Chapter

Application of High-Power Ultrasound in the Food Industry

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Abstract

The purpose of this chapter is to summarize potential applications of the high-power ultrasound technology (5 W/cm^2; 20–100 kHz) in the food industry. Those applications are mainly related to the improvement in mass and energy transfer in different processes when ultrasound is applied in water or through air, e.g., reduction in dehydration; thawing and freezing times and energy costs of plant-, meat-, or fish-based products; increase the extraction yields of intracellular compounds with biological activity; reduction of chemical health risks such as cadmium or acrylamide; etc. The influence of some physical parameters like temperature and pressure in cavitation intensity and the potential of this technology to even inactivate microorganisms in food products and surfaces in contact with food will be discussed. Several examples of these applications will be presented, with reference to some of the industrial or pilot plant systems available in the market to be implemented in the food industry.

Keywords: mass transfer, heat transfer, cavitation, food preservation, food quality

1. Introduction

Ultrasound is considered an emerging technology in the food industry that is gaining interest due to its potential to improve several process including mass and energy transfer processes among others. It also enables to obtain safer and higher quality products than with traditional procedures. Furthermore, it should be remarked that it is also considered a safe, nonpolluting and environmentally friendly technology [1].

Ultrasonic technology consists of the application of mechanical waves with frequency over the threshold of human hearing (>16 kHz) [2]. Depending on its frequency and intensity, the ultrasonic spectrum can be further divided into low-frequency (20–100 kHz) high-power (>1 W/cm^2) ultrasound and high-frequency (>100 kHz) low-power (<1 W/cm^2) ultrasound. Low-power ultrasound is applied for noninvasive and nondestructive analyses, and it is mainly used in other areas such as medicine and cosmetics. In the food industry, this type of ultrasonic waves is basically used for process and quality control (e.g., fluid flow and container filling control, location of foreign bodies, or evaluation of the homogenization and/or emulsification efficiency). In contrast, high-power ultrasound is able to produce changes in the material or process to which they are applied, and it is used in a large variety of processes in the food industry (e.g., surface cleaning and decontamination, microbial and enzymatic inactivation, degassing, defoaming, and improvement of mass transfer, among others). Therefore, high-power ultrasound is the one of great interest in the food industry, and in this chapter, it will be discussed in more detail.

2. Effects of ultrasound in food matrices mechanism of action

Ultrasonic sound waves propagate through air, water, and solid media, generating pressure variations that cause the vibration of particles in the medium. The effects of the application of high-power ultrasound in food products are therefore dependent on the medium of propagation (liquid, solid or gas) and also on the parameters of the process such as frequency, intensity, pressure, and temperature, among others. Applying ultrasound in liquid medium is the simplest and the most common process in the food industry. Cavitation is the main phenomenon responsible of ultrasound effects when applied to a liquid. Basically, cavitation occurs when the microbubbles present in the liquid increase in size as a result of the cycles of high and low pressure generated by the ultrasonic waves until they become unstable and collapse releasing a large amount of energy (theoretically up to 5000 K and 1000 atm) [1]. As a consequence, different effects are generated. These can be divided into physical and chemical effects. Within the physical effects, microjets and microstreaming phenomena are the most relevant ones. Microjets are high-pressure water streams projected to the surface of solids that lead to the formation of pores and surface erosion, causing the release of material into the medium depending on the intensity of the jets. By contrast, microstreaming occurs in the middle of the surrounding liquid, and when its speed is high enough, it can break membrane cells, release intracellular enzymes, etc. [3]. These physical effects are more likely to occur at low frequencies (20–40 kHz) when the number of cavitation spots is low but the energy associated to them is higher. At higher frequencies (80–100 kHz), the number of spots is higher, but bubble size is smaller, so the energy released is lower and the prevalent effects are mainly chemical [4]. The primary radicals that are generated by ultrasound are H• and •OH, which can be then recombined to form other reactive species (H_2, H_2O_2) [5]. Therefore, depending on both the ultrasound intensity and, mainly, frequency, different effects, physical or chemical, are produced.

On the other hand, when an ultrasonic wave passes through a solid medium, it produces a series of alternating contractions and expansions, a phenomenon known as the "sponge effect," which facilitates the transfer of matter with the medium surrounding the solid [6]. Moreover, this mechanical stress can cause the formation of microchannels in the interior of the solid, also favoring mass transfer processes. In this case, it is unlikely that the cavitation phenomenon would occur in the liquid phase of the solid matrix [7].

Finally, although the application of high-intensity ultrasound is more complicated in gas medium, its effects on the solid/gas interface are particularly interesting, including pressure variation, oscillating flow, and microstreams [8]. The development of efficient ultrasonic systems to be applied in for gas medium is highly limited by the power loss that occurs when sound waves are propagating through air and by the mismatch between acoustic impedances of gases and solids or liquids [9]. As it will be discussed below, its main application is the improvement of food dehydration processes and defoaming.

3. Factors affecting cavitation

In the food industry, ultrasound is applied trough a liquid media in most applications, becoming cavitation the main mechanisms of action in these processes, as pointed out above. However, in order to apply ultrasound effectively to these food matrices, it is necessary to consider a group of factors influencing the cavitation phenomenon, including the characteristics of the ultrasound source (frequency, amplitude, ultrasonic supplier), characteristics of the treatment medium (solid particles, gas bubbles, viscosity), and treatment conditions (pressure and temperature) [2]. Regarding the characteristics of ultrasound source, the frequency and amplitude are the most important parameters that condition the effects of the treatment. As stated above, frequency determines the size of the bubbles and, thus, the intensity of the implosion. Amplitude is directly related to the amount of energy supplied to the system and the ultrasonic intensity [3]. At high amplitudes, the oscillation of the bubbles is higher, being the implosion more powerful and leading to further effects derived from cavitation. However, depending on the desired effects, this may not always be of interest, and therefore it is essential to optimize the treatment parameters. For example, for hydrating thawed cod fillets, the highest weight gain (18%) of fillets after 48 hours of hydration was observed when applying the 10% of the power of an ultrasound system of 35 kHz and 200 W. When ultrasound was working at the maximum amplitude of the system (100%), 12% of weight gain was observed, which was a lower value than that of the control process without using ultrasound (14%) [10]. As it will be discussed later on, both frequency and amplitude condition the ultrasonic supplier which defines the way of application of ultrasound to the product and its effects.

