

Review Article

Modification of Food Systems by Ultrasound

L. M. Carrillo-Lopez,¹ A. D. Alarcon-Rojo,² L. Luna-Rodriguez,¹ and R. Reyes-Villagrana¹

¹Facultad de Zootecnia y Ecología, CONACYT-Universidad Autónoma de Chihuahua, Perif. Francisco R. Almada Km 1, 31453 Chihuahua, CHIH, Mexico

²Facultad de Zootecnia y Ecología, Universidad Autónoma de Chihuahua, Perif. Francisco R. Almada Km 1, 31453 Chihuahua, CHIH, Mexico

Correspondence should be addressed to A. D. Alarcon-Rojo; aaalarcon3669@gmail.com

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This review describes the mechanism, operation, and recent potential applications of ultrasound in various food systems, as well as the physical and chemical effects of ultrasound treatments on the conservation and modification of different groups of food. Acoustic energy has been recognized as an emerging technology with great potential for applications in the food industry. The phenomenon of acoustic cavitation, which modifies the physical, chemical, and functional properties of food, can be used to improve existing processes and to develop new ones. The combination of ultrasonic energy with a sanitizing agent can improve the effect of microbial reduction in foods and, thereby, their quality. Finally, it is concluded that the use of ultrasound in food is a very promising area of research; however, more research is still needed before applying this technology in a wider range of industrial sectors.

1. Introduction

Consumers demand foods with organoleptic and nutritional characteristics similar to those found in nature; in addition, food products should have a sufficiently long shelf life to allow their freshness during distribution and storage before consumption. This can be achieved by the use of minimal processing technologies that preserve food, reduce processing times, and improve the shelf life of food products [1] while preserving a significant degree of nutritional quality and sensory characteristics. This has led to an increasing interest in the development of emerging technologies with potential applications in the food industry, including ultrasound.

Ultrasound is acoustic energy considered a mechanical, nonionizing, nonpolluting type of energy [1], with great potential for use in production processes of high quality food products. Ultrasound produces changes in the physical, chemical, and functional properties of food products [2]; it can therefore influence the quality of various food systems, improving their productivity and performance [3].

Ultrasound is used successfully in the food industry to improve quality and process control. It is used to assess

the composition of meat, fish, and poultry products and in quality control of vegetables, cheeses, oils, breads, and cereals. Other applications include detecting adulteration of honey and protein analysis [4]. There are also several reports of the application of ultrasound in mass transfer and marination processes, meat tenderization, crystallization, freezing, drying, degasification, filtration, foam production and reduction, and emulsification, as well as homogenization and inactivation of microorganisms [1] and enzymes.

Several theories have been proposed to elucidate the mechanism of ultrasonic treatment. This review describes the theoretical foundations (mechanism and operation) of this phenomenon, as well as the effects and potential applications of ultrasound in food.

2. Basics of Acoustic Waves

2.1. Introduction. Acoustic waves are a vibrating disturbance of the environment and need an emitting source and a means of propagation to travel and transmit, unlike electromagnetic waves that can propagate in any medium, including vacuum.

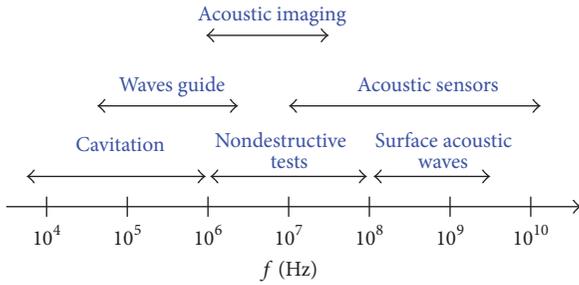


FIGURE 1: Applications of the acoustic waves.

TABLE 1: Frequency scale of the acoustic waves.

Acoustic frequency spectrum	
Name	Range, (Hz)
Infrasound	<20
Audible sound	20 < AS < 20 k
Ultrasound	20 k < US < 1 G
Hipersound	HS > 1 G

Because of this, acoustic waves are also called mechanical waves. These can be propagated in two ways, in longitudinal mode and in transverse mode. In longitudinal mode it means that the acoustic energy emitted propagates in the same direction in which the acoustic wave travels; on the contrary, in the transverse mode, the emitted acoustic energy propagates perpendicularly in the direction in which the acoustic wave travels [5].

In this context, the acoustic waves also comply with Snell's law, in optics [6]. It also presents the phenomenology of absorption, diffraction, dispersion, scattering, transmission, and reflection [7]; and this occurs through a propagation medium such as a solid or a fluid (both liquid and gaseous), as well as in a biological tissue and so on, and where the main parameter is the acoustic impedance (Rayls) of propagation medium that is given by the product of the volumetric density (kg/m^3) and the propagation velocity (m/s) of the medium [8]; it should be noted that, in solid materials, the longitudinal and transverse propagation velocity is obtained. The acoustic waves have well defined parameters such as amplitude, intensity, power, and frequency, and it is the latter that provides the working spectrum of the acoustic waves. Some of the applications that have the frequency dependent acoustic waves are described in Figure 1 [9–14].

