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Review article

# Ultrasound treatment of meat: Effects on quality and potential applications

**Guillermo P. Pantuhan**[a,*], **Arnold R. Elepaño**[b], **Katherine Ann T. Castillo-Israel**[c]

[a] *Department of Agricultural and Biosystems Engineering, College of Agriculture, Mindanao State University - General Santos City, General Santos City 9500, the Philippines*

[b] *Institute of Agricultural and Biosystems Engineering, College of Engineering and Agro-Industrial Technology, University of the Philippines Los Baños, Los Baños 4031, the Philippines*

[c] *Institute of Food Science and Technology, College of Agriculture and Food Science, University of the Philippines Los Baños, Los Baños 4031, the Philippines*

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## Abstract

**Importance of the work**: Ultrasound has been recognized as a promising and green emerging technology. However, its ability to really improve existing food processing technologies has not been clearly reported.

**Objectives**: To present current studies on the effects of ultrasound on meat quality as applied in food processing technology systems.

**Materials and Methods**: A systematic review was applied based on a search strategy and analysis of recent research findings on the ultrasound treatment of meat products. The treatment effects on different quality parameters were summarized and potential applications were analyzed.

**Results**: Ultrasound application induced different physical and chemical influences on meat products, with such effects being strengths or weaknesses, depending on the processing technique and the intended meat quality. The underlying mechanism is primarily cavitation which causes degradation of proteins, enlargement of myofibrillar spaces, oxidation reactions, generation of ions and activation of enzymes. Along with microjets, the sponge effect creates microchannels in meat that enables more effective transport of materials into and out of muscle tissues. When proper ultrasound parameters are applied, the treatment can effectively improve the microstructure, pH, water holding capacity, texture, color, anti-microbial properties and sensory attributes of meat products.

**Main finding**: Important parameters must be critically investigated to scale up experimental ultrasound treatments and achieve the target quality in the final products. Most of the recent studies have used ultrasound frequencies in the range 20–55 kHz and power levels in the range 150–600 W. Duration of treatment has varied widely, depending on the type of meat and initial ultrasound settings.

* Corresponding author.
E-mail address: guillermo.pantuhan@msugensan.edu.ph (G.P. Pantuhan)



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## Introduction

The global food industry is adapting to evolving consumer preferences and demands for safe, high-quality products through technological innovation. Hurdle technology and emerging methods, such as 'green food processing', are gaining traction for their efficacy (Chemat and Ashokkumar, 2017; Boateng and Nasiru, 2019). Technologies, such as high pressure, electrical pulses, micro-filtration and ultrasonication, offer promise for food preservation but require specialized equipment and trained personnel (Alarcon-Rojo et al., 2019; Sireesha et al., 2022). Ultrasound stands out among non-thermal techniques due to its simplicity, efficiency and cost-effectiveness (Singla and Sit, 2021). It can regulate, enhance and accelerate processing without compromising food quality (Dong et al., 2022).

Ultrasound technology, characterized by sound waves above human hearing frequency, influences fluid characteristics with energy intensities in the range 10–1,000 W/cm$^2$ (Al-Hilphy et al., 2020; Barretto et al., 2023). While classified as non-thermal, ultrasound generates some heat, typically raising temperatures by 1–10°C (Zhang and Abatzoglou, 2020). It can effectively inactivate pathogens on product surfaces and preserve nutritional content (Fan et al., 2021). In meat processing, the application of ultrasound can cause several changes in the physical structure, as well as in the technological and sensory qualities of the meat (Barretto et al., 2023). However, ultrasound has had both conflicting positive and negative effects on different meat products, possibly due to the different parameters used in the research. Furthermore, the use of ultrasound in the industry has been developed on a relatively small scale (Al-Hilphy et al., 2020). Understanding optimal conditions for industrial-scale ultrasound implementation is crucial for its widespread adoption (Boateng and Nasiru, 2019).

This review aimed to explore the impact of ultrasound on processed meat quality and its potential role in various food processing techniques. A systematic literature review was applied of some research in the last 5 yr by conducting a search strategy based on "ultrasound on meat" and related keywords in different scholarly search engines, with analysis of the findings. By investigating the effects of ultrasound on food quality, this review should contribute to advancing food processing technologies to meet evolving industry demands for safe, high-quality products.

## Overview of Ultrasound

Sound is a type of pressure wave that moves in a single direction (Watson, 2015). Its classification as a sound wave is based on its frequency (Fig. 1). Infrasound is a wave with frequencies below the threshold of human hearing and is applied in submarine sonar technology. Typically, the human hearing range spans approximately 20–20 kHz (Bermudez-Aguirre, 2017). Generally, the ultrasound spectrum is divided into two zones. Power ultrasound (PUS) encompasses the frequency range from 20 kHz to approximately 1 MHz, while diagnostic ultrasound, operating at frequencies greater than 1 MHz, is primarily utilized for medical and industrial imaging purposes. The PUS spectrum can be further classified into two zones based on frequency: low-frequency (20–100 kHz) and high-frequency (>100 kHz to 1 MHz) (Villamiel et al., 2017).

In terms of energy density, PUS can be categorized into either low-intensity (LIU) with intensities less than 1 W/cm$^2$ or high-intensity ultrasound (HIU) with intensities surpassing 1 W/cm$^2$ (Bermudez-Aguirre, 2017). LIU is recognized for its non-invasive, accurate, fast, cost-effective and easily implementable characteristics (McDonnell et al., 2014), while, the energy in HIU is potent enough to disrupt intermolecular connections, and at intensities (>10 W/cm$^2$), strong cavitation occurs, capable of altering certain physical properties and promoting chemical reactions (Villamiel, 2017). Both LIU and HIU have been explored in food processing and have varying effects. Nonetheless, LIU has been generally reported as a nondestructive technique, while HIU can substantially modify the physical and chemical attributes of food products.

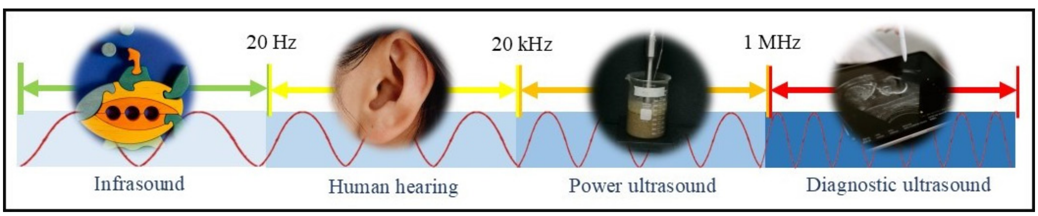


**Fig. 1** Sound spectrum

Ultrasound comprises mechanical sound waves generated through the oscillation of molecular movements within a propagation medium (Humphrey, 2007). In an ultrasound system, electrical energy is converted into vibrational energy, then ultimately into mechanical energy, which is transmitted through the medium (Berlan and Mason, 1992). Primarily, an ultrasound apparatus consists of three key components: a generator, a transducer or converter and a probe or horn. The generator supplies energy to the system, while the transducer converts electric energy from the power source into acoustic energy. Lastly, the ultrasonic bath, probe or horn emits the sound waves into the medium or sample (Santos et al., 2008).

