Review Article

A Review on the Effect of Ultrasonic-Assisted Curing on the Quality of Meat Products

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Abstract

Meat products can deteriorate during storage posing a threat to human health due to the action of microorganisms and enzymes. Curing is widely used as a preservation method that can extend shelf life, improve product quality, and impart flavor. In industrial production, business operators seek to enhance the curing efficiency of their products, while consumers expect stable product quality. These demands have prompted the exploration of efficient solutions for curing. Ultrasound technology has attracted widespread attention as a new nonthermal food processing technology due to its potential for reducing processing time, improving meat product quality, and lowering costs. Numerous studies have shown that ultrasound treatment can effectively enhance curing efficiency and improve meat product quality through cavitation effects, mechanical effects, and thermal effects. The basic principles of ultrasound technology and the impacts and mechanisms of ultrasound-assisted curing techniques on curing efficiency and quality in meat products are discussed. This review aims to provide a valuable theoretical foundation for the application of ultrasound technology to address the health risks and costs caused by slow curing efficiency and unstable product quality.

Keywords: Curing, Mass transfer, Meat processing, Meat quality, Preservation, Ultrasonic treatment

1 Introduction

The high contents of proteins and polyunsaturated fatty acids in meat products render them susceptible to spoilage caused by endogenous autolytic enzymes and external microorganisms. During the spoilage process, proteins, fats, and other constituents of meat decompose into compounds such as ammonia, amines, and malondialdehyde, which generate unpleasant odors and alter coloration and texture [1]. Factors causing meat deterioration include internal factors (e.g. moisture content, protein content, and pH) as well as external factors (e.g. temperature, light conditions, gas composition, pressure, and packaging) [2]. Currently, meat product preservation techniques primarily include physical, chemical, and biological methods. These methods include low-temperature storage [3], irradiation treatment [4], modified atmosphere packaging [5], ultrahigh-pressure treatment [6], antimicrobial packaging [7], preservative addition [8], and curing [9]. Different approaches are employed based on distinct antimicrobial principles. From a production standpoint, it is desirable to preserve meat products in a cost-effective manner that is easy to implement while enhancing efficiency and product quality. From a consumer perspective, ensuring product safety and improving quality are paramount. Curing not only has the advantage of low cost but also enhances the flavor of the product. Due to these unique characteristics, curing has become a common processing technique [9]. Curing is a crucial step in the production of meat products to enhance their quality and prolong shelf-life. The curing process involves various physical and chemical transformations including mass transfer, protein oxidation, and fat oxidation [10]. The substances present in brine, such as salt and water, as well as components found in muscle tissue, including fat and protein, undergo diffusion. Ultimately, driven by concentration gradients, substances are transferred from regions of high concentration to those of low concentration until equilibrium is achieved. During curing, proteins and fats also undergo biochemical reactions, such as decomposition and oxidation due to interactions with oxygen and active ingredients present in the curing solution [11]. Curing with salt can effectively extend the edibility of meat by elevating cell osmotic pressure while reducing water activity to inhibit microbial growth [12]; thus, salting emerged as a prevalent meat preservation technique in ancient Chinese cooking.

Following curing, meat products undergo alterations in tenderness, water holding capacity, color, cooking loss rate, texture characteristics, and microstructure. Traditional and widely employed curing methods include dry curing [13], wet curing [14], injection curing [15], and tumbling curing [16]. While these methods are straightforward to execute and impart a distinct flavor to meat products, they suffer from drawbacks such as uneven penetration, a long processing time, susceptibility to spoilage and inconsistent product quality [17]. In light of advancements in food industrialization and the growing consumer demand for superior food quality, numerous researchers have studied alternative curing processes with advantages such as reduced processing time, ease of operation, and enhanced product quality. Examples of these processes include high-pressure and ultrahigh-pressure curing [18], vacuum tumbling [19], pulsed vacuum curing [20], pressurized-tumbling-assisted curing [21], and ultrasonic-assisted curing [22].