2.2. Acoustic Waves in the Ultrasound Spectrum. Acoustic waves are divided into a field of work given by the spectrum of frequencies. Table 1 describes the most common spectrum of acoustic waves.

The spectrum of the ultrasound is given in a frequency range between 20 kHz and 1 GHz. In ultrasonic waves there are two main applications, that is, in nondestructive and destructive tests. In the first, inspection tests are performed to determine the acoustic properties of the material, as well as to determine fractures and deterioration of the same. Also,

there is the area to generate the ultrasonic waves and to detect them, made by emitting devices and acoustic detectors, which are development mainly by piezoelectric materials [15].

On the other hand, the destructive tests are used to remove tissue or matter from a very precise area, like the ultrasound used in medicine [16]. But here is another important parameter, the acoustic intensity (W/m^2), where the combination of ultrasound and the increase in acoustic intensity can generate two effects, acoustic cavitation and shock waves and modulating frequency [17].

The acoustic wave in frequency of the ultrasound in steady state generates the phenomenon known as acoustic cavitation; this happens in the compression and expansion of the waves [18, 19].

2.3. The Effect of Acoustic Cavitation. There are different tools to generate the effect of acoustic cavitation; this can be generated by means of shock waves or by steady state. There is a great field of study about this phenomenon and it is still an area of current exploration, in which the description of the phenomenon continues in the areas of sonoluminescence, sonophysics, and sonochemistry [43].

In an ultrasonic system, electric energy is transformed into vibrational energy, that is, mechanical energy, which is then transmitted into a sonicated medium. Part of the input energy is lost (turned into heat); the other part can cause cavitation. A fraction of the energy of cavitation produces chemical, physical, or biological effects [44].

The basis of many applications of ultrasound at a frequency range of 20 kHz to 1 MHz is acoustic cavitation, which occurs in regions under rapidly alternating high-amplitude pressure waves [45] and consists of the growth and collapse of gas bubbles within a liquid medium [25]. Vapor or gas bubbles are created by the change of average distance between molecules and the decrease in pressure. The bubbles grow in areas of low pressure, collapsing violently when passing to high pressure areas (Figure 2) and producing temperatures close to 5000 K, as well as pressures above 1000 atm [46] due to the release of the energy stored during expansion. However, the heat produced by the implosion of the bubbles is instantly dissipated, so there is no substantial temperature rise in the medium [45]. When the intensity increases, the size of the bubbles also increases, and thereby the energy released during collapse.

Acoustic power is the total energy radiated by the ultrasonic source per unit of time; it can be calculated from acoustic intensity and the area of the radiating surface [47]. The frequency determines the radius of resonance and the lifetime of the bubbles; the higher the frequency, the smaller the bubbles and the lower the energy released. A direct result of the high temperatures after the collapse of the bubbles is the production of chemically active radicals by the dissociation of vapors [28].

The efficiency of the cavitation mechanism depends on the frequency and intensity of the transmitted ultrasound waves, as well as on the physical properties of the observed sample. When the frequency increases, the number of formed bubbles increases, but their diameter is smaller (Figure 3), and

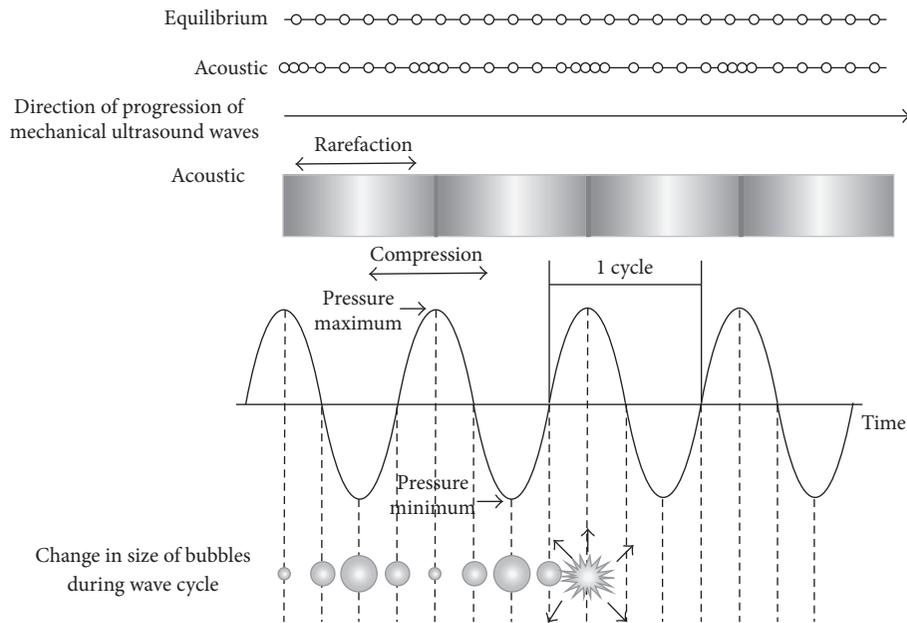


FIGURE 2: Ultrasonic cavitation [46].