## Cavitation Phenomenon and Sponge Effect

Ultrasound induces various effects on food materials; however, they can be categorically attributed to either the cavitation phenomenon or sponge effects (Fig. 2). Ultrasound waves promote cavitation in liquids, forming bubbles that oscillate between compression and rarefaction states, releasing energy upon collapse. This process generates localized high temperatures and pressures, reducing resistance in the boundary layer and creating hydrodynamic forces and turbulence (Flint and Suslick, 1991). Microjets produced near surfaces enhance cell membrane permeability (McNamara III et al., 1999). The collapse of cavitation bubbles produces shockwaves that can potentially damage tissues. The pulsating bubble growth further induces acoustic streaming, enhancing mass transfer and mixing on the surface. Bubble implosion can loosen molecular bonds, intensifying reactions and producing more free radicals (McDonnell et al., 2014), which can lead to chemical alterations in food. Primarily, the extent of ultrasound cavitation is influenced by the frequency and power level, with ultrasonic frequency being the key factor in determining the efficiency of ultrasonic chemical reactions (Chandrapala et al., 2012). Thus, higher levels of frequency and intensity in the ultrasound application can lead to higher cavitation effects. However, high-power, single-frequency ultrasound may damage food muscle structure (Bian, 2022). This implies that while HIU may improve processes more than LIU, this may also potentially cause greater degradation in food quality.

The principal mechanism responsible for the improved internal mass transfer facilitated by ultrasound is known as the "sponge effect". This phenomenon entails the transmission of sound waves through the food sample, resulting in the repetitive compression and decompression of the tissues (de la Fuente-Blanco et al., 2006). When ultrasound waves are applied in solid-liquid systems, they effectively damage tissues, forming microchannels that induce modifications in concentration gradients and diffusion coefficients (Carcel et al., 2007). Consequently, the sponge effect helps to maintain unobstructed microchannels for moisture transport and encourages moisture diffusion in solids (Siro et al., 2009). In a way, the sponge effect is a direct consequence of cavitation; however, the former has more influence on the internal mechanisms of food, while the latter has a more pronounced impact on food surface erosion and modifications, as well as their subsequent effects,

## Effects of Ultrasound on Meat Quality

Ultrasound has varying effects on the quality of meat. The cavitation phenomenon and sponge effects induce several physical, mechanical and chemical alterations in food, leading to changes in properties in diverse processing techniques (Table 1). Treatment parameters cited in the following discussion can be found in Table 1. Many of these effects are even conflicting, largely due to the differences in the methods conducted; however, most of the research under study has used ultrasound frequencies in the range 20–55 kHz, levels of power of 23.5–840 W and intensity of 9.6–460 W/cm$^2$, which all fall within HIU.

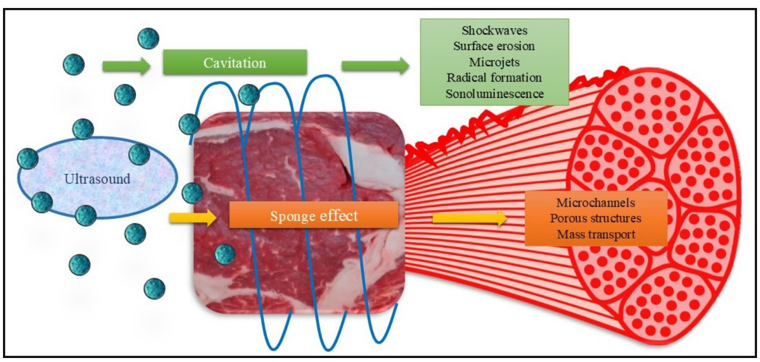


**Fig. 2** Overall effects of ultrasound on meat

**Table 1** Potential applications of ultrasound in combination or as pretreatment in meat processing

| Processing method (meat) | Treatment parameters | Effect on meat quality | | | | | Effect on processing | Reference |
|---|---|---|---|---|---|---|---|---|
| | | Microstructural changes | pH and WHC[a] | Texture | Color and sensory | Other findings | | |
| Wet salting (beef silverside *biceps femoris*) | 20 kHz, 600 W at 100 g/L, 200 g/L and 300 g/L of NaCl in water for 30 min, 60 min and 120 min | Reduced denaturation temperature of myofibrillar proteins; no effect on lipid peroxidation | No effect on pH | | Reduced lightness (L*), redness (a*), and yellowness (b*) | Increased salt content; reduced water activity | Reduced salting time; accelerated wet salting | Sanches et al. (2021) |
| L-histidine marination (bovine *semitendinosus* muscle) | 20 kHz, 300 W (15.6 W/cm$^2$) for 5 min in 1.5g/L L-histidine solution at 4–10°C | Weakened myofibrillar structure; increased actomyosin solubility | Increased pH; increased WHC | Improved tenderness | | Avoided excessive liquid withdrawal | Accelerated marination; optimized tenderness | Shi et al. (2022) |
| Sodium bicarbonate marination (chicken breast meat) | 20 kHz, 300 W at 4°C for 10 min in 6% salt and 2% sodium bicarbonate solution | Reduced myofibrillar fragmentation index (MFI) | | Reduced shear force | | Increased marinade uptake; reduced cooking loss | Accelerated marination; more tender meat | Xiong et al. (2020) |
| Wet salting (pork topside ham) | 20 kHz, 600 W in 50 g/L and 100 g/L salt-water solution for 30 min, 60 min, 90 min and 120 min | | | | | Increased salt diffusion coefficients | Shortened salting time; improve salt solution | Sanches et al. (2023) |
| Low-temperature marination (pork loin) | 23.6 kHz, 26.8 kHz, 32.3 kHz, 40 kHz and 55 kHz, 23.5 W in 55 10% NaCl solution at 6.8°C for 25 min | | Increased WHC; increased pH only at 40 kHz and 55 kHz | Reduced tenderness, hardness, and chewiness | Increased lightness; higher abundance of volatile flavor compounds | Reduced cooking loss | Enhanced marination | Guo et al. (2024) |
| Brining (pork *bicep femoris*) | 20 kHz, 350 W (31.02 W/cm$^2$) for 1 hr in 6% NaCl solution | Greater fragmentation of muscle fibers | | | | | More efficient curing process | Jin et al. (2023) |
| Brining (yellowfin tuna fillet) | 40 kHz, 840 W in 2.5%, 5.0%, 7.5% and 10% brine NaCl at 4°C for 0–120 min | | Increased WHC | Decreased hardness and chewiness; increased adhesiveness and springiness | Increased L* and b*; decreased a* | Enhanced salt diffusion more uniform salt distribution | Faster brining process | Yao et al. (2022) |