In the field of meat product curing, ultrasonic-assisted treatment has emerged as a novel and environmentally friendly nondestructive technique. Its widespread adoption can be attributed to its simple equipment, ease of operation, high curing efficiency, and ability to enhance product quality. This study focuses primarily on the advancements in ultrasonic technology for meat product curing and explores the impact of ultrasonication on various aspects, such as texture, color, flavor compounds, lipid oxidation, protein structure, and moisture content. By providing a theoretical framework for enhancing both the efficiency and quality of meat product curing, this study serves as a valuable reference for researchers aiming to improve their understanding of this domain.

2 Ultrasonic Technology

Ultrasonic waves are sound waves with a frequency exceeding 20 kHz, which is beyond the upper limit of human auditory perception [23]. These waves can be categorized as low-intensity (frequency greater than 100 kHz and power level less than 1 W/cm^2) or high-intensity (frequency ranging from 20–500 kHz and power level greater than 1 W/cm^2). Low-intensity ultrasonic waves are employed for sample detection, whereas high-intensity ultrasonic waves are used in food processing [24]. When ultrasonication is applied to a sample, cavitation, mechanical, thermal and chemical effects are induced. These effects significantly influence the texture, flavor, color, lipid, protein, moisture, and other aspects of meat products (Figure 1).

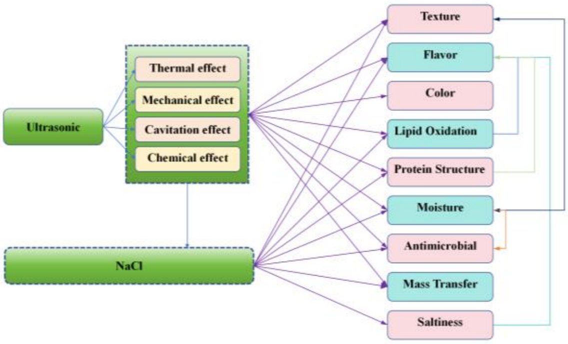

Figure 1: The diagram illustrating the impact of ultrasound on the quality of meat products.

The principle of cavitation effects involves periodic half-cycle decompression/compression of ultrasonic waves, leading to bubble generation, growth, and rupture within the liquid in the sample (Figure 2). Upon bubble rupture, temperatures can reach 5000 K and pressures can rise to 1000 atm, resulting in shock waves and microjet streams that disrupt cell structures [25], [26].

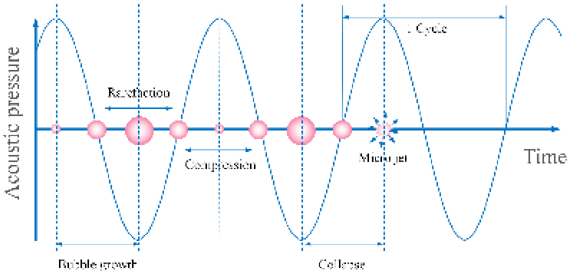

Figure 2: Ultrasonic cavitation (adapted from [25]).

The mechanical effects of ultrasonic waves encompass two aspects. First, mechanical action is generated by the microjet and the shock wave resulting from cavitation [27]. Second, ultrasound accelerates particles within the medium, converting sound energy into mechanical energy and thereby disrupting the original structure of the medium [28].

The thermal effect refers to the heat generated when particles oscillate at a high frequency under the influence of ultrasonic waves; both shock waves and microjets produced during cavitation can also elevate the temperature of the medium. Moreover, the medium experiences high-frequency vibrations and mutual friction induced by ultrasound, resulting in the generation of heat [29]. Via this phenomenon, the medium absorbs the energy carried by ultrasound and converts it into thermal energy. Based on these thermal effects, researchers [30] have proposed an equation for calculating the ultrasonic intensity.

$$P = cm\frac{dT}{dt} \tag{1}$$

where c is the heat capacity of the solvent ($J{\cdot}kg^{-1}{\cdot}°C^{-1}$), m is the mass of the solvent (kg), and dT/dt is the temperature change (°C).

Chemical effects refer to the formation of free radicals caused by ultrasonication, and these free radicals can react with substances in meat [31]. For example, ultrasonic treatment can dissociate water molecules and generate hydroxyl radicals, which can lead to the oxidation of proteins in meat, affecting their quality and shelf life [32]. Consequently, the structural composition of muscle tissue changes during ultrasonic-assisted curing, thereby enhancing both the quality and curing efficiency of meat products. Ultrasound-assisted curing equipment is characterized by simplicity, convenience, and environmental friendliness.

