Ultrasound applications in poultry meat processing: A systematic review

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Abstract: Ultrasound (US) is classified as a nonthermal treatment and it is used in food processing at a frequency range between 20 kHz and 1 MHz. Cavitation bubbles occur when the US strength is high enough to generate rarefaction that exceeds the intermolecular attraction forces in the medium. Currently, US is widely used in meat industries to enhance procedures, such as meat tenderization, emulsification mass transfer, marination, freezing, homogenization, crystallization, drying, and microorganism inactivation. In addition, combining ultrasonic energy with a sanitizing agent has a synergistic effect on microbial reduction. When poultry meat is treated using US, the expected quality is often better than the traditional methods, such as sanitization and freezing. US can be considered as a novel green technology for tenderizing and decontamination of poultry meat since both *Escherichia coli* and *Salmonella* are sensible to US. US improves the physical and chemical properties of meat proteins and can lead to a decrease in the α-helix in intramuscular protease complex in addition to a reduction in the viscosity coefficients. Therefore, ultrasonic treatment can be applied to enhance the textural properties of chicken meat. US can also be used to improve the drying rate when used under vacuum, compared with other traditional techniques. This review focuses on the potential of US applications in the management of poultry industries as the demand for good quality meat proteins is increasing worldwide.

Keywords: ultrasound, poultry, meat processing, physicochemical properties

1. INTRODUCTION

Increases in consumer preferences in addition to the growing demand to deliver healthy and high-quality food products are driving the advancement of food processes globally. Technological innovations are considered as the best available option for achieving the above functionality. Such innovations that include the use of microfiltration, high pressure, electrical pulses, and ultrasonics are specifically developed for flexibility, power-efficiency, economy, and sustainability. In fact, ultrasound (US) is used in the "Green Food Manufacturing" to achieve high-quality and safe food products (Chemat & Ashokkumar, 2017). US is an emerging technology used for improving biochemical and functional characteristics of meat products (Altemimi, Lakhssassi, Baharlouei, Watson, & Lightfoot, 2017; Altemimi, Watson, Choudhary, Dasari, & Lightfoot, 2016; Saleem & Ahmad, 2016a). Recent studies have demonstrated that US has greatly enhanced the functional quality of dietary proteins, such as egg proteins (Arzeni, Pérez, & Pilosof, 2012). The world's population is expected to increase by 2 billion persons in the near 30 years; and therefore, demand for high-quality meat is expected to increase (Mullen et al., 2017). In addition to the sensory properties, flavor, juiciness, and tenderness are the main characteristics of meat quality (Aaslyng & Meinert, 2017). US is a modern technology that has many applications in food processing. It could be defined as a higher sound wave than the waves that can be perceived by human ears (Aaslyng & Meinert, 2017). However, US frequencies that are greater than 20 kHz cannot be heard (Al-Hilphy, Verma, Niamah, Billoria, & Serivastav, 2016). The energy intensity of the US ranges from 10 to 1,000 W/cm^2 at frequencies between 20 and 100 kHz and has a significant impact on the chemical and physical properties of fluids (Dhankhar, 2014). When the sound moves to a certain medium, it generates pressure waves and disturbs particles in the media (Povey & Mason, 1998), resulting in the formation of cavities and/or bubbles. The growing cavities obtained by successive cycles of US become unstable resulting in their collapse, which generates high temperature and pressure affecting the biological materials and tissues at both macro and microscopic levels (Alarcon-Rojo, Janacua, Rodriguez, Paniwnyk, & Mason, 2015). The US can be used at high-frequency with low-intensity (>1 MHz, <1 W/cm^2) or at low-frequency with high-intensity (20 to 100 kHz with 10 to 1,000 W/cm^2). Both types are useful for food processing (Mason, 1996; Mason, Paniwnyk, Chemat, & Abert Vian, 2010). In terms of meat processing, the US can modify the cell membrane, which can help in curing, marinating, drying, and tenderizing tissues (Alarcon-Rojo et al., 2015). US curing increases brine transfer into meat and reduces the processing time and its effect on the product quality (McDonnell, Lyng, & Allen, 2014). Using US (ultrasonic bath at 40kHz and 110W) and sodium chloride (in marinating with increasing time) led to an increase in meat hardness, weight loss, and a change in color parameters (lightness and redness), but also resulted in reducing the water-holding capacity (WHC), water content, and pH (Gómez-Salazar, Ochoa-Montes, Cerón-García, Ozuna, & Sosa-Morales, 2018). It has been shown that chicken meat treated by US probe (22 kHz, 27.6 W/m^2) inhibited the number of mesophilic bacteria (Piñon et al., 2019). Using US -assisted vacuum drying of minced meat resulted in less

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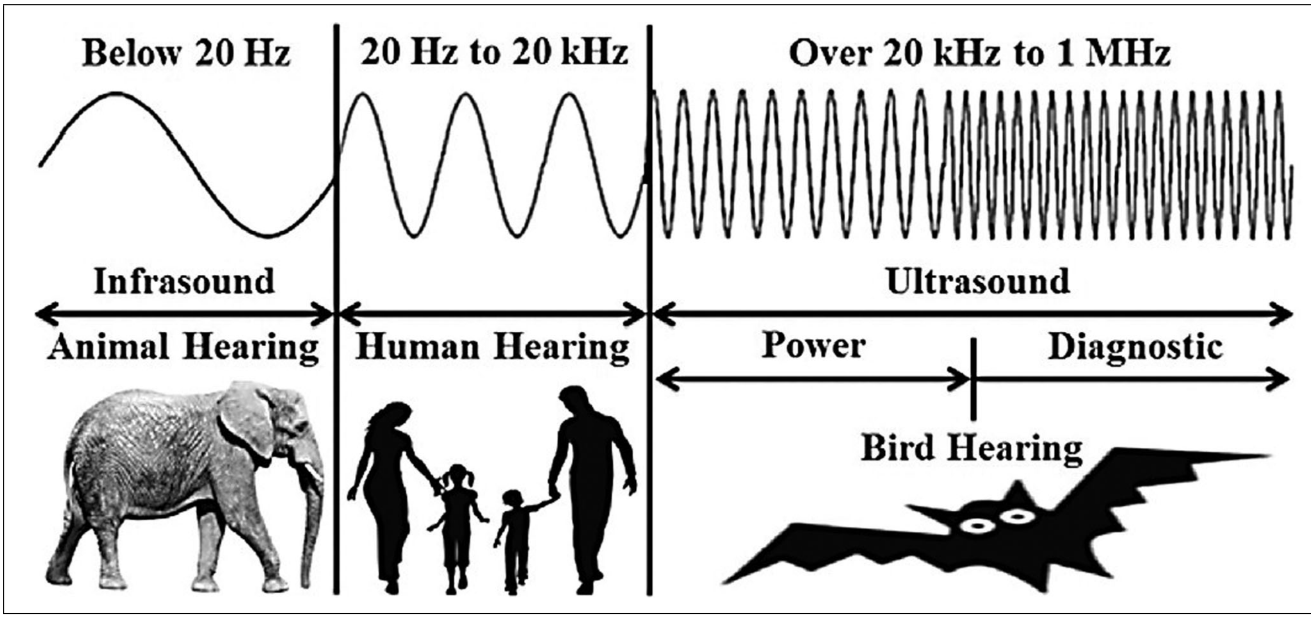