**Table 1** Continued

| Processing method (meat) | Treatment parameters | Effect on meat quality | | | | | Effect on processing | Reference |
|---|---|---|---|---|---|---|---|---|
| | | Microstructural changes | pH and WHC[a] | Texture | Color and sensory | Other findings | | |
| Salting (*Culter alburnus* fish fillet) | 40 kHz, 0 W, 100 W, 150 W, 200 W, 250 W and 300 W for 15 min at 20±1°C in 1.5% salt solution | Intensified structural degradation of muscle fibers | | Increased hardness and chewiness | Enriched flavor compounds | | | Liu et al. (2022) |
| Brining (pork leg sub-primals) | 37 kHz, 22 W/cm$^2$ for 0 min, 10 min and 30 min in 10% NaCl solution | | Increased pH and WHC | Reduced shear force | No change in color; decreased acceptance due to saltier perception | Reduced drip losses up to 50% | Generally positive pre-treatment method | Garcia-Galicia et al. (2022) |
| Papain treatment (bovine *semitendinosus* muscle) | 40 kHz, 460 W/cm$^2$ for 15 min, 10±1°C at 100 TU/mg of papain | Reduced stability and integrity of microstructure; degradation of actin, myosin, and troponin complex | Increased pH | Improved tenderness | | | Improved tenderization, especially when ultrasound is applied prior to enzyme treatment | Marino et al. (2023) |
| Papain treatment (spent-hen breast meat) | 40 kHz, 300 W for 10 min, 20 min, 40 min and 80 min at 45 U/g of papain | Destroyed muscle fibers | Increased WHC | Reduced shear force | Increased brightness (L*) | Reduced drip loss; increased cooking loss | Improved quality at <20 min application time | Cao et al. (2021) |
| Leek extract treatment (bovine *Longissimus lumborum*) | 100 W and 300 W for 10 min, 20 min and 30 min at 16.9 and 33.8 U/mg of leek-derived proteases | Severely degraded muscle proteins | Increased water binding capacity (WBC); reduced pH at 300 W but no effect at 100 W | Reduced shear force and hardness | | Reduced filtering residues; increased emulsion capacity and stability | Improved tenderization; increased proteolytic activity | Mehrabani et al. (2022) |
| Collagen peptide treatment (chicken breast meat) | 20 kHz, 200 W (15.6 W/cm$^2$) for 5 min at 4°C and collagen peptide solution of 0.15g/100mL | | | Decreased hardness; increased elasticity | No effect on color | Reduced drip loss and cooking loss | | Zou et al. (2022) |
| Cooking (spiced beef) | 20 kHz, 400 W, 600 W and 800 W for 120 min cooking time in boiling spice solution | Decreased total volatile basic nitrogen (TVB-N) and slow rise in thiobarbituric acid (TBARS) during storage | Slowed decline of pH during storage | Reduced hardness and chewiness | Reduced lightness (L*), a* | Decreased total viable count | Maintained quality during storage | Zhang et al. (2021) |

**Table 1** Continued

| Processing method (meat) | Treatment parameters | Effect on meat quality | | | | | Effect on processing | Reference |
|---|---|---|---|---|---|---|---|---|
| | | Microstructural changes | pH and WHC[a] | Texture | Color and sensory | Other findings | | |
| Cooking (broiler meat) | 40 kHz, 120 W/cm² at 50°C, 60°C, 70°C and 80°C | Lower TBARS at 50°C | No effect on pH | Increased tenderness | Increased lightness; higher sensory scores at higher temperature | Reduced cooking loss at higher temperature | Improved meat quality upon cooking | Ashar et al. (2022) |
| Low-temperature short-time heating (yellow-feathered chicken breast meat) | 40 kHz, 0.2 W/cm² at 55°C for 15 min | Reduced degradation of proteins; reduced lipid oxidation | | Maintained texture | | Inactivation of proteases; inactivation of microorganism | Maintained meat quality during storage | Li et al. (2021) |
| Fresh storage (bovine *longissimus lumborum*) | 37 kHz and 90 W/cm² (bath), and 24 kHz and 400 W (probe) for 25 min and 50 min; 4°C storage temperature | Higher area of interfibrillar spaces | Decreased WHC; no significant difference in pH | Improved tenderness | Increased lightness (L*) | Increased counts of total aerobic and coliform bacteria | Improved meat quality; increased lactic acid bacteria counts in the bath system | Carrillo-Lopez et al. (2022) |
| Freezing-thawing (bovine *longissimus dorsi*) | 45 kHz, 160 W, 240 W, 320 W and 400 W for 30 min at 4±1°C | | Increased WHC (highest at thawing) and pH | Reduced hardness; improved springiness | | | Improved meat quality upon thawing | Wang et al. (2021) |
| Chilled storage (chicken breast meat) | 40 kHz, 9.6 W/cm² for 0 min, 30 min and 50 min at 4°C | | | | | | | Piñon et al. (2020) |
| Plasma-activated water (chicken muscle, rough skin and smooth thin skin) | 40 kHz, 200 W for 30 min, 45 min and 60 min at 4°C, 25°C and 40°C, and 309 µL, 580 µL, 846 µL and 1160 µL PAW | No effect on protein and lipid oxidation | Reduced pH | | No effect on sensory qualities | Reduced microbial load | Maintained quality | Royintarat et al. (2020) |
| Thawing (large yellow croaker) | 20 kHz, 28 kHz and 40 kHz, 0.9W/L at 20±1°C (from -18±1°C frozen state) | Maintained stability of myofibrils; reduced lipid oxidation | Increased WHC | Higher hardness, springiness, resilience and chewiness | No significant change in color | Lower thawing and cooking loss | Increased thawing rate (greater when multifrequency) | Bian et al. (2022) |
| Saline thawing (mirror carp) | 200 W at 10°C (from -18°C) in 0.05%, 0.10% and 0.20% salt solutions | Inhibited oxidation reactions | | Decreased shear force but better texture than air-thawed samples | No significant change in color | Lower thawing and cooking loss | Faster thawing rate; better quality of meat after thawing | Li et al. (2022) |