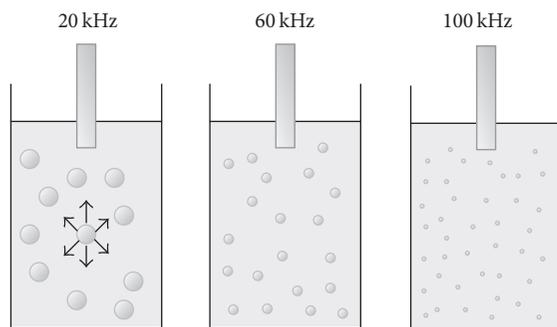


FIGURE 3: Influence of frequency on the number and diameter of cavitation bubbles [48].

the amount of energy released during implosion is minimum [48].

The propagation of ultrasound is a nonlinear phenomenon associated with various factors [49] and involving the properties of ultrasonic waves (speed, frequency, length, width, and intensity). Tsaih et al. [50] indicate that as the intensity of ultrasound increases, it generates higher acoustic pressure, which leads to a greater and more violent collapse and a consequent increase in the chemical or physical effects. Thus, this phenomenon can produce a range of effects on biological tissues and materials.

Ultrasound lies in a range of 20 kHz to 10 MHz and is divided into three categories: (1) ultrasound with high power ($>5 \text{ W cm}^{-2}$ or 10 to 1000 W cm^{-2}) and low frequency (20 to 100 kHz); (2) ultrasound with average power and intermediate frequency (100 kHz–1 MHz); and (3) ultrasound with low power ($<1 \text{ W cm}^{-2}$) and high frequency (10.01 MHz)

[51]. Ultrasound can be applied using three different methods: (a) directly to the product; (b) coupling the product to a device; (c) immersion in an ultrasonic bath [1].

3. Potential Applications of Ultrasound in Food Systems

3.1. Meat. Numerous studies have been focused on obtaining meat with better technological and sensory qualities [27]; in this regard, ultrasound has shown both positive and negative effects. The discrepancies in the results are due to intrinsic (species, age, ageing, and type of muscle) and extrinsic factors (ultrasonic systems, time, intensity, and frequency); thus, it is necessary to show a summary of the effects of ultrasound on the physicochemical characteristics and tenderness of the meat (Tables 1 and 2).

3.1.1. Effect of Ultrasound on the Chemical Characteristics of Meat. The initial pH of the meat (semimembranosus muscle) increased when applying ultrasonic treatment (2.6 MHz, 10 W cm^{-2}) before rigor mortis; but the final pH did not differ significantly [26]. Ultrasound has no influence on the pH of postrigor meat [20, 21]; but the depletion factor indicates that there is an effect on metabolism and the actin-myosin interaction [52].

The parameters CIE $L^*a^*b^*$ were not affected by treatment with ultrasound [21, 52]; the heat generated was not sufficient to induce denaturation and oxidation of the color pigments (Mb, metMb) [20]. The color measurements made by Pohlman et al. [53] in meat subjected to ultrasound (22 W cm^{-2}) indicate changes to a lighter color (lower L^*), less red (lower a^*), more yellow (higher b^*), more orange (larger hue angle), and less brightness compared to the

TABLE 2: Studies of ultrasound aimed to improve of meat quality.

Meat	Purpose	Conditions	References
Steers meat (<i>longissimus lumborum</i> and <i>semitendinosus</i>)	Impact on the ageing of meat and characteristics quality	24 kHz and 12 W cm ⁻² for 240 s	Jayasooriya et al. [20]
Beef (<i>semimembranosus</i>)	Influence of ultrasound in pH of meat, its color, and shear force	45 kHz and 2 W cm ⁻² for 2 min	Stadnik and Dolatowski [21]
Beef (<i>semitendinosus</i>)	Effects on meat quality and connective tissue collagen	40 kHz, 1500 W for 10, 20, 30, 40, 50, or 60 min	Chang et al. [22]
Poultry (breast)	Influence of ultrasound together with either a protease inhibitors cocktail	24 kHz, 12 W cm ⁻² for 4 min after 7 d of storage	Xiong et al. [23]
Holstein bulls (<i>longissimus lumborum</i>)	To develop a novel process for improving meat tenderness	20 kHz, 100 and 300 W for 10, 20, and 30 min	Barekat and Soltanizadeh [24]

control. Furthermore, Stadnik and Dolatowski [21] observed that ultrasound accelerates total color change by limiting the formation of MbO₂ and slowing the formation of metMb.