Figure 1–The spectrum of sound (Al-Hilphy et al., 2016).

drying time and peroxide value, in addition to higher rehydration (Aksoy, Karasu, Akcicek, & Kayacan, 2019). Despite the fact that ultrasonic waves have immense applications and are extensively used to enhance a wide range of characteristics for a range of matrices and operations (Alarcon-Rojo et al., 2015), the industrial ultrasonic applications have been developed at a relatively small scale (Awad, Moharram, Shaltout, Asker, & Youssef, 2012). This review aims to investigate the effect of US on the physicochemical, microbiological, rheological, functional properties, and nutritional content of poultry meat.

2. US WAVES: BRIEF OVERVIEW

US is a nonpolluting, nonionizing, and noninvasive source of mechanical energy and hence considered as an acoustic energy (Chemat, Zille, & Khan, 2011). Recently, US technology has been considered as an evolving approach with a huge potential for monitoring, enhancing, and speeding up processes without harming the food quality (Awad et al., 2012). The frequency determines the type of sound wave as illustrated in Figure 1 the infrasound refers to the frequency of the sound wave below the frequency of human ear hearing, the range of frequency from 20 Hz to approximately 20 kHz is the one that can be heard by humans, and when the frequency is above 20 kHz, it is called US. This US spectrum is divided into two zones: (1) power US with frequency ranging between 20 kHz and 1 MHz, and (2) diagnostic US with frequency above 1 MHz, which is used for industrial imaging and medical purposes (Feng, Barbosa-Canovas, & Weiss, 2011). Based upon the data presented by Leong, Ashokkumar, and Kentish (2011), the US waves are based on sound waves that range from 20 kHz to 10 MHz and are broadly categorized into three main types (Figure 2). The electrical energy (in ultrasonic device) is converted into vibrational energy (mechanical energy) (Berlan & Mason, 1992), ultimately transmitted via sonicated medium. High-intensity ultrasound (HIU) commonly known as high-power US potentially alters the mechanical, physical, and chemical characteristics of food. US waves having high-frequency (1 to 10 MHz) and low-intensity (<1 W/cm^2) exhibit rational applications, which provide detailed knowledge about the physicochemical characteristics of food products, such as condition, composition, and structure. It has been shown that HIU is a promising technology to enhance the color, flavor, and tenderness of fresh meat (Alarcon-Rojo et al., 2015; Turantaş, Kılıç, & Kılıç, 2015). Unlike traditional analytical techniques, it is a nondestructive and noninvasive method providing easy measurements, which is simple and automated to be applicable in both research laboratories and manufacturing plants. The two types of sound waves propagate in parallel and perpendicular. Sound waves propagation depends on the medium. Parallel waves are named longitudinal waves and perpendicular waves are called shear waves (Feng et al., 2011). Longitudinal waves can transfer in solid, gas, liquid phases, and have short wavelengths in relation with the transducer dimensions, production of sharp beams, and high velocities. In shear waves, particle movements are perpendicular to the direction of wave diffusion and since liquid and gas do not support stress shear underneath traditional conditions, shear waves will solely propagate in solid phase. The speed of shear waves depends on the material in which it is propagated and this velocity is relatively low compared to longitudinal waves. Longitudinal speed depends on the state of the material and can be used to determine the specific enthalpy of partly frozen meat (Miles & Cutting, 2007). Longitudinal speed is sensitive to variations in the structure, like fiber direction in meat and crushed meat composition. The velocity of US pulse depends on the acoustic properties of the medium, in addition to the velocity of sound propagation that is larger in solids than liquids and better in liquids than gas (Kasaai, 2013). In an ultrasonic system, the electric power is transformed into vibrational energy that transmutes to US in the medium (Berlan & Mason, 1992). In the same context, a low conversion was obtained from an electrical to aquastical energy (27%) and cavitation (9%) when using US (Berlan & Mason, 1992; Mamvura, Iyuke, & Paterson, 2018). Monteiro et al. (2020) stated that the energy density parameter cannot be used for comparison among varied US processes and different products were generated when applying US energy density with different parameters.

US is created through a compression succession and rarefaction cycle faradic via sound waves to the molecules of the medium

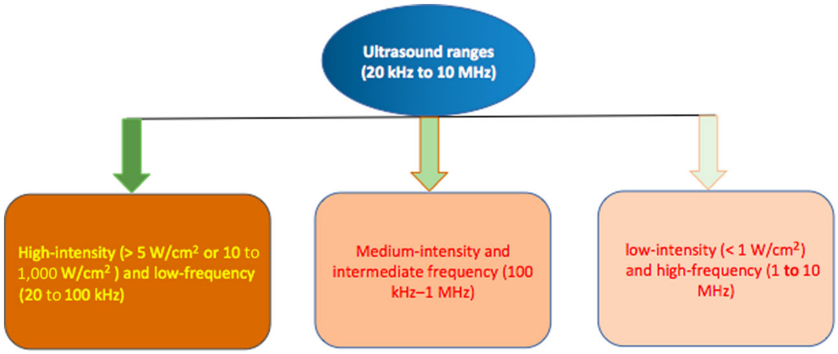

Figure 2–Types of ultrasound with respect to sound waves ranges.