**Table 1** Continued

| Processing method (meat) | Treatment parameters | Effect on meat quality | | | | | Effect on processing | Reference |
|---|---|---|---|---|---|---|---|---|
| | | Microstructural changes | pH and WHC[a] | Texture | Color and sensory | Other findings | | |
| Ultrasound-assisted thawing (common carp) | 30 kHz, 0 W, 100 W, 300 W and 500 W at 4°C (from -18°C) | | | | Increased L* and b* (except) at 300 W; decreased a* | Increased thawing and cooking loss; loss of immobilized and free water | Accelerated thawing process | Sun et al. (2021) |
| Convection drying (Asian seabass fish skin) | 32 kHz, 150 W for 30 min, then at 45°C, 55°C and 65°C drying temperature | More porous microstructure | | | | Lower activity | Increased drying rate; reduced specific energy consumption | Fikry et al. (2023) |
| Drying (tilapia) | 40 kHz, 130 W for 15 min and 30 min in 10% salt solution, then drying at 35±2°C and 1.3 m/s air velocity | More porous structure | | | | Decreased Aw | Decreased drying time | Rios et al. (2020) |

[a]WHC = water holding capacity.

*Protein*

Meat, comprising muscle fibers and intramuscular connective tissue, undergoes structural changes during ultrasound treatment. Generally, it has been reported that HIU assisted in the degradation, as well as conformational changes, in the proteins present in meat.

One of the indications of protein degradation is an increase in the myofibrillar fragmentation index (MFI) in treated meat such as spent-hen breast meat, brined pork and marinated chicken breast meat (Table 1). MFI is a measure of the average length of myofibrils; this implies that a shorter length of myofibrils indicates greater meat tenderness. After treatment, muscle fibers are damaged, as manifested by the different sizes and shapes of myofibrillar structures (Cao et al., 2021) HIU helps to accelerate the hydrolysis of proteins that promotes the cleavage and solubilization of myofibrillar proteins, as well as the dissolution of sarcoplasmic proteins (Xiong et al., 2020; Jin et al., 2023). It results in the disappearance of myosin heavy chains and alpha-actinin (Marino et al., 2023) and the degradation of desmin and troponin-T (Wang et al., 2021). Increased MFI in ultrasonicated meat has been directly correlated to increasing ultrasonic power and application time (Kang, 2017). From the referenced materials, excessive protein degradation occurs at ultrasound power levels >300 W, while at lower power levels, modifications only occur on the surface.

Furthermore, the microjets brought about by ultrasonic cavitation results in decreased temperature and enthalpy of protein denaturation, which produces structural instability in the proteins (Sanches et al., 2021). The protein conformational changes with unstable structure expose disulfide bonds, thereby increasing the presence of the sulfhydryl group which is related to Ca2+-ATPase activity (Shi et al., 2022). Generally, these changes also result in an increase in the pleated β-sheet structure and a decrease in the α-helix helical structure of the proteins (Sanches et al., 2021). Ultimately, such improvements in the myosin structural properties reduce the dense aggregation of muscle proteins and improve water retention (Bian et al., 2022).

In addition, ultrasonicated meat has a greater gap or space between myofibrillar proteins (Marino et al., 2023; Liu et al., 2023), larger pores between muscle fibers (Wang et al., 2021; Xiong et al., 2020) and extensive myofiber swelling (Shi et al., 2022). The mechanical effects of ultrasound cavitation could loosen tightly connected myofibrils, as well as erode tissue surfaces. This can cause altered structures of sarcomere, especially around the I-band and the Z-line. Furthermore, HIU can change protein conformation by burying the acidic groups. This change causes myofibrillar proteins to move further from their isoelectric point, creating space between myofilaments. The decreasing strength of myofibrils also creates microchannels that cause the swelling effect (Shi et al., 2022). Thus, changing protein structures from applying ultrasound promotes separation of muscle membranes (Xiong et al., 2020). In the ultrasound-assisted plasma-activated water (UAPAW) treatment of chicken meat, the meat surface became more porous with ultrasound; however, the surfaces of rough and smooth skin did not change because of their denser structures (Royintarat et al., 2020). After ultrasound-assisted papain treatment of chicken breast, the gaps between myofibrils became wider and they displayed a greater degree of dissolution, particularly after 80 min of application time (Cao et al., 2021). In dried seabass fish skin subjected to ultrasound pretreatment (USP), the formation of microchannels increased the porosity of the meat, resulting in the more rapid removal of water and the release of materials such as exudates, fats and collagen (Fikry et al., 2023). This was also observed in dried tilapia subjected to USP, which resulted in a porous structure with large and irregular cavities (Rios et al., 2020).

Furthermore, ultrasound induces degradation of structural proteins such as collagen. Collagen is the primary component of connective tissues and is mainly responsible for the inherent toughness of slaughtered meat. Ultrasonicated meat was observed to have higher soluble collagen content, since the mechanical force and heat generation from cavitation bubbles helped in opening the collagen fibers, as well as in their denaturation. Greater collagen solubility has been linked to higher power intensity (Marino et al., 2023). In dried seabass skin following USP, there were no globules of lipid droplets or collagen matter detected along its cross-section, indicating that ultrasonic cavitation had aided in the destruction of fat and collagen molecules (Fikry et al., 2023).

Endogenous enzymes in meat are also reported to be activated by HIU. Meat contains proteolytic enzymes, such as cathepsins and calpains, which contribute to the degradation of postmortem meat. The implosion of cavitation bubbles during HIU disrupts cell walls and lysosomes, leading to the release of lysosomal enzymes, such as cathepsins, and calcium ions from the sarcoplasmic reticulum (Mehrabani et al., 2022). Since the activity of calpains depends on calcium ions, their activity increases with the rising release of calcium through cavitation (Shi et al., 2022). Once activated, these endogenous enzymes further increase the degree of myofibril fragmentation by cleaving the peptide bonds inside the proteins, which leads to the production of macromolecular molecules (Jin et al., 2023). Other cellular protease systems could also accelerate cellular biochemical reactions, causing further disintegration of myofibrils and connective tissues (Cao et al., 2021).