Currently, ultrasonic equipment can be divided into two main types: probe-type (Figure 3(a)) and bath-type equipment (Figure 3(b)). The probe-type equipment used in experimental research for ultrasound-assisted curing primarily includes ultrasonic generators, ultrasonic probes, water-bath tanks (cooling tanks), and curing pools [33]. The ultrasonic waves generated by the ultrasonic generator interact closely with the surfaces of samples immersed in the curing liquid. A water bath tank surrounding the curing pool is used to absorb the heat released during curing and maintain a constant temperature. In contrast, bath-type ultrasonic equipment primarily comprises a transducer and tank. The transducer is positioned at the bottom of the bath to convert electrical energy into vibrational energy carried by acoustic waves. Bath-type ultrasonic equipment is widely employed for the extraction of bioactive components [34].

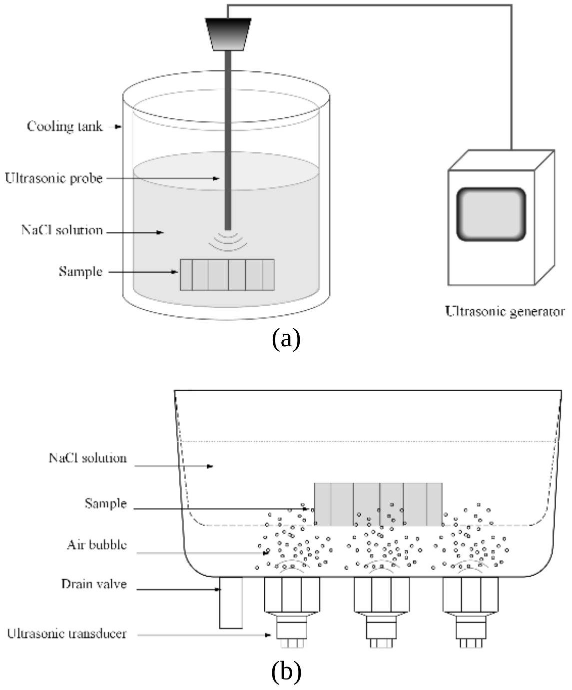

Figure 3: Schematic diagram of ultrasonic-assisted curing equipment.

In the field of meat processing, although the technology has become relatively mature, there is still room for improvement in terms of meat quality and processing efficiency. Ultrasonic technology, as an environmentally friendly processing technique, has been widely researched and applied in many processes such as extraction [35], thawing [36], sterilization [37], foaming [38], emulsification [39] and drying [40].

By incorporating ultrasound into the meat processing procedure, it is feasible to reduce both the duration and temperature, while simultaneously enhancing food texture and nutritional value. Moreover, this technique effectively prevents the formation of toxic compounds due to elevated temperatures [41]. Ultrasound devices offer simplicity in operation and occupy minimal space while being environmentally friendly with zero pollutant emissions. Ultrasound technology can effectively reduce curing time, enhance production efficiency [42], and prolong product shelf life [43]. This ensures uniform substance penetration, elevates product quality standards, and maintains overall product integrity without compromise. Research has demonstrated that ultrasound can modify myofibrillar protein characteristics and improve tissue permeability [44]. Additionally, ultrasound treatment enhances tenderness, improving water retention [45] and flavor [46].

3 Application of Ultrasonic Technology to Enhance Meat Curing Efficiency

In the process of meat product curing, ultrasonication is employed to enhance salt penetration and optimize curing efficiency (Table 1). Ultrasound-assisted curing can significantly improve muscle tissue permeability, increase the diffusion coefficient of sodium chloride, and enhance the sodium chloride penetration rate (Figure 4), thereby effectively reducing marination time [9]. Inguglia *et al*., [47] conducted a study on pork and demonstrated that ultrasonic treatment could shorten the curing time by four times compared with conventional soaking. Zhao *et al*., [33] employed binary images to visually demonstrate that the diffusion of sodium chloride could be significantly accelerated in beef treated with varying ultrasonic intensities compared with the control group. McDonnell *et al*., [48] investigated the impact of ultrasonic mechanical action on material diffusion in pork using a mass transfer model based on Fick’s second law, and the findings indicated an increase in the sodium chloride diffusion coefficient with increasing ultrasonic intensity. Jin *et al*., [49] treated pork immersed in a 6% curing solution with ultrasonication at a power of 315 W and observed a significant reduction in curing time compared with the traditional method requiring 3 days.