Water retention capacity is a meat quality parameter with economic importance; therefore, it is important to evaluate it in meat treated with ultrasound. The results mentioned that ultrasound increases the rates of meat exudate and water loss [22]. However, Jayasooriya et al. [20] do not mention changes in drip loss (24 kHz, 12 W cm⁻²); similarly, Smith [54] reports no effect on the water retention capacity of meat. In contrast, other authors indicate that ultrasonicated meat has an increased water-holding capacity [22, 53, 55], similar to a meat in advanced postmortem stage; they suggested an increase in the ageing rate of meat due to structural changes in myofibrillar proteins induced by ultrasound; this has been confirmed by photograms of the microstructure of these proteins [22].

Furthermore, there are reports that ultrasound causes the degradation of proteins with a molecular weight higher than 20–25 kDa and increases the activity of calpains and the release of lysosomal contents, which have a positive effect on tenderness [20].

3.1.2. Effect of Ultrasound on the Structural Components of Meat Related to Texture. The postmortem degradation of myofibrillar proteins is closely linked to structural changes that result in increased meat tenderness during the ageing process [56]. It has been proposed that acoustic cavitation induces mechanical disruption of the structure of myofibrillar proteins [22], as well as the fragmentation of collagen macromolecules and the migration of proteins, minerals, and other compounds, with a consequent acceleration of proteolysis or protein denaturation [57].

It is also possible that the application of ultrasound induces changes in the amount of ATP available in the muscle during the prerigor stage [52], accelerates the onset of rigor mortis [21], and increases the ageing rate of meat [58]. There have been experiments with the application of ultrasound to increase meat tenderness [20–22] and reduce the ageing period without compromising other quality characteristics of meat [22, 55].

Low-frequency and low-intensity ultrasound seem to be particularly suited for softening meat [21, 59]; several studies report a significant effect on reduction of the cutting force and some are presented in Table 2. Shear force has been evaluated in the following beef muscles: *longissimus lumborum* and *semitendinosus* muscles (24 kHz and 12 W/cm² for 240 s) [20], *semimembranosus* muscle (45 kHz and 2 W cm⁻² for 2 min) [21], *semitendinosus* muscle (40 kHz, 1500 W for 10, 20, 30, 40, 50, or 60 min) [22], also poultry (24 kHz, 12 W cm⁻² for 4 min after 7 d of storage) [23], and pork (2.5 to 3 W cm⁻² for 180 min) [57]. A more recent report by Barekat and Soltanizadeh [24] indicated that applying ultrasound in addition to papain to young Holstein bulls (*Longissimus lumborum*) for 10, 20, and 30 min (20 kHz, 100 and 300 W) had significant effect on tenderness.

With regard to the effect of ultrasound on the collagen structure, the results are heterogeneous. It has been reported that low-frequency ultrasound has no effect on the content of soluble collagen [60] or the content of insoluble collagen [20]; but Chang et al. [60] showed that ultrasound had a significant effect on the characteristics of collagen, especially on its thermal properties, without having any effect on the content of insoluble collagen; moreover, Chang et al. [60] reported effects on collagen solubility during cooking.

The contribution of connective tissue to meat toughness is greater than that of fat; however, in addition to fragmenting collagen, ultrasound disrupts cell membranes and promotes the formation of free radicals [61]. Consequently, it intensifies oxidation of meat due to the increase in the rate of chemical reactions [4]; however, Stadnik [62] mention that sonication can be an effective method to improve the technological properties of beef muscle without affecting lipid oxidation. Furthermore, after analyzing samples treated with ultrasound (45 kHz, 2 W/cm² for 120 s) and stored in refrigeration, Stadnik [62] reported values of 2-thiobarbituric acid reactive substances (TBAR's) that do not compromise the oxidative stability of meat.

3.1.3. Other Applications of Ultrasound in Meat. Ultrasound has been applied to meat for various purposes (Table 3). Regarding the cooking of beef, ultrasound improves cooking

TABLE 3: Application of ultrasound in meat for various purposes.

Meat	Effect	Conditions	References
Beef (<i>longissimus</i> and <i>pectoralis</i>)	Ultrasound-assisted cooking for improving cooking time, moisture retention capacity, and energy efficiency	20 kHz, 1,000 W	Pohlman et al. [53]
Pork (<i>longissimus dorsi</i>)	Influence of ultrasound on the mass transfer process during meat brining depended on the intensity applied	20 kHz, 450 W	Cárcel et al. [66]
Pork (<i>longissimus dorsi</i>)	Ultrasound-assisted meat curing obtained better distribution of the brine, reduced water loss, and caused favourable microstructural changes in meat tissue	20 kHz, 2–4 W cm ⁻²	Siró et al. [57]
Pork (<i>longissimus thoracis</i> and <i>lumborum</i>)	Ultrasound-assisted meat curing for accelerating the mass transfer achieves a 50% reduction in processing times with no adverse effects on quality in the production of wet-cured cooked hams	20 kHz, 4.2, 11, or 19 W cm ⁻² , 10, 25, or 40 min 1 W cm ⁻²	McDonnell et al. [64]
Chicken breast	Dye (methylene blue) penetration is an indication of meat permeability when using ultrasound and so it is estimate of marinating of meat	40 kHz, 22 W cm ⁻² , 15 and 30 min	Leal-Ramos et al. [63]
Hen breast	Ultrasound-assisted marination for improvement of meat tenderness, improvement efficiency, and cooking yield	24 kHz, 12 W cm ⁻² , 4 min	Xiong et al. [23]
Pork	The NaCl and moisture effective diffusivities were improved and promoted changes in meat texture	40 kHz, 37.5 W dm ⁻³ 15, 30, 45, 60, 90, and 120 min	Ozuna et al. [65]
Pork (<i>longissimus dorsi</i>)	Improving the diffusion of sodium chloride	20 kHz, 2–4 W cm ⁻²	Siró et al. [57]