On the other hand, the microstructure of ultrasonicated meat products may be affected by changes in the tertiary and quaternary structures of proteins, leading to reversible or irreversible denaturation. This can cause aggregation between molecules and other meat compounds to form a three-dimensional network through crosslinking (Sanches et al., 2021). In stored spiced beef which had undergone ultrasound-assisted cooking (UAC), the protein degradation was lessened during storage compared to untreated samples. The total volatile basic nitrogen (TVB-N) in ultrasonicated meat did not change significantly during storage. TVB-N is mainly associated with ammonia and the amines produced by the breakdown of animal proteins by autolytic enzymes and spoilage bacteria. Aggressive free radicals produced after HIU can slow down autolytic enzymes and microbial actions, resulting in decreased protein degradation (Zhang et al., 2021). The lower the TVB-N value, the less destruction of tyrosine and methionine occurs in the protein, indicating better nutrient preservation (Bian et al., 2022). In the case of ultrasound and low-temperature short-time heating (ULTSTH) of chicken meat, proteolytic activity was not detected; thus, the treated samples had low levels of protein degradation. The myofibrillar bundles were intact, and there were no noticeable changes in the membrane of muscle fibers during the whole storage period (Li et al., 2021). Following ultrasound-assisted thawing (UAT) of large yellow croaker fish, the treated samples had lower values of TVB-N than air- or water-thawed meat, indicating less protein degradation and nutritional loss in these UAT samples (Bian et al., 2022). Similarly, lower TVB-N values were observed in mirror carp that has undergone ultrasound-assisted saline thawing (UAST). HIU promoted the entry of salt ions into the meat, which, in turn, inhibited the growth of microorganisms and the formation of protein aggregations (Li et al., 2022). Following UAT of common carp, microstructural damage was only apparent after applying a high ultrasound power level. In the 100 W and 300 W groups, only the outer membrane of the muscle was damaged, with the interior remaining relatively intact. At 500 W, the muscle bundle space was larger, with the inner structure receiving more damage (Sun et al., 2021).

### *Lipids*

Generally, it is accepted that cavitation from ultrasound can promote lipid oxidation in foods by forming free radicals, which accelerate oxidative reactions (Alarcon-Rojo et al., 2019). Moderate lipid oxidation is beneficial to the formation of the unique flavor of sauced pickled beef; however, an excessive oxidation reaction can lead to nutrient loss, meat spoilage and off-flavor generation (Zhang et al., 2021). The formation of these free radicals depends on various factors such as the temperature of the wet salting process, the type and amount of osmotic agent and ultrasound parameters such as frequency, power and the distance between the probe and the meat (Inguglia et al., 2018). Applying UAC to broiler meat, the ultrasonicated samples at higher cooking temperature had the highest thiobarbituric acid reactive substances (TBARS), which are formed as a by-product of lipid peroxidation. The high TBAR values were also linked to temperature 'hot spots' caused by ultrasonic cavitation (Ashar et al., 2022). Following -assisted salting (UAS) of *Culter alburnus* fish, the TBARS values for the treated meat were generally higher than for the control group, reaching twice as much for the 300 W group (Liu et al., 2023).

Following UAS of beef silverside *biceps femoris*, it was found out that the ultrasound had had no effect on lipid oxidation. This was attributed to the magnitude of the ultrasound power (600 W) in relation to the larger distance used between the ultrasonic probe and the samples (Sanches et al., 2021). Similarly, there were no significant differences in lipid oxidation between UAPAW-treated and untreated chicken meat, since the ultrasound power (200 W) was deemed too low to induce oxidation, even in proteins (Royintarat et al., 2020).

Following UAC of beef, the rate of lipid oxidation was reduced compared to untreated meat, and it only showed a slightly increasing trend during the entire storage period (Zhang et al., 2021). Similar observations were reported for chicken meat pretreated with ULTSTH, where the TBARS values only showed moderate growth during storage. This was attributed to inactivation of lipoxygenase activities. Similarly, the degree of protein oxidation was reduced compared to untreated samples, evident as the low presence of protein carbonyls, which can be generated from the direct oxidation of the side chains of the amino acid residues, from oxidative fragmentation of the backbones of the polypeptide chains and from lipid oxidation (Li et al., 2021). The faster rate of thawing also discouraged oxidation reactions in UAT-treated mirror carp (Li et al., 2022). In addition, Guo et al. (2024) reported a minimal degree of lipid oxidation in pork loin following ultrasound-assisted low-temperature marination (UALTM).

### *pH*

The biochemical mechanisms that drive changes in postmortem meat are pH dependent, with a higher pH level being beneficial for liquid retention in meat (Dong et al., 2022). After HIU, the pH increased in *semitendinosus* muscles in beef, pork leg sub-primals and large croaker (Table 1). The rise in pH can be attributed to changes in the protein structure. The bubbles generated by cavitation can increase the surface pressure on the sample, induce the reaction of the protein side chain, cause protein denaturation and decrease the acidic groups of protein (Wang et al., 2021) or result in exposure of more basic groups (Zhang et al., 2021). In addition, ultrasonic cavitation releases the amino acids and basic amines in meat (Marino et al., 2023), and breaks the bonds involving imidazole, hydroxyl and sulfhydryl groups (Bian et al., 2022).

The mechanical damage during HIU causes the release of ions from the cellular structures into the cytoplasm (Garcia-Galicia et al., 2022). Beef muscle that had been marinated with ultrasound-assisted L-histidine enabled greater exchange of the marinade solution with the internal media in the tissue which to some degree increased the muscle pH and released salt-soluble proteins onto the tissue surface (Shi et al., 2022).

On the other hand, there have been reports on decreased pH levels in ultrasonicated meat, such as *longissimus lumborum* muscle in beef. The application of 300 W reduced the meat pH, while lower power levels did not produce any significant effect. Similarly, 30 min HIU resulted in decreased pH, while shorter application times of 10 and 20 min increased the pH of the meat. The reduction in pH can be linked to a shift in the position of ion groups in the tissue which can boost the meat's buffering capacity, thereby preventing a major pH change (Mehrabani et al., 2022). Following UAPAW of chicken meat, the pH was lowered mainly because of the activated water used (Royintarat, 2020). Following UAST of mirror carp, the low pH readings were associated with the accumulation of inorganic phosphoric acids and lactic acid, produced by the destruction of adenosine triphosphate and glycolysis under anaerobic conditions in muscles during the freezing-thawing process (Sun et al., 2021). With UAC spiced beef, there was only a slight decrease in the pH value of each ultrasonic group compared to the untreated samples. This was attributed to the limited microbial metabolism and the dissolution of $CO_2$ into water. These results implied that HIU could help stabilize pH levels and slow the onset of rancidity during cold storage (Zhang et al., 2021).