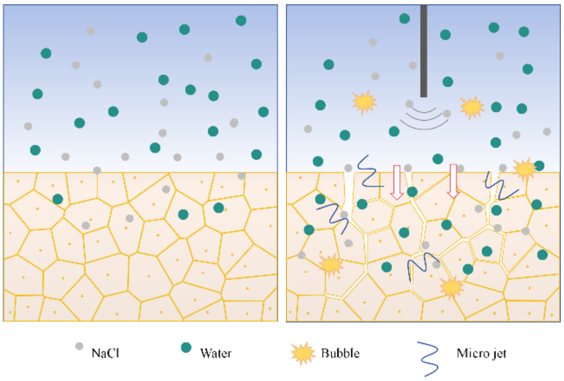

Figure 4: The schematic diagram of the mechanisms of ultrasound curing.

Table 1: Examples of the application of ultrasonic-assisted curing to improve curing efficiency.

Meat Type	Parameters	Results	Ref.
Pork	Frequency: 20 kHz Intensity: 5.09 W/cm^2 Time:15, 30, 60, 90, 120,150 and 180 min.	1. A kinetic model of diffusion during salting was established. 2. Ultrasonic treatment significantly enhanced the diffusion coefficient of salt. 3. The water holding capacity of the sample decreased.	[50]
Tuna	Frequency: 40 kHz Intensity: 840 W	The application of ultrasound enhanced the effective salt diffusion coefficient from 402.8% to 653.21% during the brining process.	[51]
Rabbit	Frequency:40 kHz Intensity: 110 W	The NaCl content increased more rapidly with ultrasonic treatment than without ultrasonic treatment.	[30]
Sea bass	Intensity: 100, 300 and 500 W Time: 30, 60 and 90 min Frequency: 20.5 kHz	1. The transfer rate of NaCl was improved. 2. Treatment decreased the hardness and chewiness and improved the water-holding capacity. 3. Treatment enhanced protein degradation, total free amino acid levels, and the relative contents of volatile flavor compounds such as aldehydes and esters.	[52]
Pork	Intensity: 600 W Frequency: 20 kHz	Treatment shortened the curing time and improved salt diffusion in pork.	[53]
Chicken	Frequency: 25, 45 and 130 kHz Power: 4.7, 5.5 and 7.2 W Duration: 1, 3 or 6 h	At 130 kHz, the time required for salt to penetrate into the meat was reduced from 6 h to 1 h, significantly reducing the marinating time.	[42]
Beef	Frequency: 40 kHz Acoustic energy density: 0.031 W/mL	Ultrasound-assisted treatment shortened the salting time by improving the diffusion of salt in beef.	[54]

Factors such as the frequency, intensity, and processing time of ultrasonic waves strongly influence the mass transfer process (Table 1). Under specific conditions, an enhancement in mass transfer has a substantial effect. Guo *et al.*, [55] investigated the influence of ultrasonic waves with different frequencies on sodium chloride mass transfer in pork muscle. The results demonstrated that ultrasonic-assisted curing significantly increased the sodium chloride content in pork compared with static curing, and the optimal ultrasonic frequency was found to be 26.8 kHz. Inguglia *et al.*, [42] observed a positive correlation between ultrasonic frequency and sodium content in chicken meat. Furthermore, the application of ultrasound at 130 kHz significantly reduced the curing time from 16 h, the duration required for the control sample without ultrasound-assisted marination, to just 6 h. Kang *et al.*, [56] found that the ultrasonic intensity had a significant effect on the mass diffusion coefficients of water and sodium chloride in the curing process and that the mass transfer efficiency increased with increasing ultrasonic intensity.