time, moisture retention capacity, and energy efficiency [53]; therefore, this method could be a fast and energy-efficient way to enhance the quality attributes of cooked meat. The technology of ultrasound-assisted meat curing is proposed as an alternative to the traditional process of meat curing; its aim is to accelerate mass transfer [63] of brine into meat, preserve sensory attributes [64], obtain a better distribution of solutes [65], and reduce water loss [57].

It has been shown in solid-liquid systems that acoustic waves improve the kinetics of mass transfer [66] due to the physical disruption of tissues, which creates microchannels and causes changes in the concentration gradients and diffusion coefficients [1, 67]; longer implementation times cause denaturation of proteins [57].

During the meat curing process, the transfer of mass (saturated NaCl solution) into meat depends on the intensity thresholds (39 and 51 W cm⁻²); above them, the transfer of mass is proportional to the intensity of ultrasound [66]. Ultrasonic treatment is also reported to significantly improve salt diffusion; the diffusion coefficient increases exponentially with increasing ultrasound intensity [57]. McDonnell et al. [64] achieved a reduction of up to 50% in processing times during the production of cured hams, without adverse effects on the quality; they inferred that ultrasound has potential advantages for the processing of other meat products.

However, Smith [54] applied low-intensity ultrasound in chicken marination and reported lower water absorption,

less drip loss, lower cooking yield, and no significant effects on hardness. Contrary to this, Ozuna et al. [65] observed greater tenderness in pork meat marinated with ultrasound. The results are not yet conclusive, and further studies are needed on the effects of ultrasound on meat properties before recommending the use of ultrasound at industrial scale. Although numerous techniques are used for cooking meat other than conventional heating, the flavor of the meat and the consumption of energy are sometimes far from optimal. It can be concluded that power ultrasound has an important effect on the texture and maturation of meat from various species by weakening myofibrillar and connective tissues and reducing cooking losses without affecting other quality parameters. Moreover, salting with ultrasound could be a surface phenomenon that can accelerate mass transfer and extract proteins. The benefits of ultrasound on mass transfer are very convincing and industrial implementation could be very close.

3.2. Dairy. Ultrasonic processing is among promising new nonthermal processes that could bring about large-scale improvements in different processes of the food industry, including the dairy industry. It has been observed that high-intensity ultrasound induces changes in the functional properties of food. Ultrasound is considered as an alternative method for reducing the size of fat globules and can be applied effectively to homogenize milk [48]. Increases in

exposure times and power levels increase the efficiency of homogenization [68], with significant reductions in the diameter of fat globules [69]. Ultrasound treatment causes alterations in the secondary structure of milk proteins, aggregation of protein particles, and denaturation [70]. In addition, ultrasound produces alterations in the composition and structure of the membrane of fat globules, which improves the efficiency of homogenization in casein gel, compared to conventional methods [71]. It has also been shown that ultrasound depolarizes the particles of gamma-carrageenan and reduces their size, allowing for better homogenization of nanoparticles in a dispersion mixed with beta-lactoglobulin. Thus, ultrasound could have a significant potential in the enrichment of acidified milk drinks [72]. The interaction between β -lactoglobulin and sodium alginate, before and after ultrasound treatment, generates biopolymer nanoparticles that may be used to enrich transparent liquid food products [73]. The changes induced by high-intensity ultrasound depend on the nature of the proteins and their degree of denaturation and aggregation [74]. The most important factor in the application of ultrasound in processes of emulsification and homogenization of milk is to control possible negative effects such as oxidation of fats, inactivation of enzymes, and protein denaturation [75]. Ultrasonic waves propagate faster in milk with low percentage of fat, generating a greater number of small cavitation bubbles, the implosion of which produces thermal energy that causes an immediate increase in temperature and changes the physical properties of milk. Serum proteins are widely used to improve the functional properties of milk such as emulsification, thickening, and foaming [67]. Sonication is used to generate foam in the fluid-fluid interface; the air bubbles produced by sonication are entrained in the mixture [76]. This approach has been used to create aerated β -lactoglobulin gelatin and gels for use in food applications [77].