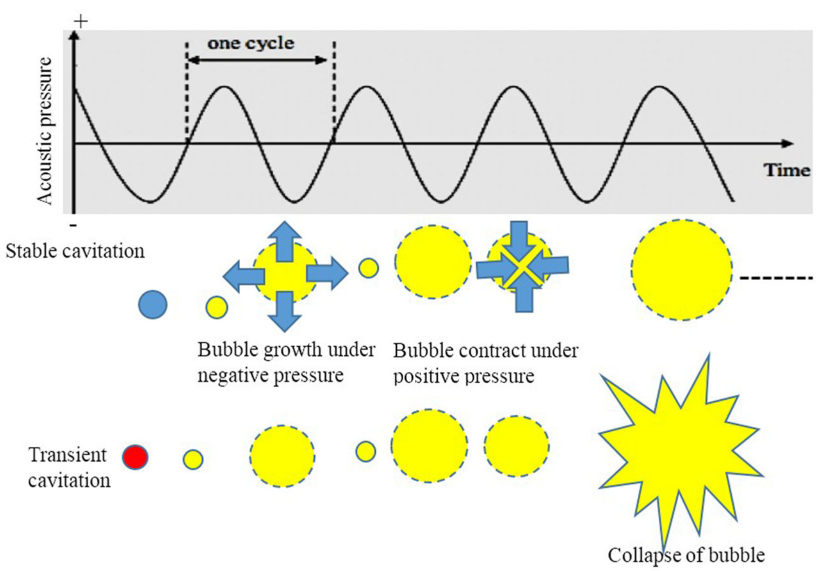

Figure 3–Formation of cavitation using ultrasound.

through its traveling (Rastogi, 2011) as illustrated in Figure 3. Cavitation bubbles occur when the adequate high US power forms the rarefaction, encroaching the charming forces among molecules in a medium. Cavitation bubble can be categorized into transient and stable cavitation (Zheng & Sun, 2005). Microstreaming occurs when the cavitation bubbles move during stable cavitation. The microcurrents are formed due to the diffusion of dissolved gases into and out of the bubbles. Microstreaming presents several advantages, including degassing related to the rupture of the cell membrane (Chemat et al., 2011; Rastogi, 2011). Bubbles grow at few cycles to reach the critical size and become unsteady and fiercely collapse at high acoustic pressure (Mason, Riera, Vercet, & Lopez-Buesa, 2005). When the bubble collapses at the time of transient cavitation, it generates high temperatures (4,727 °C) and high pressure (100 MPa). This leads to an outwardly propagation of shockwaves and causes violent disturbances inside the instantaneous surroundings. These microprocesses break the chain of polymers and/or disrupt cell walls of biological tissues. The breakdown of water molecules generates reactive free oxygen and hydrogen radicals that interact with other molecules (Riesz & Kondo, 1992).

Bekhit (2017) reported that in case of high-power ultrasonic, the pressure generated by longitudinal waves in addition to the obtained cavitation in liquid phases leads to bubbles formation. In low-power US, the sound velocity, acoustic impedance, and attenuation coefficient play a major role. Sound velocity is a function of sound wave length and frequency as shown in Eq. 1, which depends on the temperature and material:

$$c = f\lambda \quad (1)$$

where c is the sound velocity, f is the frequency, and λ is the sound wave.

Whole energy transfers from an emitter to a receiver in ideal medium, but in case of true material, the wave amplitude decreases as distance traveled increases due to attenuation. Attenuation is produced due to sound wave absorption and scattering in the material due to the change from sound energy to heat. The relationship between attenuation coefficient and amplitude is given by Eq. 2 (Jambrak, Herceg, & Grbavac, 2014):

$$A = A_o\ e^{-\alpha x} \quad (2)$$

where A is the amplitude at later time, x is the amplitude at zero time, and α is the attenuation coefficient.

3. US IN POULTRY MEAT PROCESSING

US (28 W/L, 25 and 130 kHz, 5 to 30 min, 10 °c) was primarily used in the meat industry to improve the cooling process of broiler chickens (Flores et al., 2018) and tenderness of meat (De Hooge et al., 2017; Henchion, McCarthy, Resconi, & Troy, 2014; Jayasooriya, Torley, D'Arcy, & Bhandari, 2007). US of low intensity is now being used regularly to improve the quality, taste, and tenderness, which are the most important quality attributes of consumer acceptance. Furthermore, several new researches have demonstrated the valuable uses of high-intensity US waves on fresh meat. A large number of researches have been reported on the potential application of US in meat industries in diverse domains, such as in bacterial inhibition (Caraveo, Alarcón-Rojo, Renteria, Santellano, & Paniwnyk, 2015), freezing (Zheng & Sun, 2005), thawing (Miles, Morley, & Rendell, 1999), cooking (Chemat et al., 2011), meat brining (Cárcel, Benedito, Bon, & Mulet, 2007), and tenderizing (Peña-Gonzalez, Alarcon-Rojo, Garcia-Galicia, Carrillo-Lopez, & Huerta-Jimenez, 2019). Texture, pH, WHC, oxidative stability, and sensory qualities (color) are the most important properties of meat quality with significant impact on industrial settings (Abdalhai, Bashari, Lagnika, He, & Sun, 2014). US treatment leads to the change in protein structure of chicken meat, which enhances the emulsification and gelling characteristics (Li, Kang, Zhao, Xu, & Zhou, 2014). During the last few years, various studies analyzed the influence of US power on processed poultry meat and a summary can be found in Table 1.

3.1 Effect on different physicochemical properties

In the meat industry, high-intensity ultrasonic assists in tenderization that accelerates maturation and mass transfer, reduces cooking energy, increases shelf life, improves functional properties of emulsified products, facilitates cleaning mold, and improves the surface sterilization of equipment (Alarcon-Rojo et al., 2015). Leal-Ramos, Alarcon-Rojo, Mason, Paniwnyk, and Alarjah (2011) reported that the use of ultrasonic (40 kHz, 22 W/cm^2, 15 or 30 min) to treat chicken breast led to the increase in mass transfer and meat weight.

Texture plays an important role in judging the quality of meat by the consumers (Morton, Bhat, & El-Din Ahmed Bekhit, 2019). US is considered as the ideal method to tenderize meat (Meek et al., 2000). It has been reported that lysosomal rupture and disruption of myofibrillar protein and animal tissue led to tenderize the meat (Lyng, Allen, & McKenna, 1997). The violent hydrodynamic forces because of a collapsing bubble or transient cavitation can cause severe harm inside biological media like meat, thereby damaging the fiber structure of the muscles (Smith, Cannon, Novakofski, McKeith, & O'Brien, 1991). In an independent study, low-frequency and high-intensity US baths on beefsteaks had no effect on the tenderness of intact beefsteaks (Lyng et al., 1997). However, other studies were able to tenderize semitendinosus beef muscle after sonication for 2 and 4 min only (Smith et al., 1991). US treatments were used to enhance the disruption of myofibrillar structures and increase proteolysis of chicken meat by running the apoptosis chain (Chen et al., 2015). US categorically does not affect the initial structure of chicken proteins. It has been shown that US induces changes in the secondary structure of chicken proteins and tear of tertiary and quaternary structure (Wang, Han, Ma, Yu, & Zhao, 2017). The fragmentation of actin filaments and myofibrillar fraction due to the action of US (300 to 600 W, 40 kHz for 30 min) resulted in the tenderization of goose meat (Li, Wang, Sun, Pan, & Cao, 2018).