Besides the state of the treatment medium (solid, liquid or gas), solid particles, gas bubbles, and viscosity also influence cavitation. The presence of solid particles and gas bubbles act as nucleation points which enhance the formation of bubbles reducing the effects of cavitation. Regarding the viscosity of the medium, bubble formation is more difficult the higher the viscosity of the medium is, but the implosion is more powerful. Moreover, ultrasound has interesting effects in viscous products in order to improve energy transfer as it will be discussed below.

Finally, temperature and static pressure are key factors conditioning cavitation which are modified depending on the application. Thus, the increment of temperature reduces the viscosity of the medium and raises the vapor pressure enabling bubble formation. However, the amount of vapor inside the bubbles increases with temperature, producing the cushioning of the collapse and leading to a lower intensity of cavitation. Therefore, it is considered that there is an optimal temperature at which acoustic cavitation is maximum [11]. On the contrary, when pressure increases, cavitation is hindered, but when the implosion happens, the energy released is considerably higher. Based on these effects of temperature and pressure, two processes have been defined: manosonication (MS) and manothermosonication (MTS) which have been shown to offer new possibilities of ultrasound at temperatures near or even above 100°C as it will be commented later on.

In summary, many factors have to be considered when designing ultrasound equipment and processes in the food industry in order to secure an efficient application.

4. Basic ultrasound systems used in the food industry

Since the application of ultrasound in the food industry is very dependent on the ultrasound supplier, it is worthy to consider this point.

There are different ultrasound systems for food applications depending on the treatment medium and the desired effect. It is essential to achieve a successful fit between application system and treatment medium in order to be able to transfer the maximum amount of acoustic energy to the medium. As indicated, the application of ultrasound through liquid medium is the most used in the food industry. For this application, commercial equipment can be divided into two types: ultrasound water baths (indirect application) and probes or horns (direct application). Ultrasonic water baths are widely used due to their lower price and easy maintenance. They consist of a tank to which one or more piezoelectric transducers (40–130 kHz) are connected at the bottom or at the sides and the generated sound waves are propagated through the water or other liquid medium in which the food product is immersed (**Figure 1(a)**) [12]. The ultrasonic intensity is low (0.1–1 W/cm^2), and the treatment is less homogeneous throughout the volume due to the formation of nodes [11]. In the food industry, this type of equipment has been used for surface cleaning, degassing, enzymatic and microbial inactivation, improvement of mass transfer, etc. [13]. On the other hand, horn or probe is a direct system in which the food product is in contact to the ultrasound supplier. These equipment allow to apply higher intensities (>5 W/cm^2) than water baths, but they are more expensive. In these systems, three parts can be differenced (**Figure 1(b)**): the transducer, the amplifier of the ultrasonic signal, and the horn. The tip of the horn has to be introduced into the sonication medium, so this design is mainly used for treating liquid foods, but application in solids has also been described [14, 15]. Depending on the shape of the horn, its application will be determined and used for cell disruption, homogenization, cutting of soft products, etc. [16].

The equipment developed for the application of ultrasound through the air (called airborne) is less common due to the difficulty of its design. The type of transducer used for this application differs depending on the application: stepped plate, ribbed plate, stepped-ribbed plate, and cylindrical radiator [1, 13, 17]. The basic structure is a piezoelectric transducer in sandwich configuration and an amplifier or horn (**Figure 1(c)**). The horn is attached to a radiator which vibrates, and due to its surface, the resistance increases, and the differences in impedance between the transducer and medium are reduced. This kind of systems is very well described in the works of Gallego-Juárez et al. [1] and Charoux et al. [17], among other publications.

5. Applications of high-power ultrasound in the food industry

In recent years, numerous applications of high-power ultrasound have been developed in food processing, including product quality control, emulsification, food preservation, and improvement of mass and energy transfer processes. Some of these applications are summarized in this part of the chapter.

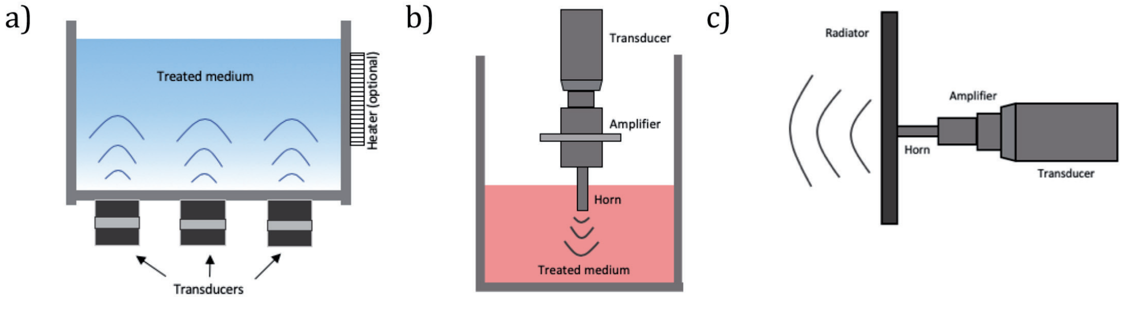

Figure 1.
Ultrasound generation systems: (a) ultrasonic bath, (b) probe or horn, and (c) airborne transducer.

5.1 Emulsion formation

The use of ultrasound for obtaining emulsions was one of the first applications in the food industry. An emulsion is a heterogeneous system formed by two immiscible liquids in which one of them is dispersed in the other in the form of small droplets with a diameter—in general—lower than 1 mm.