Another application of ultrasound is the crystallization of lactose. A recovery of 92% lactose was obtained from milk serum solutions after 5 min sonication, compared with 15% using conventional stirring [78]. The cause of the improvement in crystal nucleation is that acoustic cavitation bubbles provide a heterogeneous surface for nucleation; the effects on crystal size and morphology may be related to the shear forces associated with ultrasound and the breaking up of nascent agglomerates [79].

It has also been found that ultrasonic homogenization of milk before inoculation of the starter improves viscosity in yogurt [80]. Vercet et al. [81] showed that the simultaneous application of heat (40°C) and ultrasound (12 s at 20 kHz) under moderate pressure (2 kg cm⁻²) improves the rheological properties of yogurt. These changes can be attributed to the denaturation of milk serum proteins and their association with caseins by effect of ultrasound; denatured serum proteins associated with casein micelles can act as bridging material between casein micelles, facilitating the formation of bonds in the yogurt matrix, which results in firmer yogurt gels [82]. Kartalska et al. [83] suggest that substituting thermal pasteurization with ultrasonic treatment provides optimal conditions for the development of lactic acid bacteria. Ultrasonic treatment has a positive effect on the

fermentation process, probably due to the homogenization of the colloidal system of milk under sonication. Riener et al. [84] found that milk yogurt containing 1.5 or 3.5% fat and treated with thermosonication (45°C, 10 min, 24 kHz) had almost twice the water-holding capacity and good texture properties. Electron microscopy showed differences in the microstructure; that of thermosonicated yogurt was similar to a honeycomb and more porous. Furthermore, the average particle size in thermosonicated yogurt was less than one micron, significantly smaller than in conventional yogurts. Gursoy et al. [85] prepared yogurt drinks using milk samples processed by thermosonication or conventional heating (10 min at 90°C) and observed that thermosonication (70°C, 100, 125, and 150 W) caused a significant decrease in serum separation values, while the apparent viscosity increased with ultrasound power.

The effect of ultrasound on the rheological and foaming properties of ice cream has also been studied [86]. The ice cream mixes treated with ultrasound alone had a minimal increase in foam volume; the greatest increase in foam volume was observed in ice cream mixes subjected to a combined mechanical and ultrasonic treatment. Moreover, the foam of ice cream mixes with higher protein content was more stable. It was concluded that the optimal treatment time was 10 min.

The combination of ultrasound with other technologies reduces processing time and increases efficiency in industrial production processes [87]. Shanmugam et al. [88] emphasize that the minor changes in milk caused by the shear forces of acoustic cavitation suggest the potential for optimizing this technique for industrial applications. The optimization can be achieved by fine adjustments of power density, temperature, processing time, and so on.

Ultrasound, used in combination with high hydrostatic pressures, can be useful to preserve various food properties such as texture, as well as sensory, organoleptic, and microbiological characteristics. Karlović et al. [89] applied ultrasound and high hydrostatic pressures to goat milk. The milk was exposed to ultrasound at 100 W of nominal power and to high pressures of up to 600 MPa. The maximum treatment time was 9 min. They reported an improvement in the homogenization of fat globules, the diameter of which was significantly influenced by the high pressure. The application of both processes improved the stability and quality of the emulsions.

Ultrasound is a nonthermal alternative for pasteurization that allows obtaining a final product of higher quality. High-amplitude ultrasound reduces the microbial content of milk. The effectiveness of ultrasound as a decontamination technique can be enhanced by combining it with other treatments such as pressure, heat, and antimicrobial solutions [4]. Ultrasound has been studied as an alternative to heat pasteurization. Cameron et al. [90] observed a reduction in the presence of potential pathogens to negligible or acceptable levels. The viable cell count of *E. coli*, *Pseudomonas fluorescens*, and *Listeria monocytogenes* decreased by almost 100% after 10 min of ultrasound treatment, without detrimental effects on the total protein or case content of pasteurized milk. However, ultrasonication was ineffective in deactivating the alkaline

phosphatase and lactoperoxidase enzymes regularly used by the dairy industry as indicators of the efficiency of thermal processes.

Treatment with high-intensity ultrasound causes milk to release volatile compounds, which leads to an unpleasant taste. This was reported by Riener et al. [91], who found that when milk is subjected to ultrasonic treatment, it releases benzene, toluene, 1,3-butadiene, 5-methyl-1,3-cyclopentadiene, 1-hexene, 1-octene, 1-nonene, p-xylene, n-hexanal, n-heptanal, 2-butanone, acetone, dimethyl sulfide, and chloroform. Aldehydes can be produced by the decomposition of hydroperoxides generated by ultrasound-induced photooxidation, whereas the series of C6–C9 1-alkenes might be generated by the pyrolytic cleavage of fatty acid chains. The formation of benzene can be attributed to the cleavage of the side chains of amino acids such as phenylalanine. The release of these volatile compounds produces a scent of burning rubber [91].

