

Ultrasound in Food Technology

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Ultrasound is composed of mechanical sound waves that originate from molecular movements that oscillate in a propagation medium. The waves have a very high frequency, approximately 20 kHz, are divided into two categories (i.e. low intensity waves and high intensity waves) and cannot be perceived by the human ear.

Ultrasound is commonly associated with the biomedical field.

ultrasound applications

low power

high power

ultrasound in food technology

ultrasonic extraction

antimicrobial activity of ultrasound

1. Introduction

Sound is an oscillation of particles (i.e., atoms and molecules) in an elastic medium. The oscillations displace the particles around the resting position and along the direction of propagation of the wave caused by vibratory movements. These vibrations are produced by a given object, which is called the source of sound, which transmits its movement to the adjacent particles by virtue of the mechanical properties of the medium. When oscillation begins, the particles transmit their movements to neighbouring particles, and these particles in turn transmit their movements to others, causing a local variation in pressure; therefore, a simple vibratory movement propagates mechanically to produce a sound wave (or acoustic wave) ^[1]. Ultrasound (US) is defined as waves of a mechanical nature that require an elastic medium to propagate ^{[2][3]}. Sounds and ultrasounds differ in frequency: sound waves propagate at frequencies audible to the human ear (from 16 Hz to 16–20 kHz), while US waves propagate at frequencies greater than 20 kHz (upper limit of audibility for the human ear) up to frequencies of 10 MHz, which then proceeds to the so-called hypersonic region. Ultrasound, which is composed of mechanical waves, propagate in a medium through the transfer of energy and not of particles; the latter, in fact, simply oscillate around their equilibrium position, with the transfer of energy from one particle to another. The oscillation propagates in the medium in various directions, and therefore, distinguish as longitudinal waves and transverse waves. In longitudinal waves, the oscillatory movement of the particles in the transmission medium is parallel to the propagation direction, while in the transverse waves the movement is perpendicular. The longitudinal (or compression) waves propagate in any medium, while the transverse waves only propagate in solid media. The US wave is a longitudinal wave characterized by the alternation of compression and rarefaction cycles of the medium in which it propagates, which entails variations in the pressure of the medium; energy is transferred from the motion of particles. This process of compression and rarefaction of the particles in the medium and their subsequent collapse is known as the phenomenon of cavitation, the most important effect of high-energy US waves ^{[4][5]}. In particular, cavitation is a physical phenomenon that leads to the formation and activity of bubbles (or

cavities) inside a liquid when it is subjected to the action of high-speed pressure and depression waves generated by ultrasound waves in an intense ultrasonic field. During the depression phase, numerous bubbles are created inside the liquid. During the second phase of ultrasound compression, the enormous pressure exerted on the bubble decompresses until it implodes, i.e., collapse on itself. The bubbles have a diameter of a few micrometres, while the lifetime of the bubbles is on the order of microseconds. Two types of cavitation have been distinguished: in the first type, known as stable cavitation, the bubble remains stable around an equilibrium size for many compression-decompression cycles; in the second type, known as transitory or unstable cavitation, the bubble grows in a single cycle, doubles its size, and then collapses.

The chemical effects of US vary, and three distinct phases have been identified in the reaction environment: the gaseous environment inside the bubble cavity, the liquid-bubble interface, and the liquid. In the gas phase, pyrolysis reactions occur, such as the pyrolysis of water. In the bubble-liquid zone and the liquid mass, various radicals can form, and the most frequently encountered radical in the aqueous environment is the hydroxide radical $\text{OH}\cdot$, which is highly reactive and readily attacks organic substrates present in the reaction environment or recombines with another $\text{OH}\cdot$ radical to form H_2O_2 . In the interface area, where the temperatures are very high, solute reactions with $\text{OH}\cdot$ radicals or thermal degradation reactions may occur. The diffusion of these radicals is mainly due to the disruption of the cavitation bubble and subsequent formation of smaller bubbles. Non-volatile solutes react in the interface zone or in the liquid, and volatile solids enter the bubble and degrade during bubble collapse. The effects of radicals are important because they induce molecular sonolysis and degradation of the solvent and solute structure. In contrast, mechanical effects alter electrochemical processes, modify the properties of certain solids and alter the liquid-liquid and gas-liquid systems by facilitating the formation of solid-state emulsions and solute dispersion in the solvent [6][7]. Historically, US has developed similar to a branch of acoustics. In parallel to the progress in understanding the propagation of acoustic waves, we have witnessed the development of technologies capable of generating US. As described above, US waves are sound waves with a frequency range ranging from 20 kHz to 10 MHz. Further subdivisions within this range have been identified [8]; these subdivisions may in fact have substantially different characteristics, depending on the frequency at which they are generated and the amount of energy generated by the acoustic field. In particular, US power influences chemical reactivity and is grouped into two subfamilies: A) high-energy US characterized by low frequencies (20 kHz–100 kHz), which are used in some food technologies, and intermediate power US processes characterized by medium frequencies (100 kHz–1 MHz); and B) low-energy diagnostic US that is used in physical measurements, mainly for medical and diagnostic uses, and is characterized by high frequencies (5 MHz–10 MHz). Although cavitation is considered an event to be avoided in many fields, other fields exploit cavitation produced in a controlled manner, such as the military, which uses torpedoes that travel at very high speeds, or ultrasonic cleaning systems used to clean small objects, where the implosions of the bubbles clean even the most delicate and unreachable surfaces. In the medical field, controlled cavitation is used to remove kidney stones (lithotripsy), which are precisely crushed through the formation of microbubbles that implode the solid formations inside the kidneys, as well as for diagnosis and analgesic thermal effects [9]. Cavitation is also used in aesthetic medicine to eliminate or reduce adiposity, a technique known as non-surgical non-bloody liposuction (Ultrasound Lipoclasia). In addition, acoustic cavitation has been used to facilitate the delivery of small molecules and macromolecules, including