Li and Fogler [18, 19] originally proposed a mechanism for explaining the emulsifying capacity of ultrasound that was later confirmed by high-speed photography [20], consisting of two steps. First, the acoustic waves generate instability at the interface of the two liquids, causing large drops of oil to propel them into the aqueous phase. Second, cavitation produces microcurrents and shear forces that reduce the droplet size needed to form the emulsion [21].

There are many studies on ultrasound-assisted emulsion preparation [20, 22–24]. In general, these studies conclude that it was possible to obtain emulsions that have smaller particle size, are less polydisperse, and are more stable than by agitation by using ultrasound. For example, in a study comparing the use of ultrasound with traditional agitation [25], the application of ultrasound allowed the elaboration of a nanoemulsion of mustard oil in water with an interfacial area of 67-fold greater than that obtained mechanically. In addition, the sonicated emulsions had a narrower particle size distribution (0.82–44.6 μm) than the control emulsions (8.1–610 μm).

Due to the emulsifying capacity of ultrasounds, they are recently being used as encapsulation systems in the food industry [26]. Some high-value nutrients are encapsulated in the food matrix to avoid functional losses, organoleptic losses, undesirable reactions with other compounds, etc. Ghasemi and Abbasi [27] combined the alkalization of pH with the application of ultrasound (25 kHz, 600 W) to encapsulate oils with a high content of polyunsaturated acids in skimmed milk.

5.2 Food preservation

5.2.1 Microbial and enzyme inactivation

The main agents responsible for food spoilage are enzymes and microorganisms. Moreover, pathogenic microorganisms are responsible of food poisoning and food outbreaks, requiring therefore their control or inactivation. There are several strategies to limit their action (i.e., reducing temperature, controlling water activity, etc., of foods) and to inactivate them, mainly by heat treatments. Thermal pasteurization and sterilization are the most common technologies used for enzyme and microbial inactivation in order to obtain safe and stable food products. However, the intensity of these treatments can lead to loss of nutrients and deterioration of sensory characteristics and functional properties of food [16, 28]. Due to this, technologies which enable to inactivate those agents at lower temperatures are under evaluation being ultrasound a possibility.

Bacterial inactivation with ultrasound has been widely studied and even suggested as a possible food preservation method [29–31]. Microbial inactivation is mainly induced by the physical effects of cavitation such as shear forces, shock waves, and microcurrents that can damage cell integrity by weakening or breaking cell envelopes [32, 33]. However, its lethal effect is reduced and requires prolonged periods of time [34, 35], limiting its application as a food preservation system. Due to its low bactericidal efficacy and in order to increase its lethality, ultrasound is applied over atmospheric pressure (manosonication, MS), combined with heat (manothermosonication, MTS) and with other nonthermal technologies (pulsed electric fields, high hydrostatic pressures, UV light) [36, 37]. From all these combinations, MS and MTS showed the most promising results since vegetative cells and even bacterial spores can be inactivated at low temperatures (40°C) [32, 33, 38], as summarized in **Figure 2**. The possibility of inactivating vegetative cells and spores opens the way to design alternative processes to thermal pasteurization and sterilization by using MTS treatments at lower temperatures than those used in traditional thermal treatments [32–33, 38]. However, the required ultrasound intensities to achieve several log_{10} cycles of microbial inactivation are still far away for its industrial application due to technical limitations.

Likewise, ultrasound is also effective for inactivating enzymes, but very long processing times are required. However, when combined with heat (thermo-sonication, TS), pressure (MS), or heat and pressure (MTS), processing times can also be reduced. For example, the application of MTS is able to reduce the heat resistance of enzymes by 2–400-fold such as alkaline phosphatase, polyphenol oxidase, peroxidase, lipase, lipoxygenase, pectin methylesterase, and polygalacturonase compared to heat treatments applied at the same temperature [32, 39–45]. As an example, **Figure 3** shows the activity reduction of pectin methylesterase of tomato juice treated by heat, MS, and MTS treatments at 62.5°C and 1 minute. As can be observed, the MTS treatment led to a complete inactivation of the enzyme, being this effect higher than the addition of the heat and MS inactivation effects when applied separately (synergistic effect).

5.2.2 Microbial decontamination and surface cleaning

Cleaning and decontamination of food equipment and/or surfaces in contact with food are among the first applications of ultrasound in the food industry besides emulsification. The main phenomena responsible for its effect are cavitation and microstreaming formed in the washing liquid. The collapse of the bubbles generates high-pressure microjets that impact the surface which favor the dissolution of compounds and the release of the particles (including microorganisms) adhered to the solid. The surfaces of the solids have irregularities and pores limiting the cleaning effectivity of traditional systems. However, ultrasounds are able to get access and get a deeper cleaning enhancing also the effectiveness of chemical cleaning by favoring the release of contaminants such as oils, proteins, and even microbial biofilms, making them more accessible to chemicals [12, 46]. Nevertheless, it is important to notice that as the ultrasonic field is not uniform throughout

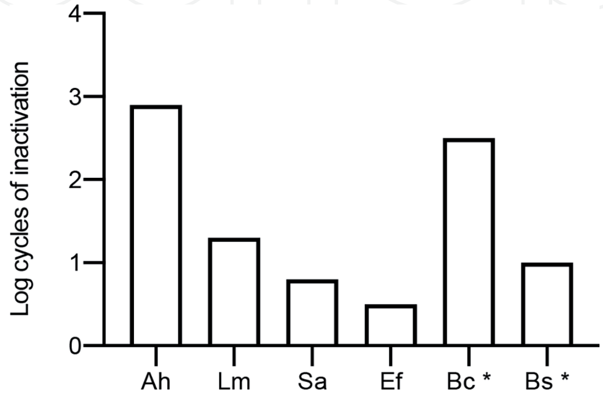

Figure 2.
Log_{10} cycles of inactivation of Aeromonas hydrophila *(ah),* Listeria monocytogenes *(lm),* Staphylococcus aureus *(Sa),* Enterococcus faecium *(Ef),* Bacillus circulans *(Bc) (spore), and* Bacillus subtilis *(Bs) (spore) treated in McIlvaine buffer pH 7.0 with MS (0.2 MPa, 40°C, 450 W and 4 minutes, for spores 15 minutes*). Adapted from [31, 45].*