There were no pH changes in marinated pork loin treated with low-frequency ultrasound (23.6 kHz, 26.8 kHz and 32.3 kHz) but the pH increased at 40 kHz and 55 kHz. At lower ultrasonic frequencies, mechanical oscillations and cavitation are more prominent, which could inhibit microorganism metabolism and decomposition of reducing protein and amino acids, resulting in fewer alkaline substances being produced. On the other hand, at higher frequencies, fewer acidic groups could react with the free radicals generated by ultrasound, resulting in an increase in the pH (Guo et al., 2024). It has been argued that though the change in pH was statistically significant, the actual values were numerically close and so the treatments may have had only a slight effect on meat quality, with the small difference perhaps being linked to meat type, stiffness time and ultrasonic characteristics (Jayasooriya et al., 2007).

### *Water holding capacity*

The ability of meat to retain moisture is considered one of its most important quality parameters. Most of the water in the meat muscle is held within the myofibrils, between the myofibrils, between the myofibrils and the cell membrane (sarcolemma), between muscle cells and between muscle bundles (Huff-Lonergan and Lonergan, 2005). Thus, a high water holding capacity (WHC) in meat is desirable.

Increased WHC after HIU has been observed in *Longissimus* and *semitendinosus* muscles in beef, spent-hen breast meat, pork leg sub-primals, pork ham, *Culter alburnus* fish, brined tuna and large yellow croaker (Table 1). One of the factors affecting WHC is the meat pH level. A drop in the pH causes shrinkage of polypeptide chains which decreases the WHC. As consequence of a higher pH level due to structural changes from ultrasonic cavitation, the number of ionized amino acid groups increases, as well as the polarity of the proteins. This results in the binding of hydrogen bonds with free water in the tissue (Mehrabani et al., 2022). In addition, structural modifications cause the bound water in cells to bind more tightly with proteins and other molecules (Cao et al., 2022; Guo et al., 2024). At the same time, there is an increase in the thickness of muscle fibers and in the myofibrillar diameter where more water can be retained (Mehrabani et al., 2022). The rupture of myofibrils also precipitates more salt-soluble proteins, which could increase the content of immobilized water (Cao et al., 2022; Bian et al., 2022; Zou et al., 2022), as well as hinder water migration out of muscle tissues (Liu et al., 2023). Furthermore, ultrasound induces oxidation of myosin, causing polymerization that may help in improving the WHC (Yao et al., 2022).

The improvement in the WHC of ultrasonicated meat may also be attributed to the formation of small, uniformly structured spaces between myofibrillar proteins caused by cavitation. This causes the gel microstructure to become denser and more uniform, which can firmly hold water molecules (Garcia-Galicia et al., 2022). Likewise, the increase in myofibrillar gaps is helpful to form complex protein network structure which is conducive for retaining water (Wang et al., 2021). During marination, the solution-trapping capacity of myofibrils is also enhanced due to the water-retaining and cohesiveness-enhancing properties of salt-soluble proteins. Additionally, the ultrasound-modified gel structure with higher electrostatic repulsion further improves this capacity. In other words, the more tightly trapped water in the meat was retained, accompanied by lower fluid losses in meat (Shi et al. 2022).

On the other hand, a lower WHC was reported in ultrasonicated meats such as for the *longissimus lumborum* in beef. A decrease in the WHC significantly reduced the juiciness and performance. The reduced WHC was more pronounced using a longer application time (50 min) which could have caused disruption of micro-channels in the intermyofibrillar spaces (Carrillo-Lopez et al., 2022). This was also observed in ultrasonicated chicken breast meat where a longer application time (>40 min) negatively affected the WHC (Cao et al., 2021).

### *Texture*

Tenderness, hardness and other texture qualities of meat have had varied responses to ultrasound treatment. Improved tenderness is commonly manifested as a decreased shear force in ultrasonicated meat. The reduction in hardness by ultrasound may be due to the mechanical rupture of myofibrillar protein structures (Zhang et al., 2021; Garcia-Galicia et al., 2022), an increase in the gap between muscle filaments (Zou et al., 2022) or the activation of calpains and cathepsins that promotes the degradation of myofibrillar proteins (Xiong et al., 2020; Wang et al., 2021; Mehbarani et al., 2022). The higher pH value in treated meat, to some extent, maintained the calpain activity for continuous tenderization (Shi et al., 2022). When combined with exogenous enzymes, the synergistic effect further degraded myofibrils and connective tissues, including collagen macromolecules (Cao et al., 2021). Following the ultrasound-assisted brining (UAB) of tuna, the destruction of tissue structures and production of micro-channels not only reduced hardness but also improved adhesiveness in the meat (Yao et al., 2022).

While some studies have reported that tenderness in ultrasonicated meat improved regardless of the treatment time (Carrillo-Lopez et al., 2022), other findings claimed that the effect of ultrasound on the hardness depended on both the time and the power level, such as increasing the power from 100 W to 300 W and the application time from 10 min to 30 min further reduced hardness in beef (Mehbarani et al., 2022). In common carp, the lowest shear force was recorded in meat following UAT at 500 W (Sun et al., 2021).

Following UAS of *Culter alburnus* fish, the meat remained hard after ultrasound at 100–250 W. There was only a significant reduction in hardness at 300 W, possibly due to excessive destruction of muscle fibers and protein degradation (Liu et al., 2023). In spiced beef, the decline of hardness was delayed in the ultrasonic groups compared to the control group. Applying 800 W produced no significant change in the hardness (Zhang et al., 2021). Similarly, chicken muscle and skin following UAPAW showed no changes in hardness because the applied power (200 W) may have been too low to alter texture (Royintarat et al., 2020).

Following the ULTSTH of chicken meat, there was a significant improvement in maintaining textural quality due to inactivation of endogenous proteases (Li et al., 2021). Following UAT of large croaker fish, texture in multifrequency ultrasound-assisted thawed fish showed better texture and greater hardness, with levels almost the same as in fresh samples. It was theorized that denaturation of myofibrillar proteins from cavitation had fewer adverse effects on the fish texture upon ultrasound-assisted thawing than from air-thawing or water-thawing; thus, the treatment was more able to maintain fish quality (Bian et al., 2022). Following UAST of mirror carp, the reduced hardness was due to the destruction of muscle fibers by the formation of ice crystals. However, treated samples had significantly higher shear force than air-dried samples, implying that the treatment was able to maintain the textural properties of fish (Li et al., 2022).