Chicken actomyosin is the main protein complex in animal muscles, in particular when ATP is lost after slaughtering (Li, Xu, & Zhou, 2012). Zou et al. (2018) studied the effect of different US power (100 to 150 W) on the physicochemical properties and functional performance of chicken actomyosin and found that the absolute zeta potential of sonicated chicken actomyosin was higher. Treated chicken actomyosin by ultrasonic resulted in a decrease in the α-helix and enhanced its fluorescence intensity. In addition, protein hydrophobicity and reactive SH groups increased significantly at the US power of 150 W. The authors also suggest that sonicated chicken actomyosin became thermally unstable. However, they concluded that the power range of 100 to 150 W was suitable to modify chicken actomyosin in optimizing its functional properties. Wang, Yang, Tang, Ni, and Zhou (2017) have studied the effect of ultrasonic on the structure and solubility of chicken myofibrillar protein and noticed that the reactive sulfhydryl groups, surface hydrophobicity, and solubility of chicken myofibrillar protein treated by US increased when compared to the control. The myofibrillar protein contains a collection of proteins, such as actomyosin, actin, and myosin (Zhang, Yang, Zhou, Zhang, & Wang, 2017). The structural and biochemical properties of sonicated chicken actomyosin (at 120 W) at different periods were studied (Saleem & Ahmad, 2016a). The study reported that the actomyosin gelling properties and regular three-dimensional network of actomyosin gels improved significantly by using ultrasonic treatment in addition to increasing WHC using ultrasonic treatment.

Pagán, Mañas, Raso, and Condón (1999) stated that sterilizing meat by heat and US led to more tender meat. Using US to treat meat tissue causes the break of the muscle cell integrity and the progress of the enzymatic reactions (Boistier-Marquis, Lagsir-Oulahal, & Callard, 1999). Xiong, Zhang, Zhang, and Wu (2012) treated hen breast meat by ultrasonic at the intensity of 24 W/cm^2 and frequency of 12 kHz for 15 s, and then stored at 4 °C for 1 to 12 days. The obtained results showed a reduction in shear force; however, the cooking loss was not affected by the ultrasonic treatments. The study reported that the muscle degradation was caused by US and proteases like the calpain system and cathepsins. Zhao et al. (2014) treated chicken breast and soybean gels (4 to 8 °C) with ultrasonic at 450 W, 20 kHz for 0, 3, 6, 9, and 12 min (4 or 2 s pulses) and found an increase in viscoelastic gel and improved water-binding, fat-binding (WFB), and textural properties, in addition to the homogeneous network microstructures. Xiong et al. (2012) studied the impact of ultrasonic treatment and proteolytic enzyme inhibitors on cooking loss of hens. The results reported that ultrasonic treatment had no effect on the cooking loss, but the combined treatments of inhibitors of exogenous proteolytic enzyme and ultrasonic decreased the cooking loss of chicken meat. In addition, exogenous enzyme inhibitors reduced the cooking loss. Li et al. (2014) used a combination of different salt contents (1%, 1.5%, and 2%) and US at a frequency of 40 kHz and 300 W power at varied times ranged from10 to 40 min to study their effects on the functional characteristics of chicken breast meat. The results showed that cooking loss, storage modulus (G′), texture, WHC, and loss modulus (G″) were significantly affected by the salt level. The results also reported that WHC and texture improved by using US for 10 and 20 min. Furthermore, G′ values were higher and the hardness decreased by using ultrasonic for 40 min. However, combined ultrasonic at 20 min and salt content (1.5%) had a significant effect on the cooking loss, WHC, and texture.

Color plays an important role in meat quality as it is the first parameter that the consumer encounters when purchasing a

Table 1–Influence of ultrasound waves in poultry meat processing.