4 Influence of Ultrasonic-Assisted Curing on the Quality of Meat Products

4.1 *Texture*

The structure of muscle tissue plays a crucial role in determining tenderness, hardness, springiness, fracturability, cohesiveness, gumminess, chewiness, resilience, and other qualitative characteristics of meat. There is generally a correlation between muscle tenderness and shear force, with lower shear force values indicating greater muscle tenderness.

The combined effects of cavitation and mechanical forces generated by ultrasound synergistically disrupt the myofibril structure, thereby enhancing the tenderness of meat products. Yeung [57] discovered that processing pork loin for 6 min at 2.2 kW and 15 kHz resulted in an increase in the meat myofibrillar fragmentation index (MFI) to 15.1%, a reduction in hardness to 87.6%, and a decrease in shear force to 87.9%. Chen *et al.*, [58] discovered that the application of low-frequency, high-power ultrasonication triggers an apoptosis cascade, thereby facilitating the degradation of myofibril structure and the hydrolysis of chicken protein. Zhou *et al.*, [44] discovered that ultrasonic-assisted treatment effectively disrupts lysosomes, myofibrils, and connective tissue in meat, leading to a significant reduction in shear force and an improvement in meat tenderness compared with static curing. Zou *et al.*, [59] discovered that combining ultrasonic treatment with sodium bicarbonate-assisted salting effectively enhances MFI, reduces shear force, and improves tenderness in chicken.

The extent of collagen cross-linking directly affects the elasticity of meat products [60], and the collagen structure can rupture when exposed to ultrasound, thereby impacting the textural characteristics of the meat. A study conducted by Chang *et al.*, [61] on beef semitendinosus muscle demonstrated that ultrasonic treatment induces collagen destabilization, with low-frequency and high-power ultrasound treatment significantly affecting collagen characteristics and meat quality properties. This is attributed to the ability of ultrasonic treatment to disrupt the orderly arrangements of collagen fibers, leading to degeneration, granulation, and aggregation in the extracellular space. These alterations substantially influence the textural properties of meat.

Ultrasonic treatment enhances cathepsin activity by promoting the release of cathepsin from lysosomes and the release of calcium from sarcoplasmic intracellular stores [62], thereby disrupting the structural integrity of myofibrillar proteins, reducing their stability, and ultimately improving meat tenderness (Figure 5). Gao *et al.*, [63] treated Muscovy duck breast meat with ultrasonication and observed a significant increase in peptide content and hydrophobic amino acid content in the treated group compared with the control group, suggesting that ultrasound treatment has the potential to enhance protein hydrolysis. This enhancement can be attributed to ultrasonic cavitation disrupting lysosomal membranes, thereby stimulating the release of tissue proteases and calpains, resulting in the breakdown of proteins into smaller peptides and individual amino acids. Protein hydrolysis not only improves meat tenderness but also contributes to flavor enhancement through the generation of peptides and amino acids [64]. Wang *et al.*, [65] demonstrated that ultrasonic treatment at a frequency of 20 kHz and intensity of 25 W/cm^2 effectively accelerated the degradation of desmin and troponin-T in the *M. semitendinosus* muscle of beef, leading to the disruption of thin filaments or actomyosin and improved beef tenderness. The observed acceleration was attributed to the regulation of calpain activation and protein degradation. Transmission electron microscopy (TEM) analysis of the ultrasonicated samples revealed swelling in the A-band, irregularity near the Z-line area, and interfiber gaps. Ultrasound is also believed to enhance the binding affinity between enzymes and substrates, accelerate protein decomposition rates, and influence the structural integrity of meat. Ultrasound has been shown to enhance the binding affinity between enzymes and substrates, thereby facilitating protein decomposition kinetics [66]. This phenomenon may also contribute to alterations in meat texture.