It could be concluded that ultrasound has a very good milk homogenization effect at high-amplitude levels compared with conventional homogenization. The acoustic cavitation is responsible for some structural changes, particularly in the protein particles. Thermosonication treatment could be successfully used in the production of yogurt drink and improve its major quality parameters such as delayed serum separation and increased apparent viscosity. Ultrasound has also the potential to facilitate the production of commercial yogurt in which supplementation with milk solids can be substantially reduced. Ultrasound treatment after inoculation results in a decreased fermentation time and increased water-holding capacity. However controlled and optimized application of ultrasound demands application of specific ultrasound frequency and optimal treatment time. In general, high-intensity ultrasound seems to be a potential alternative to the conventional processing to obtain good quality products.

3.3. Fruits and Vegetables. The increased consumption of fruit and vegetables worldwide has increased the need to have greater control of the nutritional, sensory, and microbiological qualities of these foods [92]. Emerging technologies have been developed to preserve food as long as possible without the use of additives and without affecting its nutritional value and sensory attributes; these technologies must also be cost-efficient and should use environmentally friendly products [93]. Many studies have focused on the effect of ultrasound as an alternative to washing methods that prevent the adhesion of microorganisms to the tissues of fruits and vegetables [94–98]. This technology is often combined with other sanitizing agents in the washing fruits and vegetables, as in the case of chlorine dioxide in plums, apples, and lettuce [33, 41]; exogenous polyamines (putrescine) in peach [99]; and sodium hypochlorite in lettuce [31]. Ultrasound is useful for decontaminating surfaces when applied in combination with other methods. High temperature, high pressure, ultraviolet radiation, pulsed electric fields, or chemical methods are often used for cleaning and disinfection and can be applied in combination with ultrasound; in the case of fruits and vegetables, heat and pressure are not recommended because they can damage the tissues [93]. Generally, ultrasound is

combined with chemicals such as commercial sanitizers, organic acids, and other antimicrobials.

Bacterial inactivation by ultrasound has also been tested in food products derived from the processing of fruits and vegetables; in this case ultrasound is combined with antimicrobial agents such as vanillin and citral [100]. Although treatment with ultrasound can by itself cause a reduction in microorganism counts, it cannot be efficiently used in industrial applications because of its poor sterilization effect. It requires long treatment times and/or high acoustic energy, damaging fresh tissues and making them more susceptible to infestation and attacks by microorganisms. During ultrasonic treatment, microorganisms are released into the wash water, creating the risk of cross contamination; thus, this technology should be combined with other technologies to ensure sterilization [101]. Many studies show that the physical and chemical effects of ultrasound treatment are related to the amplitude of the ultrasonic waves, the exposure times, the food volume and composition, and the temperature reached by the tissues [102–104].

Table 4 describes some studies that have used ultrasound in fruits and vegetables; the results differ depending on the experimental conditions employed. Most of the studies reviewed do not provide information on important characteristics of the equipment used, such as the effective ultrasonic power fed into the system (different from the electric power of the equipment), which should be measured by calorimetry according to the method reported by M. A. Margulis and I. M. Margulis [105].

Microbial reduction (\log_{10} CFU/g of sample) seems to be more related to ultrasonic power than to ultrasonic frequency. Low power ultrasound generates greater reductions; in the case of iceberg lettuce (ultrasonic equipment with 10 W/L), the reduction was 1.5 \log_{10} CFU/g in *S. typhimurium* [30]. Ultrasound treatment destroys or removes microorganisms from fruits and vegetables by cavitation, which is a combination of mechanical effects (generation of turbulence, circulation flows, and shear stress), chemical effects (generation of free radicals that attack the chemical structure of the cell wall of the microorganisms), and physical effects (generation of extreme temperature and pressure) [106]. Combining ultrasonic energy with a sanitizer potentiates its microbial reduction effect. Regarding *S. typhimurium*, a reduction of 2.7 \log_{10} CFU/g was observed in lettuce when ultrasound was combined with chlorinated water; ultrasound alone caused a reduction of 1.5 \log_{10} CFU/g. These results are similar to those of Brilhante São José and Dantas Vanetti [32], who reported a reduction of 3.9 \log_{10} CFU/g for *S. enterica* Typhimurium when combining ultrasound with peracetic acid; by contrast, ultrasound alone caused a reduction of only 0.8 \log_{10} CFU/g. These results are relative, since studies in other plant species have not shown differences in microbial reduction between ultrasound alone and combined with antimicrobials.

Higher power ultrasound (350 W/L) induced microbial reduction of 0.6 \log_{10} CFU/g (total viable count of mesophilic microorganisms) in strawberries and of 0.5 \log_{10} CFU/g in molds and yeasts [30]. Alegria et al. [107] reported a reduction of 1.3 \log_{10} CFU/g in total mesophilic counts in shredded

TABLE 4: Application of ultrasound in fruits and vegetables for various purposes.