Sample description	Ultrasonic parameter (power [intensity]/frequency/ time/temperature)	Ultrasonic effects	References
Chicken liver	Ultrasound probe, 10 W/10 min/10 °C	Increases yield of extraction, improves extraction efficiency, and prevents chemical degradation of exposed compounds	Sun et al. (2006)
Chicken breast	40 kHz, 22 W/cm^2, 15 or 30 min/23 °C	Increment in meat weight and mass transfer	Leal-Ramos et al. (2011)
Chicken breast	Ultrasound bath for 20 min	There is no impact on cooking loss, shear force, and water retention capacity	Smith et al. (2011)
Hen breast meat	12 W/cm^2, 24 kHz, 15 s, 0, 1, 3, and 7 days at 4 °C	Decreased shear force. The cooking loss did not change	Xiong et al. (2012)
Chicken. pectoralis major. Meat paste suspensions (PSE)	Ultrasound probe 750 W/20 kHz/0, 3, and 6 min/2.49 to 25.34 °C	Gel resistance, water-holding capacity, and pH were increased by using high ultrasound intensity. Viscosity and elasticity were higher. PSE meat quality had been improved	Li et al. (2014)
Soybean gels and chicken breast	450 W/20 kHz, 0 to 12 min/pulse time was 4 or 2 s, 4 to 8 °C	Increased viscoelastic gel. Enhanced textural properties and WFB. More uniform network microstructures	Zhao et al. (2014)
Chicken breast	300 W/40 kHz at 10, 20, 30, and 40 min	In sonicated gel, a comp of act structure was produced after 20 min, but in 40 min, aggregation of protein widely increased and cavities. In 20 min, myofibrillar water ratio was increased after ultrasound treatment and gelation properties were enhanced. WHC was improved at 10 and 20 min, but it was reduced at 40 min	Li, Kang, Zou, Xu, and Zhou (2015)
Chicken liver	Measurement of the ultrasonic speed of the tissue	Sound speed was reached 1,588.2 and 1,609.5 m/s at a temperature of 21.8 and 60.5°C, respectively	Martínez-Valdez, Contreras, Vera, and Leija (2015)
Chicken meat	1,500 W/40 kHz/20 °C	Enhanced the disruption of myofibrillar structures and increased proteolysis	Chen et al., 2015
Chicken pectoralis major	120 W/20 kHz. 0.5 min	The ATPasa-Ca_2+ activity was declined by using high ultrasound intensity, in addition, proteins secondary structure was changed	Saleem & Ahmed (2016a)
Chicken breast	Ultrasonic bath, 28 W/L, 25 and 130 kHz, 5 to 30 min, initial temperature 37 °C	Ultrasound reduced in approximately 40% the prechiller process time	Flores et al. (2018)
Suspension of chicken breast myofibrillar proteins (MPS)	Ultrasound probe 32.18 W/cm^2/20 kHz, Cal./6 min. Pulse/on and off were 2 and 4 s, respectively, 22 °C	Partially myosin denatures preheating in the cooking process. Reduced MPS solubility by 50%. Reactive-sulfhydryl contents were reduced that led to MPS denature. Gel strength reduced. Moisture losses and cooking increased.	Xue et al. (2018)
Goose meat	300 to 600 W/40 kHz for 30 min	The tenderization of goose meat was better	Li et al. (2018)
Chicken actomyosin	Pulsed ultrasound probe, 100 to 150 W/20 kHz/24 min/8 °C	The absolute zeta potential of sonicated chicken actomyosin was higher	Zou et al. (2018)
Chick liver, 1 chick liver: 2 deionized water (w/v)	Ultrasound probe 100 W/20 kHz, pulse on and off were 2 and 3 s, respectively, for 10 min/30 °C temperature of beaker wall	Increased sulfhydryl groups and surface hydrophobicity. Particles were smaller and more homogeneous with a higher density of holes. Improvement of emulsion stability index and emulsifying activity index. Lower motion resistance and shear stress during the rheological assessment	Zou et al. (2018)
Chicken fat	Ultrasound probe reverse ultrasound-assisted emulsification-microextraction. Ultrasound probe using 91 W for 7.5 min in ice bath	The analytical parameters clearly showed the applicability of this method was reliable for the macrolides extraction and quantification from the complex biological samples	Lorenzetti, Lista, and Domini (2019)
Chicken carcasses	Ultrasonic bath plus slightly acid electrolyzed water, 1,000 W (acoustic power 230 W)/25 to 130 kHz/30 min/16 °C	No significant effect on anaerobic glycolysis, protein oxidation, muscle structure, and shear force	Cichoski et al. (2019)
Raw chicken meat	High-power ultrasound combined with supercritical carbon dioxide	After treatment, vitamins B complex was preserved well	Morbiato et al. (2019)
Chicken breast meat	Ultrasound combined with sodium bicarbonate 300 W/20 kHz/10 min/ 4 °C	WHC, tenderness, and curing rate were improved. Protein surface hydrophobicity was decreased	Xiong et al. (2012)

product. Color is a major element in the quality of meat because it is the first sensory attribute the consumer faces. Measurement of color is important in the assessment of the commercial quality of meat (Peña-Gonzalez et al., 2019). Meat color depends mainly on the chemical characteristics of myoglobin in the meat muscle but there are also other compounds that also affect it. In chicken, these are hemoglobin, cytochrome C and derivatives, and ligands with heme compounds (Carvalho, Shimokomaki, & Estévez, 2017). The fresh meat color is defined by the redox state of myoglobin: oxymyoglobin and carboxymyoglobin will give cherry-red and red color, these two will not be detected by the human eye, deoxymyoglobin will give a purplish color and metmyoglobin will generate the brown color associated with meat discoloration. Myoglobin content in poultry meat is much lower than in other animal species—0.40 mg/g in 8-week-old poultry dark meat versus 4.60 mg/g in 3-year-old beef—and hence the paler color of its meat. For this reason, the discoloration effect the US may have will be lower in poultry meat when compared to red meats. Pohlman, Dikeman, and Kropf (1997) reported that the color of treated beef meat by ultrasonic (22 W/cm^2) changed to less redness, less brightness, with more yellow-orange with higher hue angle when compared to control meat. Sikes, Mawson, Stark, and Warner (2014) stated that the total change in color of beef meat treated by US was accelerated, oxymyoglobin was limited, and metmyoglobin formation was reduced. A perceivable color change of $\Delta E = 5.5$ was found in chicken treated with US compared with the control and was categorized as "very distinct" and detectable by the human eye (Royintarat, Choi, Boonyawan, Seesuriyachan, & Wattanutchariya, 2020). Nonetheless, Seo, Jeong, Han, Kang, and Ha (2019) and Lee, Park, Kang, and Ha (2014) have reported no changes in chicken skin color after US treatment.

Chicken meat contains high quantity of group B vitamins but after processing and cooking, this can be degraded or lost (Lombardi-Boccia, Lanzi, & Aguzzi, 2005). There are many factors that cause degradation, including the length of exposure, moisture, pH, light, temperature, and oxygen (Lešková et al., 2006). The use of US in combination with supercritical carbon dioxide (SC-CO_2) proved to be a success in preserving the vitamin content (vitamins B1, B2, B3, and B12) of chicken breast (Morbiato et al., 2019). The authors compared the use of conventional processing techniques like steam or boiling cooking and oven drying with the use of SC-CO_2 alone or in combination with high-power US. Steamed and boiled samples resulted in extreme decrease in vitamins B retention (1% to 25%)—as they are water soluble. Nonetheless, when SC-CO_2 was used, the retention was between 75% and 85% (for vitamins B1, B2, and B3) and with the help of the US, the retention was total (100%). In the case of vitamin B12, the highest retention (approximately 20%) was with the use of SC-CO_2, irrespective of the use or not of US.

