrasonic power is considered to be responsible for change in materials based on characteristics of medium. So, this power needs to be minimized in food industry in order to achieve maximum results (Feng, Barbosa-Canovas, & Weiss, 2011).

5. Conclusion

Ultrasound being non-toxic and ecofriendly is an emerging technology which is considered as green technology as it saves 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 labor, cost, energy, and should ensure the maximum production of high value and safe food products.

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Competing interests

The authors declare no competing interest.

Author details

Ishrat Majid[1]
E-mail: ishratmajid89@gmail.com
Gulzar Ahmad Nayik[1]
E-mail: gulzarnaik@gmail.com
ORCID ID: http://orcid.org/0000-0001-8372-5936
Vikas Nanda[1]
E-mail: vik164@yahoo.co.in
[1] Department of Food Engineering and Technology, Sant Longowal Institute of Engineering and Technology, Longowal, Punjab 148106, India.

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