Muscle texture is significantly influenced by the power, intensity, and processing time of ultrasonic waves. Low-frequency ultrasound can produce a stronger cavitation effect, and the damage to the muscle fiber structure is greater than that caused by high-frequency ultrasound. In general, muscle shear forces are theoretically smaller when ultrasound is more intense. Bao *et al*., [67] observed that within the power range of 200 to 400 W, an increase in power resulted in increased springiness and a gradual reduction in the hardness, chewiness, and shear force of a sample. This phenomenon can be attributed to ultrasound-induced denaturation of cytoskeletal proteins, resulting in structural instability within the muscle. However, some findings suggest that the impact of ultrasound on meat tenderness is negligible [68]. This disparity may be attributed to differences in the ultrasound parameters, equipment, and materials employed.

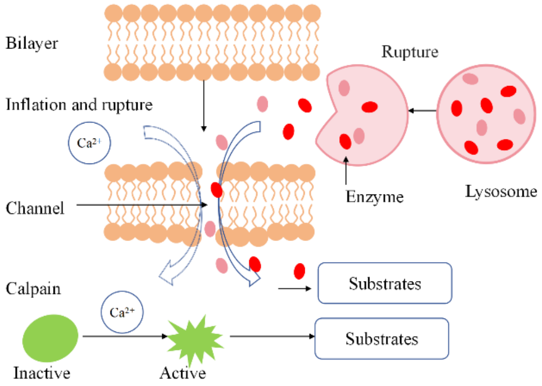

Figure 5: Schematic diagram of enzyme release and activation.

In conclusion, the impact of ultrasound on the texture of meat products can be summarized as follows: 1) The structure of muscle tissue is destroyed due to the mechanical, cavitation and thermal effects of ultrasonication (Figure 6) and 2) Endogenous enzymes are released or activated in response to ultrasound, leading to protein degradation (Figure 5).

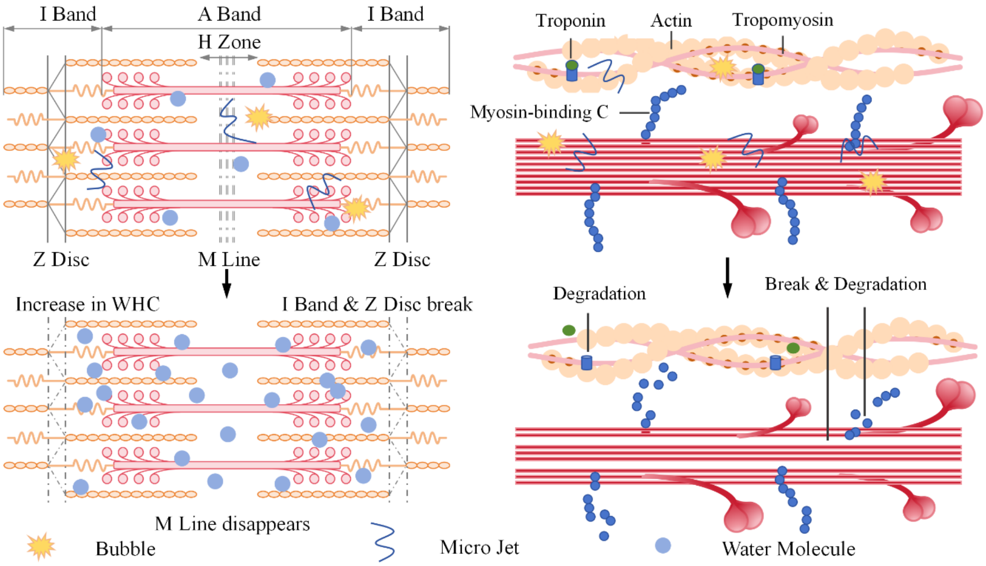

Figure 6: Mechanisms of the impact of ultrasonication on meat texture.

4.2 *Color*

Meat color plays a crucial role in consumer assessment of meat product quality. The red color observed in muscles originates primarily from myoglobin and hemoglobin. Hemoglobin is found mainly within the blood, and myoglobin constitutes a significant portion of the red color of muscle tissue.