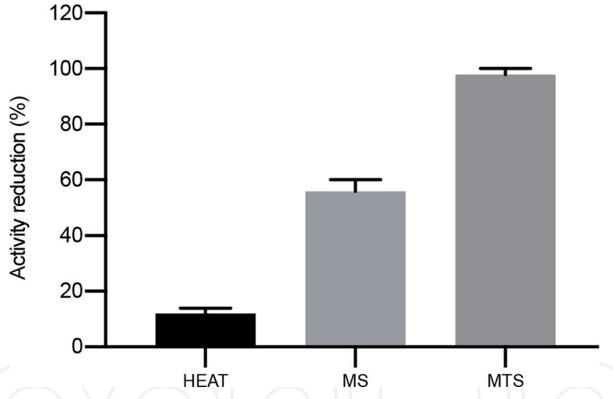

Figure 3.
Activity reduction of pectin methylesterase of tomato juice treated by heat, MS, and MTS treatments at 62.5°C and 1 minute (ultrasonic conditions: 20 kHz, 750 W, 0.2 MPa). Adapted from [40].

the treatment medium, the same levels of decontamination may not be achieved throughout the whole material or surface [47].

In the food industry, ultrasonic baths can also be used to clean and decontaminate surfaces of products such as vegetables, fruit, eggs, fish, etc., but always bear in mind that in the best scenario, a microbial inactivation of 1 Log_{10} cycle (90% reduction of the microbial population) could be achieved. Based on this, in meat industry, water-steam-based-systems combined with ultrasound have been recently proposed for poultry carcasses decontamination [48]. Thus, Boysen and Rosenquist [49] studied the inactivation of *Campylobacter* from broiler skins after applying different physical decontamination methods. They observed that steam-ultrasound was the most effective method achieving an inactivation of 2.5 Log_{10} reductions, 1 Log_{10} extra-reduction compared with other systems. However, the carcasses appeared to be slightly boiled after the treatment. Musavian et al. [50] decontaminated broiler carcasses with ultrasound (30–40 kHz) and steam (90–94°C) combination and observed additional reduction of 1–1.4 Log_{10} cycles of *Campylobacter* after applying 10 s of treatment. An example of this application is the SonoSteam system [51].

Regarding the cleaning of equipment surfaces, a widely known example in the food industry is the application of ultrasound for cleaning wine-aging barrels. It allows an effective cleaning even within the wood pores where spoilage microorganisms such as *Brettanomyces* are located, since ultrasound can remove part of the layers created by the precipitation of crystallized tartrates [52]. The additional advantage of this effect is that the aroma of the oak is maintained, reducing maintenance costs and the need to replace the barrels [53].

Finally, one of the most recent applications in terms of cleaning has been the use of ultrasound for the disintegration of bacterial biofilms generated on working surfaces of the food industry that can lead to cross-contaminant phenomena. Thus, the use of ultrasound would allow to reduce the formation or even to eliminate these biofilms, for example, in conveyor belts used for the transportation of foods inside the industry [54]. An industrial example of this application has been developed by Lubing systems [55].

Besides the ultrasound-assisted microbial decontamination, a recent study has demonstrated the potential of ultrasound for reducing the heavy metal load from foods. Condón-Abanto et al. [56] observed that the cadmium content of edible crabs (*Cancer pagurus*) was reduced by 23% after their immersion in water at 50°C for 40 minutes applying ultrasound (35 kHz, 200 W). The same treatment without ultrasound scarcely reduced the Cd content of 2%. These results open the possibility of reducing chemical contaminants or other chemical risks present in foods by using ultrasound as it will be discussed later on.

5.3 Mass transfer

The processes of mass transfer between two phases consist of the transfer of a certain component from one phase to another as a result of the difference in concentration between both phases. In the food industry, mass transfer occurs in many processes, such as the extraction of compounds of interest from inside the cells of a food product (sucrose, colorants, etc.), the elimination of water in processes like drying/dehydration, or the incorporation of solids as it happens when marinating and/or pickling.

5.3.1 Extraction

The traditional method for the extraction of intracellular compounds of interest for the food industry (sugar, colorants, bioactive substances such as polyphenols, etc.) consists on using an adequate solvent combined with other systems such as heat, agitation, etc. However, this technique has some disadvantages such as the high electrical consumption—becoming up to 70% of the required energy to extract a certain compound—high water requirements, and the use of toxic or contaminant solvents. For this reason, the food industry has struggled to find more profitable and eco-friendly methods for the extraction of compounds [16, 57], such as ultrasound, which improves the extraction efficiency by applying lower temperatures and shorter processing times than traditional extracting methods [58].

The extraction of aromatic compounds, antioxidants, pigments, and other organic or inorganic substances from tissues, mostly vegetal, has been widely investigated and successfully carried out by applying high-power ultrasound [59–63]. The application of ultrasound to a vegetable product immersed in a liquid medium can induce rapid fragmentation of the material, increasing the surface area of the solid in contact with the solvent and accelerating the mass transfer and, therefore, the extraction rate and yield [64]. Several advantages have been pointed out for the ultrasound-assisted extraction including the reduction of extraction time, energy, and the amount of solvent used and of unit operations and also a rapid return of investment [57]. As a way of example, **Figure 4** shows the extraction yield of chlorophyll from spinach leaves by using or not ultrasound (20 kHz) [57]. As observed, the amount of chlorophyll extracted was fourfold higher than in the control process after 20 minutes of maceration using ultrasound and more than double than the control after 80 minutes of extraction.