proteins and DNA. Controlled generation of cavitation has also been used for the targeted delivery of drugs to diseased tissues, including the skin, brain, eyes and endothelium [\[10\]](#). Moreover, US has been employed as a treatment for several diseases, including thromboembolism, arteriosclerosis, and cancer [\[11\]\[12\]\[13\]\[14\]](#). On the other hand, the study of the propagation of US waves in humans has allowed the construction of stable medical diagnostic instruments used in gynaecology, gastroenterology, angiology, and cardiology, which exploit the return echo resulting from an US wave that propagates inside the human body and is slowed in a different way by the different anatomical structures it crosses [\[15\]](#). Moreover, precisely because of the different acoustic impedance of the various tissues, US has been used to determine various biological effects, among which the thermal effect was the original use of US in orthopaedics, physiatrics, and sports medicine to inhibit pain and particularly in the aesthetic field to treat localized adiposity and cellulite [\[16\]](#).

In the food sector, the use of US has many advantages. In fact, US has been used to obtain phytocomplex extracts without altering their organoleptic properties, enabling researchers to understand their functional principles. Any solvent can be used for extraction based on the type of extract desired, and the process operates exclusively at room temperature, resulting in remarkable reductions in the required extraction time, instrumentation, energy and human resources. In addition, US use guarantees a reduction in the bacterial content of the final product due to the antibacterial effect of US. Finally, the US extraction process has received biological certification for use in both the food and cosmetic industries [\[17\]](#) (**Figure 1**).



Figure 1. The different fields in which ultrasound (US) has been applied.

The fields in which US has been applied exploit both its mechanical and chemical effects. The importance of the two effects varies according to the frequency used [8]. At low frequencies (20–100 kHz), the mechanical effect caused by unstable cavitation predominates, and as the frequency approaches 20 kHz, the bubbles collapse with increasing violence [18]. At medium frequencies (200–500 kHz), the chemical effect is prevalent, as a greater number of bubbles form that collapse less violently. At high frequencies (>1 MHz), both the chemical and physical effects related to cavitation are minimal, while the effect of the acoustic flow is predominant. The high frequencies are typically used to clean delicate objects, which might be damaged in the presence of cavitation.

Table 1 shows some examples of the applications of US to improve and facilitate different types of processes.

Table 1. Mechanical, chemical, and biochemical effects of US.

Mechanical Effects	References

Crystallization of fats, sugars, etc.	Luque de Castro et al., 2007 [19] ; Cook and Hartel, 2010 [20]
Degassing and destruction of foams	Dedhia et al., 2004 [21]
Extraction of aromas	Chemat et al., 2017a [22]
Filtration and drying	Tao and Sun, 2015 [23]
Freezing	Kiani et al., 2011 [24]
Mixing and homogenization	Mason et al., 2005 [25]
Precipitation of airborne powders	Riera et al., 2006 [26]
Meat tenderization	Jayasooriya et al., 2004 [27] ; Alarcon-Rojo et al., 2015 [28]
Chemical and Biochemical Effects	References
Bactericidal action	Yu et al., 2012 [29]
Wastewater treatment	Oturan et al., 2014 [30]
Modification of the growth of living cells	Guo et al., 2015 [31]
Alteration of enzymatic activity	Huang et al., 2017 [32]
Sterilization of equipment	Chemat et al., 2017b [33] ; Koubaa et al., 2018 [34]

2. US in Food Science and Technology

Over the past few years, the properties of US have aroused increasing interest in the food industry, as the induction of physical and chemical reactions can lead to a strategic advantage in the various stages of processing.