3.2 Effect on microbiological properties

Intrinsic (i.e., pH, water availability, and nutrients) and extrinsic characteristics (i.e,. processing, storage, and transportation of meat) impact the meat quality and make it highly susceptible to spoilage and infection by pathogenic microorganisms, such as *Escherichia coli*, *Campylobacter* spp., *Staphylococcus aureus*, *Salmonella* spp., Lactic acid bacteria, and *Pseudomonas* spp. A summary of the research conducted on the effect of US on the microbial properties of poultry meat can be observed in Table 2. US generates high pressure, temperature gradient, and shear during high-power US ranging from 20 to 100 kHz, which causes cell death via destroying cell membranes and DNA. The effect of high-intensity ultrasonic on bacteria depends on the type of microorganism, intensity, frequency, and duration of the US wave treatment, and the properties of the food (Joyce, Al-Hashimi, & Mason, 2011). Mechanisms involving the elimination of microorganisms by US are performed through the cavitation phenomenon, which causes a change in the microbial growth potential (Altemimi, Lakhssassi, Abu-Ghazaleh, & Lightfoot, 2017; Jørgensen, Christensen, & Ertbjerg, 2005). Morild, Christiansen, Sørensen, Nonboe, and Aabo (2011) reported that the high-intensity US reduced the counts of *Salmonella derby*, *Sal. typhimurium*, *Sal. infantis*, *Yersinia enterocolitica*, and the nonpathogenic *E. coli* by 3.3 log CFU/cm^2 for 4 s. It has been reported that the *Salmonella* spp., *E. coli*, *S. aureus*, *Bacillus cereus*, and *Listeria monocytogenes* present in the suspensions were reduced after US treatment, but the required time to inactivate these bacteria by US was longer (Herceg et al., 2013). Decontamination using US waves can be applied in poultry skin as well as in combination with lactic acid (Kordowska-Wiater & Stasiak, 2011). Treatment of chicken carcasses by using US and steam can minimize the number of Campylobacter on polluted birds (Musavian, Krebs, Nonboe, Corry, & Purnell, 2014). Piñon, Alarcon-Rojo, Renteria, and Carrillo-Lopez (2020) reported that *S. aureus*, mesophilic bacteria, psychrophilic, and lactic acid in chicken breasts increased in sonicated treatments (40 kHz, 9.6 W/cm^2 at 0, 30, and 50 min) after 7 days of storage. The differences among US times were not significant in *S. aureus*, *Salmonella* spp., *E. coli*, Lactic acid bacteria (LAB), psychrophiles, and mesophiles, but the number of microorganisms was significantly reduced after 50 min of US treatment. However, Smith (2011) reported the use of ultrasonic bath for 20 min to treat chicken breast showing that both *Salmonella* and *E. coli* were not affected. Kordowska-Wiater and Stasiak (2011) used ultrasonic (2.5 W/cm^2, 40 kHz, 3 or 6 min) to treat chicken wing surface and found that the ultrasonic treatment reduced microorganisms but also observed that *E. coli* was more sensitive to US treatments. Kordowska-Wiater and Stasiak (2011) have reported that US (2.5 W/cm^2, 40 kHz, 3 to 6 min) eliminates *E. coli*, *Pseudomonas fluorescens, Salmonella enterica* spp., *Proteus* spp., and *Enterica* sv. from chicken skin surface within 3 min (1.0 log CFU/cm^2). When the authors increased time of treatment to 6 min, the reduction of microorganisms reached 1.5 log CFU/cm^2. A combination of 30% ethanol and US was able to reduce *Salmonella typhimurium* by a >1.0 log CFU/g without altering the color or texture of chicken skin (Seo et al., 2019). However, the same authors reported that US alone was ineffective against *S. typhimurium*. Vetchapitak et al. (2020) stated that the US treatment (1,200 W/130 Hz/15 min) reduces *Campylobacter* from 0.94 to 1.19 log10MPN (most probable number)/10 g in contaminated chicken carcasses. Table 2 summarizes the effect of US application on the reduction of microorganisms.

4. OTHER US APPLICATIONS

4.1 Drying

Drying is one of the oldest preservation methods in which heat and mass transfers happen simultaneously. Drying is used as a meat processing technique for the development of different products, such as fermented sausages, meat powder, and dry cured hams. US is greatly utilized as a primary treatment technology to speed up the drying process. Application of ultrasonic destroys the membranes and increases the rate of mass transfer from the intracellular to the extracellular compartment (Nowacka, Wiktor, Śledź, Jurek, & Witrowa-Rajchert, 2012). Figure 4

Table 2–Effect of ultrasound on the reduction of microorganisms.

Description of sample	Ultrasonic parameter (power [intensity]/frequency/ time/temperature)	Ultrasonic effects	References
Chicken skin	Ultrasound with standard tip + chlorine, 100 W/20 kHz/15 s.The beaker put in ice	Reduction of *S. typhimurium* from 2.4 to 3.9/mL (log CFU)	Lillard (1993)
Chicken breast	Ultrasound bath for 20 min with solution of 91% water, 6% NaCl, and 3% sodium tripolyphosphate	*E. coli*. and *Salmonella* counts not affected	Smith (2011)
Surface chicken wing	2.5 W/cm^2, 40 kHz, time (3 or 6 min), 20 °C	Reduced microorganisms *E. coli* more sensitive Gram-negative bacteria reduction	Kordowska-Wiater & Stasiak (2011)
Chicken drumstick	20 W/L/16 min, temperature ≤28 °C	No significant effect on Campylobacter, Enterobacteriaceae, and total viable count	Haughton et al. (2012)
Chicken breast	Ultrasound probe 4.2 W/20 kHz/5 min/dT/dt = 0.005 °C/min	Reduction of psychrophilic bacteria 0.2/g (log CFU)	Piñon-Muñiz et al. (2012)
Suspension of bacteria	Ultrasound probe 0.012 to 0.13 W/m^3/20 kHz/15 min/25 °C and ultrasound bath 0.012 to 0.13 W/m^3/40 kHz/15 min/25 °C low-frequency ultrasound	They have a significant effect on *E. coli and Klebsiella pneumonia* inactivation	Joyce et al. (2011)
Bacterial suspension	Ultrasound probe 600 W/20 kHz/9 min/60 °C	The viability cells were not confirmed for *L. monocytogenes* ATCC 23074, *E. coli* 3014, *Salmonella sp.* 3064, and *S. aureus* 3048. The highest inactivation was noticed in the *B. cereus* 30 and reached 3.48 log CFU/mL	Herceg et al. (2013)
Broilers	Ultrasound bath 30 to 40 kHz/1.0 s/85 to 89 °C	Reduced *Campylobacter* and TVC to 1.0 and 0.7 log CFU/mL, respectively	Musavian et al. (2014)
Chicken breasts	Ultrasonic bath 9.6 W/cm^2/40 kHz/0, 30, and 50 min/5 °C	LAB and *S. aureus* increased. Psychrophiles decreased. The differences between ultrasound times in mesophiles were not significant. After 50 min sonication, the reduction in LAB, *E. coli, Salmonella* spp., and *S. aureus* numbers were not significant	Piñon et al. (2020)
Chicken carcasses	Ultrasonic bath plus slightly acid electrolyzed water (SAEW), 1,000 W (acoustic power 230 W)/25 to 130 kHz/30 min/16 °C	The US+SAEW combination led to the reduction of enterobacteria, mesophilic, lactic acid, and psychrotrophic bacteria	Cichoski et al. (2019)
Raw chicken meat	Ultrasound probe high-power ultrasound combined with supercritical carbon dioxide. 40 kHz/30 min/40 °C	Inactivation of inoculated *Salmonella* was inactivated	Morbiato et al. (2019)
Chicken carcasses	Ultrasound bath 1,200 W/130 Hz/15 min	Reduction of *Campylobacter* from 0.94 to 1.19 log10MPN (most probable number)/10 g	Vetchapitak et al. (2020)