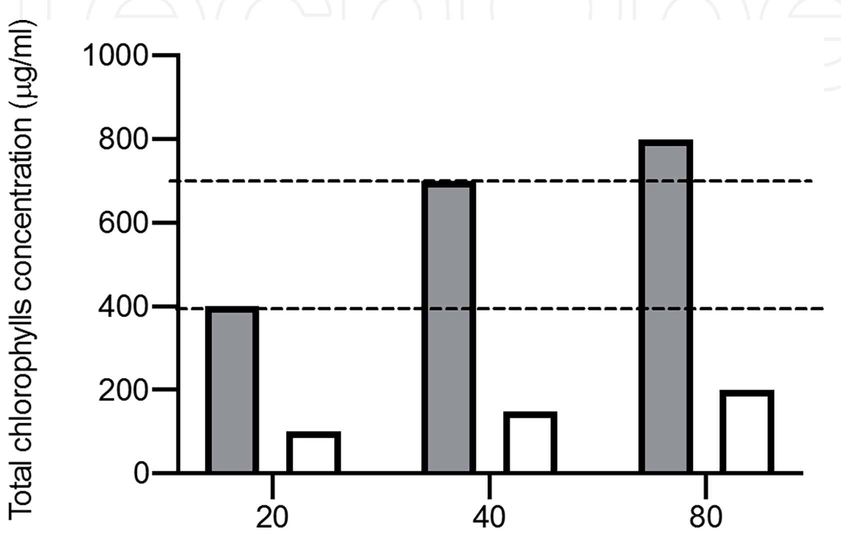

Figure 4.
Total chlorophylls concentration (µg/ml) extracted from spinach leaves treated (filled bars) or not (white bars) with ultrasound (20 kHz). Adapted from [57].

Besides the recovery of compounds of interest, also the extraction of potential risky compounds for human health is under investigation like oligosaccharides from pulses or Cd from edible crabs [65, 56]. In the same direction, the use of ultrasound has been recently evaluated for reducing the acrylamide content of fried potatoes which is a carcinogenic compound. By applying a pre-frying treatment of 30 minutes by immersing potatoes in an ultrasound water bath at 35 kHz, 92.5 W/kg, and 42°C, Antunes-Rohling et al. [66] obtained a 90% reduction in acrylamide compared to potatoes directly fried and a 50% reduction compared to potatoes soaked in water but with no ultrasound applied.

Based on the showed possibilities of ultrasound for extracting compounds of interest, different semi-industrial systems have been developed which are detailed in the revision of Chemat et al. [16]. More recently, and based on the works done in the winery industry, a continuous ultrasound system has been constructed in order to improve the extraction of polyphenolic compounds from grapes [67]. Wine is a product highly appreciated for its organoleptic properties such as color, aroma, and flavor. The application of ultrasound has been studied in the wine maceration process to favor the extraction of polyphenols responsible for color [68] and in the lees (*aging on lees*) for the extraction of polysaccharides responsible for color stability, mouthfeel, and reduction of wine's astringency [69].

5.3.2 Drying and dehydration

In the food industry, drying and dehydration of foods are important preserving processes where mass and energy transfer phenomena occur. They consist of removing a large part of the water from the food in order to improve the stability of the product, reducing its volume and weight and facilitating the handling and transport of the products [70, 71]. Currently, one of the most widespread techniques in the food industry is air convection dehydration. However, it is an energetically costly operation and, in some cases, requires long periods of time. In order to reduce drying times, some industrial strategies exist, such as increasing the temperature of the air, which can cause alterations in the composition and structure of foods, or increasing the air speed that might lead to the formation of a dry and impermeable layer that can inhibit the exit of humidity from the interior of the product [70].

Ultrasound has been evaluated as an alternative to traditional dehydration systems. In this case, the water removal process is improved mainly by the phenomenon known as "sponge effect" which enhances the diffusion of water from the interior of the product to the surface [72]. Nonetheless, cavitation of intracellular and extracellular water may also occur, forming new microchannels [73]. In addition, the application of ultrasound through the air generates turbulence that produces an important microstreaming at the interface between food and air which help remove surface moisture [74].

Ultrasound-assisted dehydration in food has been researched since the 1950s and 1960s, but it has been in recent years when major advances have been made since new family of piezoelectric transducers with extensive radiating surface have been developed [75]. There are two types of ultrasound application systems in food dehydration processes: by direct contact between the transducer and the food and by indirect contact through the air (airborne ultrasound systems). Contact systems, even though they are more efficient, can cause product damage, equipment development is complicated, and specific hygiene requirements are necessary. In any case, very promising results were obtained by De la Fuente-Blanco et al. [72], drying carrot cylinders achieving a faster loss of water than the usual dehydration by forced air process and obtaining a final moisture content in the product of less than 1%.

More studies have been carried out with airborne ultrasound systems, reducing drying times by 20–30% when applied at low temperatures and low air velocities [70]. For example, García-Pérez et al. [76] developed a convection drying equipment applying ultrasound to the air, in which the treatment chamber consisted of a vibratory aluminum cylinder coupled to a transducer (21.8 kHz, 75 W). In this study, they achieved a reduction of 26.7% in drying time of carrot skin samples when dried at 40°C and 0.6 m/s. The effect of air temperature (30–70°C) on the speed of drying with ultrasound was demonstrated by the same authors [77]. They obtained an increase in diffusion coefficient of 23.6% at 30°C, while at 70°C only 1.3%. These studies indicate that at either high air velocities or high temperatures, the effects of these parameters predominate over ultrasound.

In addition to improving convection drying processes, studies have also been carried out on the application of ultrasound in vacuum drying [78, 79] or in freeze-drying [80, 81] obtaining higher drying rates than the traditional process.

As it can be appreciated, the obtained results are promising; however, at present, pilot or industrial systems are scarce. The main technological challenges to address are basically reducing the overheating produced by the transducers and adapting the frequency and ultrasonic power to the working conditions, taking into account the acoustic impedance, attenuation, and absorption of the product to be dehydrated [73].