Currently, US is considered an emerging and promising technology in the food processing industry, since it produces permanent mechanical, chemical and biochemical changes in liquids (due to intense cavitation) and gases (for the generation of high intensity acoustic fields). Since the 1990s, the use of US has become a technological alternative that is applicable on a large scale in the processing industry [35]. Ultrasound has been applied to food technologies due to its mechanical and/or chemical effects on the processes of homogenization, mixing, extraction, filtration, crystallization, dehydration, fermentation, and degassing through its antifoaming actions, reduction of particle sizes, temporary or permanent modifications of viscosity, modulation of the growth of living cells, cell destruction and dispersion of aggregates, inactivation of microorganisms and enzymes, and sterilization of equipment [24]. Precisely for these reasons, the effects of this technology are considered interesting in the food industry, mainly due to new trends involving consumers shifting towards functional foods. Because US offers several advantages, this form of energy has been applied to improve the qualitative characteristics of high-quality foods and to ensure the safety of a vast variety of foodstuffs, all while minimizing any negative effects on the sensory characteristics of foods. Furthermore, the non-destructive nature of this technology offers several opportunities for the compositional analysis of foods [36]. The interaction of the acoustic energy with a food mainly occurs through a liquid medium since the cavitation and the physical and chemical actions induced by US play an important role in the changes in the quality of a food during its transformation. Indeed, the implosion of bubbles creates an unusual substrate for chemical reactions by mechanically breaking the cell envelope and improving the transfer of intracellular material [8]. At the solid and liquid interface, even the water jet formed by transient cavitation might contribute to some changes in the global properties of a food product. All the chemical and physical effects of US are microscopic; however, the interactions of these chemical and physical reactions induced by cavitation with the food manifests itself through macroscopic changes that are perceived by the consumer in terms of consistency, colour and flavour [8]. High-intensity US has become an effective tool for large-scale commercial applications for approximately a decade, but only recently has the equipment design been optimized and the performance of continuous-flow systems improved. As with all other more innovative processing technologies, high-power US is not a standard technology and therefore must be studied and developed for each type of application [37]. Based on the frequency used and the amplitude of the applied sound wave, a number of physical, chemical and biochemical effects can be used for a variety of applications [38]. High-frequency/low-energy US (diagnostic US) is mainly used as an analytical technique for quality control and processing steps, and for non-destructive inspection that has been applied to determine the concentration, viscosity, and composition of food, among other parameters [22][39][40]. The application of high energy/intensity US (US power) improves the quality of processed foods and results in characteristics similar to the fresh product (colour, consistency, flavour, and nutrients). Few scientific papers have documented a possible correlation between the effects of cavitation and the processing conditions used to predict possible changes in quality. Therefore, only limited conclusions have been drawn about specific foods that have been studied based on the applied parameters [8] (**Figure 2**).

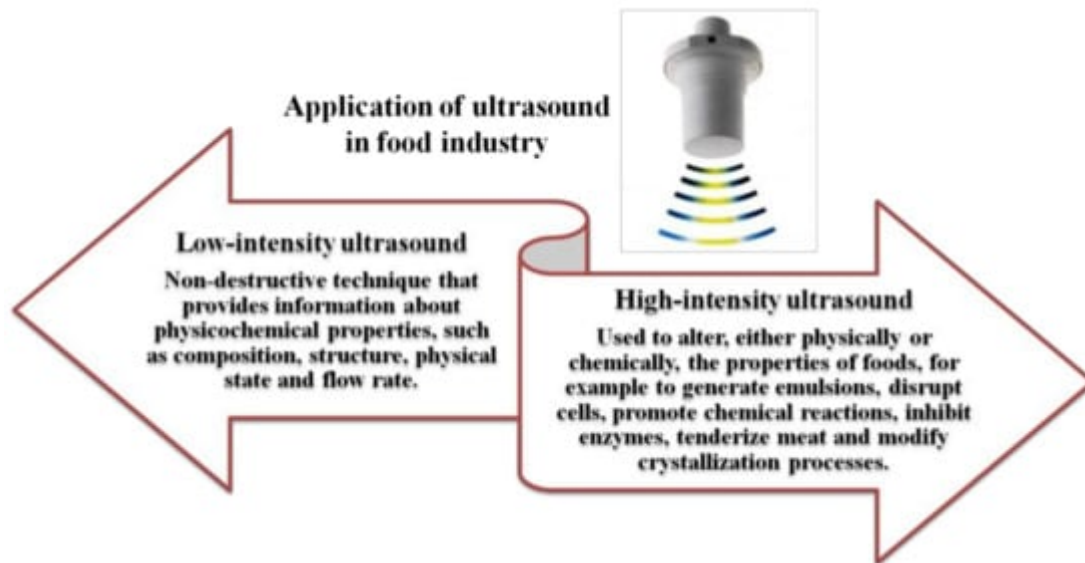


Figure 2. Applications of ultrasound in food analysis and processing.

3. US Technology in Different Processes

In the food industry, US is used to control production processes, assess food characteristics, detect defects, control fruit ripening, improve the yield and speed of extraction of food components, and evaluate the conservation state. Ultrasound has been used to improve conventional food processing unit operations by reducing energy and chemical requirements, thus offering a greener option. In food processing, the applications of US are divided into two categories, namely, replacing traditional technologies and assisting traditional technologies. In the latter case, the use of US to enhance various food processes, such as extraction, freezing, thawing, brining, oxidation, filtration, and drying/dehydration, increases the processing efficiency and improves the disadvantages of traditional technologies used during processing [\[23\]](#).

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