illustrates the drying curves of dried chicken meat by using US, vacuum, and traditional oven at 55, 65, and 75 °C. The ratio of moisture (MR) in sonicated chicken meat declined exponentially as the time increased (Figure 4). The combination of US and vacuum exhibited a higher reduction in MR compared with both oven and vacuum at all drying temperatures. Also, reducing MR using US and vacuum combination was higher than the other drying techniques. Traffano-Schiffo, Castro-Giráldez, Fito, and Balaguer (2014) reported that three stages are occurring during the drying process (drying kinetics theory). The first one is known as the induction period, where water transfer mechanisms are combined. In the second period, the maximum drying rate occurs. In the third period, the quantity of transferred water from inside to the surface is less than the evaporated water from the surrounding surface. This stage is known as falling drying rate period. Nathakaranakule, Kraiwanichkul, and Soponronnarit (2007) declared that increasing drying period causes protein denaturation of meat and the formation of the gel matrix. Using a combination of ultrasonic and vacuum displayed a shorter drying period. Başlar, Kılıçlı, Toker, Sağdıç, and Arici (2014) found that energy consumption using a combination of ultrasonic and vacuum was less than other techniques. To enhance the microorganism inhibition efficiency and raise the dehydration rate, a combination of high-power US and supercritical CO_2 can be used for dehydration (Michelino, Zambon, Vizzotto, Cozzi, & Spilimbergo, 2018). Moreover, the phenomenon of cavitation is produced after combining high-power US and supercritical CO_2, in addition to increasing the mixing as well as increasing the contact between microorganisms and the solvent. As a result, the bacterial inactivation and water extraction were enhanced. Morbiato et al. (2019) reported that dried chicken breast weight was reduced by 74.4%, 70.9%, and 75.1% when using oven drying at 75 °C after 420 min, supercritical carbon dioxide drying at 40 and 100 °C, and a combination of high-power US (US probe, 40 kHz/30 min/40 °C) and supercritical CO_2 drying after 300 min, respectively. The combination between the effect of high-power US and supercritical CO_2 raised rapidly the drying kinetic. The drying process was completely achieved in less time as a result of the ability of high US, which improved the extraction of water and made the drying process faster with less water activity. Michelino et al. (2018) declared that the drying process using a combination of high-power US and supercritical CO_2 was higher and significantly decreased

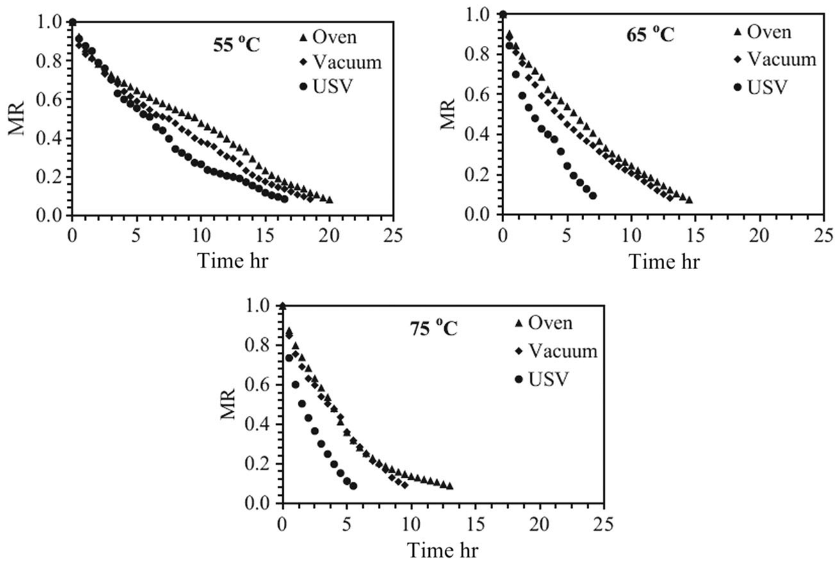

Figure 4–A moisture ratio of chicken breast meat dried by an oven, vacuum, and ultrasonic vacuum (VSV) according to Başlar et al. (2014).

the microbial load during dehydration when compared to the traditional methods.

4.2 Chilling

Chilling processes have a significant influence on the final quality of poultry carcasses, which is achieved in the poultry industry mostly using immersion in ice-water. There are two stages used in the chilling process known as prechiller and chiller. These stages result in changes in the structural and biochemical properties of chicken meat (Petrak, Kalodera, Novaković, & Gumhalter Karolyi, 1999). Flores et al. (2018) studied the effect of two operation modes (normal and sweep), and two US frequencies (25 and 130 kHz) that were used in prechilling process of chicken breast cylinders inundated in water at 10 °C for 10 min. Then, they used the best treatment (130 kHz and standard operation method) at different immersion times (5, 10, 15, 20, and 30 min). The authors concluded that the application of US in chicken breast during chilling promoted a fast and uniform cooling. US when in combination with slightly acidic electrolyzed water proved to be effective in the prechilling stage to reduce the bacterial count in chicken breasts (Cichoski et al., 2019).

4.3 Extraction

Ultrasonic-assisted extraction has been used to analyze trace organic compounds in plant and animal tissues, showing that US can increase the extraction yield (Altemimi, Choudhary, Watson, & Lightfoot, 2015; McCracken, Spence, & Glenn Kennedy, 2000; Rostagno, Palma, & Barroso, 2003; Song, Jing, Fleischmann, & Wilke, 2002; Song, Park, & Komolprasert, 2000). It has been reported that the yield extraction increases when using US due to the collapse of the micelle in the sample or matrix as ultrasonic frequencies facilitate the contact of solvents with the hydrophobic compounds (Sun, Xu, & Godber, 2006). US power also increases the contact between targeted compounds and solvent via agitating solvent of extraction, which leads to improving extraction efficiency. Besides, US prevents chemical degradation of exposed compounds. Moreover, it has been shown that chicken liver treated by US exhibited at least twice lutein value than the other treatments.