5.3.3 Marinating and pickling

Marinating and pickling are food preservation techniques used in vegetables, meat, and fish products. Brine, vinegar, or other organic acids; oil; and spices are usually used. In general, long processes are required, which involves the immobilization of the product resulting in economic costs and also potentially leading to structural damage, softening, and swelling, which might affect the quality of the product [16]. The application of high-power ultrasound between frequencies of 20 and 50 kHz has made possible to shorten pickling or brine contact times. Besides, in the case of meat such as pork loin, the water and salt content of the samples was increased (63–65% and 7–50%, respectively) when ultrasound (20 kHz, >39 W/cm^2) was applied compared to brining in static mode and with mechanical agitation. With an intensity higher than 64 W/cm^2, the water content of the samples after the process was even higher than that of fresh meat [82]. Improvement of water intake has been observed also in fish. Thus, a 6% higher water intake of thawed cod fillets after 48 hours of hydration than the standard process when applying ultrasound (40 kHz, 3.9 W/kg) was observed [10].

5.4 Energy transfer

Energy transfer (e.g., heating or freezing) together with mass transfer are common unit operations in the food industry. Both direct and indirect applications of ultrasound have been used to increase the energy transfer rates of traditional heating/freezing systems. Ultrasonic waves produce a direct heating of the product/medium due to the great energy released in the medium, as well as an intense agitation favoring a faster and more uniform heating of the product. On the other hand, the vibration caused by the indirect application of ultrasound accelerates the transfer of heat from traditional systems, both to release it in cooling processes and to provide it when heating.

5.4.1 Heating

The use of ultrasound to improve heating of liquid and solid foods is known since the 1960s [83]. However, scarce scientific information has been published till recent years. It has been described that ultrasound (20 kHz, 75 W) can increase the conductive heat transfer when applied in metals by 2.3- and 5.5-folds [83], becoming this effect the basis of the design of heat exchangers including ultrasound systems [83, 84]. In the case of liquid foods, the application of ultrasound of 20 kHz also improved the convection heat transfer in this case up to 25-fold in water [85]. In the case of viscous liquids such as puree, creams or soups, ultrasound not only improved the energy transfer but also the uniformity of the heating. Thus, an increase in energy transfer of 33 and 43% when heating tomato soup assisted with 45 and 450 W of ultrasound (20 kHz), respectively, was observed (**Figure 5**).

Finally, the application of ultrasound in hot water to heat solid products resulted in a faster heat transfer, reducing the time to apply pasteurization treatments or even to cook food products and therefore getting higher quality products [16].

Some authors have studied the improvement of heating for food cooking by using ultrasound. One of the first studies was conducted by Pohlman et al. [86] who evaluated the effects of ultrasound for cooking different pieces of beef. An ultrasonic field of 22 W/cm^2 was applied and compared to the traditional cooking of beef in a convection oven up to 70°C in the center. Ultrasonic cooking reduced the cooking time by 54% and the energy consumption of the process by 42%. In addition, samples cooked with ultrasound were cooked more uniformly and showed higher water retention, lower cooking losses, and lower hardness. In recent years, more studies have been conducted on this topic. More specifically, ultrasound has been used to accelerate heat transfer in the pasteurization of packaged sausages [87] and of ready-to-eat whole brown crab [88], to evaluate the frying-assisted ultrasound process of meatballs [89] and for the cooking of mortadella [90]. Even more, improvements in heat transfer have been observed at boiling water temperatures and over atmospherically pressure. Thus, 20% and up to 32% reduction in the cooking times were observed when boiling macaroni at 100°C or chickpeas at 120°C and 0.09 MPa, respectively, in an ultrasonic field of 40 kHz and 25 W/kg by using a new patented ultrasound system [91, 92].

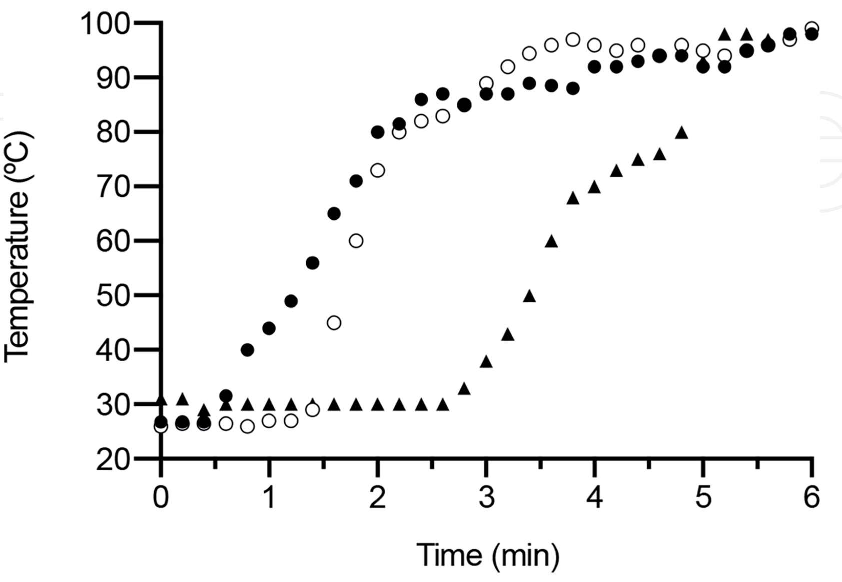

Figure 5.
Evolution of the temperature during the heating of tomato soup at different ultrasound (20 kHz) intensities: 0 (▲), 45 (◯), and 450 W (●).

In summary, the application of ultrasound allows to reduce the heating times by enhancing the energy transfer in liquid, viscous, and solid products and applying more uniform thermal treatments reducing the number of cold spots.