## *Color*

Color is an important factor in meat quality since this is the immediate characteristic seen by consumers. It is affected by the protein structure in meat, by the chemical state of myoglobin and by lipid oxidation (Nair et al., 2017). Following HIU, there was a reduction in lightness (L* in the CIELab scale) in some meat products such as silverside *biceps femoris* muscle in beef, cooked broiler meat, spiced beef and pork ham (Table 1). The pro-oxidative effect of HIU affected the integrity of the meat cell membrane, thereby facilitating the release and oxidation of molecules with Fe ions such as heme proteins (Sanches, 2021). HIU could also limit oxymyoglobin formation and decrease metmyoglobin production (Ashar et al., 2022). Higher ultrasonic power could also produce more heat and non-enzymatic browning, (mainly via Maillard and caramelization reactions) that could decrease the lightness value in meat (Zhang et al., 2021). Following UALTM of pork loin, the higher pH values in the meat facilitated the elution of myoglobin from the muscle, resulting in more rosy-colored meat (Guo et al., 2024). Following UAB of tuna, the increase in L* was attributed to the loss of water that decreased the surface moisture of the meat and its degree of light scattering (Yao et al., 2022). Following UAT of mirror carp, the reduction in L* was very pronounced at 500 W, which was considered excessive enough to destroy muscle structures (Sun et al., 2021).

The decrease in redness of spiced beef during storage could be explained by the formation of more metmyoglobin. After vacuum packaging, all samples are in a state of low oxygen content, which encourages the transformation from myoglobin to metmyoglobin. In addition, fat oxidation could contribute to the formation of more metmyoglobin (Zhang et al., 2021). When meat is soaked in an aqueous solution, myoglobin will be diluted since it is a water-soluble compound, leading to decreased redness (a*), as observed in UAB-treated tuna (Yao et al, 2022).

Other studies have reported the intensification of the color in meat and processed products. For example, with chicken meat, the improved action of papain due to ultrasound destroyed the coordination residues of heme, with the hemoglobin being converted to methemoglobin (Cao et al., 2021).

On the other hand, color was not significantly affected by HIU, following the UAB-treatment of pork sub-primals. It was hypothesized that the low ultrasound power level may not have been sufficient to denature the proteins and pigments (Garcia-Galicia et al., 2022). Following UAT of croaker fish, the light scattering caused by ice crystals changed the L* value but not by enough to cause color improvements (Bian et al., 2022). Following UAST of mirror carp, both ultrasound and salting helped to decrease water loss in the extracellular space of muscle tissues, thereby inhibiting color changes (Li et al., 2022).

### *Sensory attributes*

Following UAC of broiler meat, the ultrasonicated samples cooked at higher temperature had more flavor, juiciness and tenderness, as well as higher acceptability. In marinated pork ham, ultrasound enhanced volatile flavor substances such as aldehydes, ketones, and alcohols. The formation of these compounds is closely linked to lipid-related chemical reactions such as lipid oxidation and hydrolysis (Guo et al., 2024). In *Culter alburnus* fish, the samples treated with 200 W ultrasound exhibited fewer fishy substances, such as hexanal, 1-pentene-3-ol and 1-octane-3-ol, but along with the 300 W group, contained more umami taste-related amino peptides. Overall, the amino acids, carbohydrates and fatty acids metabolism products were enriched by ultrasound in the salted fish (Liu et al., 2023).

The overall flavor profiles of spiced beef were assessed using an electric nose, with the findings showing that at the highest ultrasound power of 800 W, there were less obvious variations in the detected flavors. This implied that PUS could delay original flavor changes and increase the shelf life of the product (Zhang et al., 2021). In UAPAW-treated chicken meat, there were no significant differences in appearance, color, texture and acceptability compared to untreated meat, Thus, the treatment maintained the sensory quality of the meat (Royintarat et al., 2020).

In contrast, HIU treatment of marinated pork leg sub-primals was less preferred than the control meat, which was attributed to the saltier flavor of the treated meat (Garcia-Galicia et al., 2022).

### *Anti-microbial properties*

In fresh bovine *longissimus lumborum*, there was a decrease in the microbial count immediately after HIU; however, the count increased during later storage. The increase of mesophiles was greater in lower frequency HIU; however, the application time had no effect, which may have been due to the vacuum packing which seemed to prevent effective cavitation from inhibiting microbial growth. In addition, there was an increase in the level of lactic acid bacteria which are beneficial as they have an antagonistic effect against pathogenic bacteria (Carrillo-Lopez et al., 2022). In chicken meat, the number of mesophilic bacteria increased after sonication, regardless of the packaging method. Aside from reduced wave penetration, the nutrients released in meat by HIU could promote the growth of mesophiles. However, HIU for 50 min was effective in the removal of *Staphylococcus aureus* and *Salmonella* spp.; hence, it could be an effective means of controlling the growth of pathogenic bacteria (Piñon et al., 2020). In addition, the bacterial counts for *E. coli* and *S. aureus* were also reduced in UAPAW-treated chicken meat (Royintarat et al., 2020).

HIU was able to effectively inhibit growth of microorganisms in spiced beef, as evidenced by the low total viable count (TVC). TVC is an important index that reflects the spoilage degree of meat products. Microorganisms can rapidly grow and reproduce by using abundant nutrients. Since cavitation effects due to ultrasound can destroy the DNA and cell membranes of microorganisms, there was no substantial change in the TVC during the complete duration of storage of the product (Zhang et al., 2021). In addition, TVC values did not increase in pork ham following UALTM treatment (Guo et al., 2024), while the TVC was undetectable even after 9 d of storage following ULTSTH of chicken meat (Li et al., 2021), emphasizing the potential of ultrasound to extend the shelf life of meat.

### *Water activity*

Water activity (Aw) is one of the main parameters used to evaluate the quality, safety and shelf life of meat products such as dried fish and cured meat. A low Aw is desirable since it signifies less availability of moisture for microbial growth that can lead to spoilage. Lower Aw values have been observed in ultrasound-treated meat, including salted beef (Sanches et al., 2021), dried tilapia (Rios et al., 2020) and dried seabass skin (Fikry et al., 2023) than in untreated samples. This was attributed to the formation of microchannels in the meat that enhanced mass transfer, consequently reducing microstructural collapse and facilitating faster removal of water during drying (Fikry et al., 2023).

## Potential Applications of Ultrasound in Meat Processing

With the influence of ultrasound on different meat quality parameters, mostly attributed to cavitation phenomenon and the sponge effect, HIU could possibly be integrated into existing food preparation procedures to speed up processes and improve food quality and acceptability.