Food	Conditions	Purpose	References
Alfalfa seeds	US 40 kHz + Ca(OH) ₂ 1%	Reduction of <i>E. coli</i> and <i>Salmonella</i>	Scouten and Beuchat [29]
Strawberries	US 40 kHz 350 W/L, 10 min	Reduction of mesophilic microorganisms, molds, and yeasts	Cao et al. [30]
Lettuce	US 10 W/L, 32–40 kHz, 10 min US + chlorinated water (25 ppm)	Reduction of <i>S. typhimurium</i>	Seymour et al. [31]
Cherry tomato	US 45 kHz, 10 min, 25°C US + peracetic acid (40 mg/L)	Reduction of <i>S. enterica</i> Typhimurium	Brilhante São José and Dantas Vanetti [32]
Lettuce apples	US 170 kHz, 6–10 min + ClO ₂ (5 and 1 ppm)	Reduction of <i>Salmonella</i> and <i>E. coli</i>	Huang et al. [33]
Truffles	US + ethanol (70%)	Reduction of mesophilic microorganisms, molds, yeasts, <i>Pseudomonas</i> spp., Enterobacteriaceae, and LAB	Susana Rivera et al. [34]
Lettuce	US 20 kHz US + 100 mg/L Ca(ClO) ₂	Reduction of aerobic mesophilic bacteria	Ajlouni et al. [35]
Spinach	US 200 W/L, 2 min + various sanitizers	Reduction of <i>E. coli</i> O157:H7	Zhou et al. [36]
Lettuce	US 37 kHz, 30 min	Reduction of <i>E. coli</i> , <i>S. aureus</i> , <i>S. enteritidis</i> , and <i>L. innocua</i>	Birmpa et al. [37]
Cabbage, lettuce, sesame, and spinach	US 40 kHz, 3 min, 23°C + electrolyzed water + washing with water	Reduction of <i>E. coli</i> O157:H7	Forghani and Oh [38]
Cranberry, nectarine, raspberry and watermelon, garlic, artichoke, leek, and onion	US 40 kHz, 20–60°C, 5, 10, 20 or 30 min	2–4-fold increase in the extraction of oligosaccharides	Jovanovic-Malinovska et al. [39]
Lychee	120 W, 10 min	Reduction in the degradation of anthocyanins and delayed browning	Chen et al. [40]
Plum	40 kHz, 100 W, 10 min	Inhibition of respiratory rate (greater firmness), preservation of flavonoids, ascorbic acid, reducing sugars, and titratable acids	Chen and Zhu [41]
Persimmon	50 kHz, 200 W, 1–10 min	Firmness retention, higher content of soluble solids, and titratable acids	Wang et al. [42]

LAB: lactic acid bacteria.

carrot and of 0.9 log₁₀ CFU/g for molds and yeasts, using ultrasound alone (45 kHz, 1 min, 25°C); when ultrasound was used under the same conditions but combined with chlorinated water (200 ppm), they observed a reduction of 1.0 log₁₀ CFU/g in total mesophilic counts and of 0.9 log₁₀ CFU/g for molds and yeasts. Ajlouni et al. [35] demonstrated that temperature is an important factor in microbial reduction in lettuce. The use of ultrasound (20 kHz, 2 min) reduced aerobic mesophilic counts by 0.90 and 0.98 log₁₀ CFU/g at 4°C and 50°C, respectively; combining Ca (ClO)₂ with ultrasound caused a greater reduction in mesophilic counts (1.02 log₁₀ CFU/g at 4°C and 1.35 log₁₀ CFU/g at 50°C).

Other potential applications of ultrasound in fruits and vegetables concern the conservation of quality parameters such as texture, color, and nutrients (Table 4). Pretreatment with ultrasound inhibits physiological activities and slows the decline in quality during storage in unripe fruits [30]. Regarding texture, it possibly delays softening by inhibiting enzymatic activity (pectin methylesterase and polygalacturonase). It has been reported that ultrasound delays the degradation of

pigments (chlorophylls, carotenoids, and anthocyanins) during ripening, maintaining the green color of asparagus [108], and inhibiting the decrease of anthocyanins in strawberries [109]. Fruit senescence is associated with reactive oxygen species and oxidative damage of mitochondrial proteins; Zhao et al. [110] found an increase in the activity of peroxidase and superoxide dismutase (antioxidant enzymes) in pears treated with ultrasound; Li et al. [111] also observed an increase in the activity of superoxide dismutase and catalase in peaches treated with ultrasound (50 kHz, 200 W, 3 min).

It can be concluded that ultrasound has a great potential in the preservation of fruits and vegetables; however, the methods and parameters used have not been standardized. Furthermore, the industrial use of ultrasonic technology in fresh produce requires manufacturing and improvement of ultrasonic equipment.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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