5.4.2 Freezing

Freezing is one of the oldest methods for food preservation. It involves subjecting food to temperatures lower than that of the freezing point causing the conversion of food water into ice and thereby limiting microbial growth and chemical and enzymatic reactions. When freezing speed is slow, large crystals with edges are formed in the extracellular liquid, causing the loss of water from inside the cells. This leads to dehydration, cell contraction, and partial plasmolysis; these phenomena, together with the damage caused by ice crystals that cause injuries in cell membranes, lead to water leakage after defrosting, producing the loss of food quality. On the other hand, quick freezing produces small ice crystals in the intracellular and extracellular space, resulting in less cell damage and in higher quality products [93]. Ultrasound-assisted freezing reduces treatment time by favoring both nucleation and controlled crystal growth [16]. These effects have been mainly attributed to acoustic cavitation and the microstreaming generated in the liquid as well as the microbubbles that act as nuclei of crystallization [94]. **Figure 6** shows the freezing curves of 2 cm × 2 cm cylinders of meat sausages frozen in an ultrasound bath at −22°C applying or not ultrasound (40 kHz, 50 W). As can be observed, application of ultrasound reduced the freezing time and even eliminated the water-ice crystal transition phase.

Several studies have been carried out on the application of ultrasound during the freezing process of foods. In most of these studies, ultrasound has been applied using ultrasound baths with the product immersed in an aqueous medium, e.g., panaria dough [95], potatoes [96], broccoli [97], apples [98], mushrooms [99], and pork loin [100]. For example, Sun et al. [101] studied the influence of ultrasound-assisted immersion freezing on the process and on the quality of common carp (*Cyprinus carpio*). The application of ultrasound at 30 kHz and 175 W reduced the freezing time of 37.2%, being this ultrasound intensity the optimal, since below it the effect of ultrasound was undetectable and above it overheating was observed due to the high ultrasound intensities applied. This increase in the freezing rate

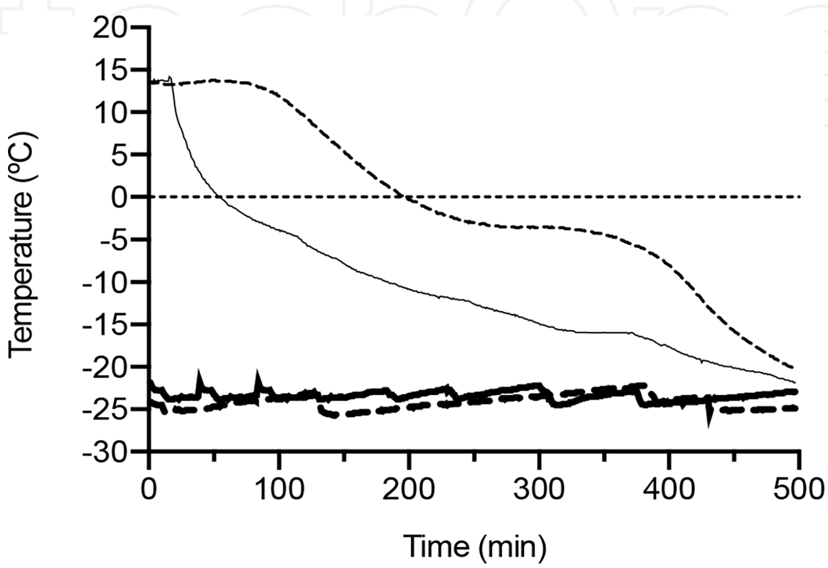

Figure 6.
Temperature of sausages (thin lines) and media (thick lines) when applying (continuous lines) or not ultrasound (40 kHz, 50 W/kg) when freezing.

resulted in an improvement in the product quality since the cooking loss (% of loss water after cooking the product) values determined were similar to those of fresh product: 7.9% in fresh product *vs* 8.3% when ultrasound was applied.

5.4.3 Thawing

Thawing is as important as freezing in the food industry, since a large proportion of frozen foods require thawing prior to their consumption. This process must be carried out as quick as possible to avoid affecting the hygienic quality of the product, but bearing in mind that the higher the speed, the worse will be the sensory characteristics of the final product because time is required for the cells to reabsorb the released water during freezing. As it has been explained, the application of ultrasound would help to improve the transfer of energy due to the cavitation and the microstreaming generated in the liquid [96]. Some studies have been carried out in beef, pork, and codfish [102]; pork *Longissimus dorsi* muscle [103]; and tuna [104]. In a study carried out by Gambuteanu and Alexe [103], thawing assisted by ultrasound in samples of pork *Longissimus dorsi* muscle was evaluated. Experiments were performed at intensities of 0.2, 0.4, and 0.6 W/cm^2 in a water bath at 15°C, and they were compared with thawing in air at 15°C and thawing by immersion on water at 15°C. The thawing rate was influenced by the intensity of ultrasound treatment: the higher the ultrasonic intensity, the shorter the thawing time. Thus, the thawing rates for air and water immersion were 0.16 and 0.29°C/min, respectively, whereas, for ultrasound intensities of 0.2, 0.4, and 0.6 W/cm^2, the values were 0.62, 0.73, and 1°C/min. Therefore, the thawing time of pork samples could be reduced applying ultrasound technology. Similar conclusions were obtained by our research group in cod fillets thawed in an ultrasound water bath at 2°C (25 kHz, 14.7 W/kg), reducing 65% the time to achieve 0°C, maintaining the water holding capacity and cook loss of the fresh product, and with a better sensorial quality than the air defrosted product (**Figure 7**).

5.5 Other applications of ultrasound in the food industry

In addition to the applications already described, ultrasound technology has been evaluated and applied in the food industry to improve other processes whose result is based mainly on mechanical effects.