*Marination and brining*

When applied to meat, ultrasound treatment induces both cavitation and the sponge effect that facilitate better mass transfer between a marinade or brine solution and the moisture and soluble components in meat. The larger myofibrillar spaces, extensive myofiber swelling and loosening of microstructure were considered to contribute to microchannels that conveniently permitted easier transport of materials (Shi et al., 2022), micro-injections on the meat surface (Garcia-Galicia et al., 2022) and a more uniform distribution of the salt (Yao et al., 2022) which is more enhanced at higher ultrasound intensity. The sponge effect also forces air trapped in the pores of the meat to escape and be replaced with brine (Sanches et al., 2020). Additionally, cavitation-induced damage in tissues releases tenderizing enzymes and deposition of salt-soluble proteins on meat, thereby tenderizing and enhancing meat (Guo et al., 2024). The application of ultrasound in the marination of chicken meat with sodium bicarbonate enabled 26.71% higher marinade uptake (Xiong et al., 2020) and reduced the brining time of tuna to one-half that for plain tuna brining (Yao et al., 2022). However, excesses in treatment parameters could lead to undesirable effects such as irreversible protein denaturation, too much salt content in the meat (Sanches et al., 2021) and a saltier perception in the taste (Garcia-Galicia et al., 2022).

Many of the recent studies have focused on ultrasound frequencies within the range 20–40 kHz, since this is sufficient to impart changes to the meat. Although higher frequencies generate more cavitation bubbles, these bubbles are smaller and collapse with less energy (Chandrapala et al., 2012); thus, they may not be effective in inducing the sponge effect and speeding up mass transport. The ultrasound power applied is usually within the range 300–600 W, since a lower power application may need to be combined with other methods such as heating (Guo et al., 2024) to effectively yield improved product quality. Furthermore, higher power levels will cause excessive nutritional losses and even increased hardness in the salted product (Liu et al., 2022). The literature is unclear regarding a suitable application time, with the available data being quite varied, depending on the meat type, solution used and prior ultrasound settings. Generally, desirable properties for brined products from tender meat, such as fish, require less ultrasound application time (<15 min), with much longer times for tougher types of meat.

*Enzyme treatment*

Ultrasound can increase the enzymatic and proteolytic activity levels in the meat, which can have a double effect on the dissolution of connective tissue proteins, thereby resulting in a more efficient tenderization process (Mehrabani et al., 2022). Generally, an ultrasound treatment before any enzyme treatment results in better tenderization effects because the increased myofibrillar spaces allow better penetration of the enzyme solution. On the other hand, ultrasound can have modulating effects when applied after the enzyme treatment, since HIU may break down the enzyme and reduce proteolytic activity on myofibrillar proteins (Marino et al., 2023). The ultrasound time may be crucial in combining HIU with enzyme treatment. For example, with n chicken meat, excessive cooking loss was recorded at 80 min, with the optimum time being 10–20 min (Cao et al., 2021). In beef, enzymatic activity decreased when the ultrasound time was increased from 20 min to 30 min (Mehrabani et al., 2022). Hence, such variations in results could suggest that the sonication time needs to be carefully studied to render the enzyme treatment effective without causing hyper tenderization.

*Dehydration*

When ultrasound is applied as pretreatment to convection drying, the altered properties of the sonicated meat may help to accelerate the drying process. The conformational changes of proteins during ultrasound treatment allow them to be denatured more easily, so that with the formation of microchannels and large pores, there is a more rapid removal of water from the meat during drying (Sanches et al. (2021). In drying seabass skin, ultrasound pretreatment reduced the drying time by approximately 19–28% and specific energy consumption by 22% (Fikry et al., 2023). Similarly, dried tilapia with ultrasound pretreatment for 15 min reduced the drying time by 19.2%, and by 8.7% for 30 min (Rios et al., 2020). However, longer application time may have drawbacks because of possible greater water retention and diffusion of solutes into the meat. Hence, further investigation is required regarding the suitable combination of ultrasound power and its application time for different meat types.

*Cooking*

Due to the higher WHC in ultrasonicated meat, there is generally a major reduction in cooking loss. As discussed earlier, a high WHC in treated meat is caused by structural changes in proteins, increased ionization and wider myofibrillar gaps where more water and salt can be retained. The increased solute and moisture gain in ultrasonicated meat prevent muscle fibers from shrinking and forcing out water during cooking (Garcia-Galicia et al., 2022). The WHC is largely affected by increasing the level of ultrasonic power, which results in increased cooking loss, with ultrasound power at 500 W reportedly greatly disrupting the muscle structure and severely reducing the WHC (Sun et al., 2021). HIU duration is also an important factor, since a longer application time can negatively affect the WHC.

### *Thawing*

Generally, ultrasound-assisted thawing is faster than air-thawing or water-thawing, since ultrasonic cavitation accelerates the melting of ice crystals and enhances the transformation of heat during the thawing process (Bian et al., 2022). Hence, ultrasound can improve the heat transmission efficiency and thawing rate (Li et al., 2022). Consequently, a shortened thawing time produced less thawing loss, since the growth of microorganisms and the oxidation of proteins and fats were also minimized (Sun et al., 2021). Salting, results in the salt mixed in the liquid medium increasing the ionic strength of muscle tissue that in turn could improve the binding ability between protein and water (Li et al., 2022). For common carp, the thawing time was reduced by as much as 39.88% using 500 W ultrasound power, although the thawing loss increased. The optimum level was 300 W, with thawing loss increasing significantly at 500 W (Sun et al., 2021). As observed, it is necessary to determine the effective combination of ultrasound power and time to prevent excessive losses during thawing.

## Conclusion

In general, ultrasound has immense potential in various meat processing techniques, since it can substantially improve meat quality. It induces cavitation in the medium that can cause protein degradation, widening of myofibrillar gaps, oxidation reactions, ionization and activation of proteases. Its sponge effect generates microchannels that can efficiently facilitate mass transport of water, solute and soluble materials in meat. Depending on the process and the desired quality of the final product, it is necessary to carefully study important ultrasonic parameters, such as frequency, power and time, since excessive application will produce undesirable negative effects. For most studies, the ultrasound frequency was within the range 20–55 kHz, with optimum results at 40 kHz, using a power level in the range 150–600 W. The impacts of application time were diverse, mostly depending on the meat type and prior ultrasound settings.

## Conflict of Interest

The authors declare that there are no conflicts of interest.

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