5. PULSED US

Pulsed US is one of the emerging technologies being used in poultry meat processing industry and food processing technology improving both the tenderness and the biophysical properties of meat (Saleem & Ahmad, 2016b). Pulsed US is a type of elastic mechanical oscillation with 20 kHz to 1 MHz. The oscillation of ultrasonic causes periodic compressions and enlargement in the liquid, which creates cavitation bubbles that fiercely breakdown and enlarge a few cycles, resulting in the changes in physicochemical properties (Al-Hilphy et al., 2016). Pulsed US causes waves of high shear energy with turbulence that can disturb the chemical bonds between molecules and increase sites of reaction, which indeed speed up the reaction (Aaslyng & Meinert, 2017). Hu et al. (2013) declared that pulsed ultrasonic is capable to increase the solubility and surface hydrophobicity of soy protein, which leads to altering protein rheological properties. Guzey, Gulseren, Bruce, and Weiss (2006) clarified that the molecular structure altered by pulsed US treatment led to improve surface activity and intramolecular mobility with the increase in the protein secondary structure and free sulfhydryl groups. Wang, Yang et al. (2017) examined the effect of treating chicken by pulsed ultrasonic with the power of 240 W at 0, 3, 6, 9, 12, and 15 min on the structural and rheological characteristics of chicken myofibrillar protein. The finding revealed that the viscosity coefficients decreased significantly by pulsed US treatment. Unlikely, the flow index value of chicken myofibrillar protein solution increased between 0 and 6 min, but no significant effect was observed between 9 and 15 min. The original structure of chicken myofibrillar protein did not change by using pulsed US treatment. Nevertheless, α-helix and β-sheet ratios increased as shown in Raman spectroscopy, andincreased β-turn of chicken myofibrillar protein was observed when treated by pulsed US. Applications of ultrasonic emulsification in food processing were described as the best method in food processing industry (Chandrapala, Oliver, Kentish, & Ashokkumar, 2012). In fact, the energy to form emulsifier is less than in the traditional methods, as well as the emulsion formed by ultrasonic was more stable (Chemat et al., 2011). Zhao et al. (2014) reported the use of pulsed US (US probe, 450 W, 20 kHz, 4 to 8 °C) to prepare emulsion for 6 min and found that emulsion treated by ultrasonic possessed a smaller oil droplet in addition to more regular and high density. Thus, preformed emulsion method by US is efficient and can be used to enhance gel properties of meat product with low saturated fats.

6. ADVANTAGES, DISADVANTAGES, AND LIMITATIONS OF THE APPLICABILITY OF US DURING POULTRY MEAT PROCESSING

6.1 Advantages

Several advantages of using US in meat processing have been reported (Chemat et al., 2011; Jayasooriya, Bhandari, Torley, & D'Arcy, 2004). These advantages include:

1. Efficient micromixing and mixing
2. Faster mass and energy transfer
3. Reduced gradient of thermal conditions, concentrations, temperature, and equipment size
4. Faster startup and processing
5. Higher production output
6. It needs less steps during processing
7. Alternative technology for modifying meat properties
8. Novel method to tenderize meat
9. Can help to bind meat pieces in restructured meat products
10. Eliminates microbial load
11. Reduced processing cost
12. Gives higher fineness to the final product

6.2 Disadvantages

Like each technique, US methods present some disadvantages. Few disadvantages of using US methods in meat processing have been reported (Jambrak, Herceg et al., 2014). These disadvantages include:

1. The production of free radicals, which can negatively impact and damage the product quality due to oxidation.
2. The difficulty to select the appropriate parameters (i.e., pressure, time, temperature, intensity, power, and amplitude) that are critical to obtain the desired product.

6.3 Limitations

Several limitations are associated with improving poultry meat processing (i.e., texture, juiciness, and tenderness). Issues related to meat product pickup and transportation impact negatively the juiciness and flavor of processed meat (Smith & Acton, 2001) reducing consumer satisfaction. Moreover, cooking losses result in an increase in phosphate level by 0.5% that gave a bitterness and dryness taste. Hatloe (1995) also disclosed that raw meat color treated by US was unwanted by consumers. There is a little literature about the use of US with the aim of enhancing poultry meat (Tan, De Kock, Dykes, Coorey, & Buys, 2018).

In addition, there are some limitations related to applying US technology in an industrial scale, such as the high cost of investment, deficiency related to the present regulative agreements, and lack in understanding the consumer satisfactions (Awad et al., 2012; Chemat et al., 2011).

7. FUTURE DIRECTIONS

The need to enhance microbial food safety and quality without losing functional, nutritional, and sensory properties has accelerated a growing global demand and interest in advanced food preservation technologies (Niakousari, Gahruie, Razmjooei, Roohinejad, & Greiner, 2018). US is a modern and emerging technology that has enormous promising applications in food industries specially in meat processing. Certain promising applications have been found recently, including the activation of oxidation reactions and enzyme inhibition (Delgado-Povedano & De Castro, 2015). US is being used by the sheep and pork meat industry for meat characterization purposes in both live animals and carcasses (Choi et al., 2018; Esquivelzeta, Casellas, Fina, Campo, & Piedrafita, 2017). Akbarnejad, Zerehdaran, Hassani, Samadi, and Lotfi (2015) found that ultrasonic measurements had high correlations with quail carcass traits and that US could be used as a way to evaluate yield and breast weight. We believe that these two fields—activation of redox reactions and imaging—can grow in the number of applications within the poultry science. In the latter, we have to take into account the resolution issues that US might have in poultry, as shorter wavelengths give better resolution but air compartments can seriously affect the readings. In addition, the versatility of US makes it a great partner when combining different technologies for increased food safety. We also expect improvements in the number and type of US probes, so that they become more manageable and easier to use.

8. CONCLUSION

US is a noninvasive and cost-effective technique used to improve different properties of meat, such as flavor, tenderness, and quality. Within the poultry sector, it is a promising technique that proved to be efficient in tenderizing the meat. In addition, US can also be applied to improve food safety and reduce microorganisms both during processing and conditioning of poultry samples. The characteristics of this technology make it attractive to be used in combination with other processing techniques, which presents a clear advantage to poultry meat processors. US can be applied in the processing line and can speed up some of the processes. In addition, processors will also benefit from a shelf life extension that permits longer storage and stability periods making possible to reach farther markets. Based upon the above facts, US can be, therefore, considered a promising tool for safer and higher quality poultry processing as an economically viable technology. Although US technology is a boon to food and meat processing, its industrial application by the poultry industry is still limited. Hence, future research should be carried out in this area with a view to commercial application of these technologies.

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AUTHOR CONTRIBUTIONS

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