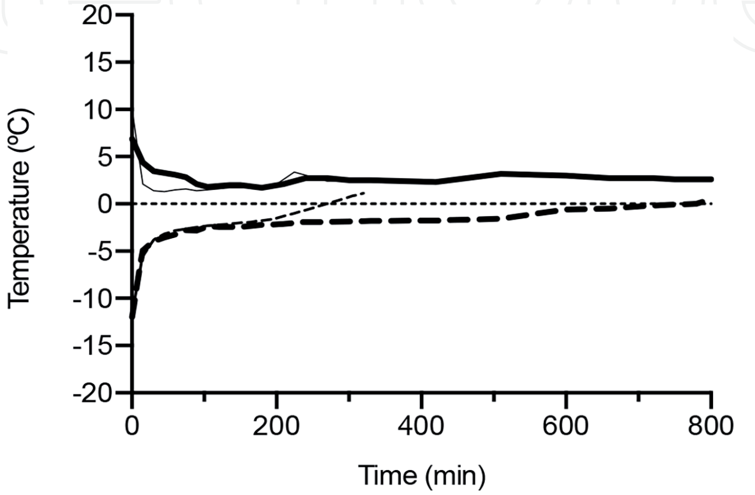

Figure 7.
Temperature of cod fillets (thin lines) and water (think lines) when applying (continuous lines) or not ultrasound (25 kHz, 14.7 W/kg) when thawing.

5.5.1 Foaming and degassing capacity

Foam is a dispersion of gas in a liquid medium that is often formed during the manufacture of many products, as a result of aeration or agitation of liquids, during vaporization of liquids, or due to chemical or biological reactions [105]. Mechanical methods are the most effective at removing unwanted foams during food processing, compared to antifoaming chemical agents. The use of ultrasound can be considered a mechanical method of foam removal, since it is based on the propagation of the sound waves through the foam, without affecting the liquid [106]. For this application, airborne transducers are mainly used [107].

Another increasingly widespread application of ultrasound is degassing. Liquids contain dissolved gases such as oxygen, carbon dioxide, or nitrogen. Conventionally, to degas a liquid, it is boiled or subjected to vacuum, reducing the solubility of the gases. Ultrasonic degassing has the advantage of not substantially increasing the temperature of the liquid. In the presence of an ultrasonic field, the gas bubbles begin to vibrate, coalesce, and grow, reaching a sufficient size to ascend to the liquid surface, being thus removed from the aqueous medium [16].

In a study that covers both applications, foam removal and degassing, Villamiel et al. [108] used 1-second ultrasonic pulses (20 kHz) in milk. At 20°C with 3 minutes of treatment, they managed to reduce foam by 80% with an energy consumption of 40 kJ/l. In order to eliminate the oxygen dissolved in milk, a more energetic treatment was necessary (240 kJ/l).

5.5.2 Filtration

High-power ultrasound has been applied to promote diffusion through membranes and porous materials. This improvement is attributed to the formation of microstreams generated within the liquid in the presence of high-energy ultrasonic fields. That is how it would facilitate the processes of filtration, ultrafiltration, dialysis, and reverse osmosis [109]. During membrane filtration, the flow progressively decays to a stationary state due to the polarization of the concentration, and the saturation of the filter. Ultrasound acts by increasing the flow and preventing saturation if applied during filtration or by breaking the deposit layer of solutes or cake on the filters, acting in this case as a cleaning method [16].

5.5.3 Texture modification

Texture plays a crucial role in influencing consumers' liking and preference of meat products. This sensation is influenced by various factors including muscle type, age and cut, its water holding capacity, and the degree of maturation, among others [110]. The application of ultrasound might help to improve meat tenderness, thus obtaining better quality products. However, the effect of high-power ultrasound on meat tenderization is not entirely clear, and this is likely because there are many factors that influence its effect, such as the characteristics of the ultrasonic field, the time of exposure, the animal species, and the type of muscle, among others. Some authors state that those studies in which ultrasound application had no effect would be due to the low ultrasonic densities (0.29–1.55 W/cm^2) or short treatment times (15 s) applied [111–113]. In any case, there are systems already in the market for tendering meat based on ultrasound [114].

In the case of meat products, ultrasound can improve cohesiveness between different pieces of meat [109] by promoting the release of myofibrillar proteins and gel formation. This effect is important in processes such as the production of cooked ham or cured meat products in which an adhesive protein exudate is required in order to act as a glue between the different parts during molding or stuffing [110].

5.5.4 Food cutting

Most processed foods are prepared in large quantities, often in blocks or in large sheets. For marketing and consumption, it is necessary to reduce their size, in many cases by cutting the product. For this propose, ultrasonic probes in the shape of a blade are used which vibrate at a certain ultrasonic frequency longitudinally or as a piston. When it comes into contact with food, it cuts it due to both the vibration and the sharp edge of the blade. These types of probes have been used successfully in the cutting of fragile, heterogeneous, and sticky products such as cream cakes, bread, pastries, biscuits, and cheese [16, 115].

6. Conclusions

Although ultrasound is a well-known technology that is commonly used in several fields such as medicine or in the automobile industry, its use in the food industry is still scarce especially in the case of high-power ultrasound. However, due to its capacity to improve mass and energy transfer phenomena—which occur in numerous processes in the food industry—it might be very helpful for producing safer and higher quality products than those obtained by traditional procedures. In addition, ultrasound is considered a safe, nonpolluting, and environmentally friendly technology, which has also contributed to attract the interest of the food industry. Finally, the lower implementation cost—up to the industrial scale—of some applications compared to other nonthermal technologies such as pulsed electric fields or high hydrostatic pressures will facilitate its industrialization in some food sectors. In any case, further research is still necessary for some applications since many factors have to be considered when designing equipment and applying ultrasound treatments in the food industry in order to achieve an efficient application.

Acknowledgements

The authors wish to acknowledge the financial support from iNOBox (Project number 281106) funded by the Research Council of Norway and the Department of Innovation Research and University of the Aragon Government and European Social Fund (ESF). L.A. gratefully acknowledges the financial support for her studies provided by the "Ministerio de Educación y Formación Profesional."

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