Heme contains ferrous ions that appear dark red in the absence of oxygen and are oxidized to trivalent iron, which is bright red, in aerobic conditions. Numerous studies have indicated that ultrasonic-assisted curing modifies properties such as lipid content, water retention capability, and protein oxidation characteristics, which subsequently influence the stability of meat product color [69]. Domínguez *et al*., [70] proposed that the stability of hemoglobin binding protein oxidation and reduction can be influenced by aldehydes released from lipid oxidation. Stadnik *et al*., [71] found that ultrasound-assisted treatment hindered myoglobin oxidation and delayed the formation of metmyoglobin, thereby alleviating overall color changes in beef. Tang *et al*., [72] demonstrated that ultrasonication can modulate mitochondrial lipid oxidation and the mitochondrial electron transport chain (ETC)-linked reduction of MetMb, thereby influencing myoglobin stability. Diaz-Almanza *et al*., [73] observed an increase in a hue of beef from 0.62 to 0.76, with a shift from red to orange values as the duration of ultrasonic exposure increased; however, there was no impact on the a* and c* values. A study conducted by Pohlman *et al*., [74] yielded similar results, indicating that ultrasonic treatment can diminish the vividness of beef color and shift it from red to yellow. Sikes *et al*., [75] observed a significant decrease in the L* value and an increase in the darkness of steaks following ultrasonic treatment compared with the untreated control group.

Despite numerous studies supporting the discernible effect of ultrasound on the color of meat products, other studies have indicated that ultrasound does not have any significant effect on the coloration of meat products [76]. Yao *et al*., [51] conducted a study on tuna and reported that after ultrasonic curing, the L* and b* values increased, while the a* value decreased. However, no significant effect was observed compared to static curing. Stadnik and Dolatowski [71] investigated beef and similarly demonstrated that although ultrasound accelerated the overall change in color of the meat, the impact was not statistically significant, possibly because of variations in ultrasonic power, intensity, time, and sample characteristics.

4.3 *Flavor*

Flavor compounds in meat products primarily originate from precursor substances that undergo a series of complex biochemical reactions during processing. These precursor substances include peptides, amino acids, sugars, nucleotides, thiamines, and lipids. During ultrasonic-assisted curing, the mechanical vibrations of ultrasound waves alter the conformation and interaction of molecules, thereby increasing the variety and concentration of volatile compounds in meat products and enhancing their flavor profile. Research has demonstrated that ultrasonic treatment for a certain duration results in an increase in aldehyde compounds. However, excessive ultrasonic exposure may lead to volatilization or depletion of aldehyde compounds [77]. Zhou *et al*., [78] demonstrated that the application of 1000 W ultrasonication combined with heat treatment at 50 °C resulted in a reduction in the content of rancid and sour compounds and an increase in the ester compound content in dry-cured ham, leading to significant enhancement of its overall flavor. Zou *et al*., [77] demonstrated that ultrasound treatment significantly enhanced the levels of essential amino acids and thiobarbituric acid reactive substances (TBARS) in beef, as well as the diversity and abundance of volatile compounds. Zhang *et al*., [79] investigated the impact of ultrasound on the flavor characteristics of unsmoked bacon and revealed the potential of ultrasonication to enhance flavor attributes by elevating nonylaldehyde, heptyl aldehyde, octyl aldehyde, 3-methylbutyral acetate n-hexyl ester, and n-propyl acetate levels. This effect was attributed to increased lipase and lipoxygenase activities, along with a higher concentration of polyunsaturated fatty acids.

Although ultrasonic treatment has the potential to enhance flavor, some scholars have argued that it may also give rise to undesired side effects. Fallavena *et al*., [80] conducted a study on beef and found that an increase in ultrasonic intensity stimulated the generation of free radicals, resulting not only in a reduction in sample shelf life but also in the formation of compounds that altered sample flavor. This result may be attributed to the high intensity of the ultrasound.

In conclusion, the impact of ultrasonic-assisted curing on flavor compounds in meat products is complicated; process conditions must be optimized on basis of distinct product properties and processing methods to effectively enhance the flavor of meat products while preserving their inherent characteristics and avoiding the formation of detrimental substances. Recently, omics-based methods have been employed to investigate the mechanism of flavor compound changes and have yielded promising results [81]. Therefore, integrating volatileomics, lipidomics, and transcriptomics approaches in experiments can elucidate the molecular mechanisms underlying the variations in flavor compounds caused by different ultrasound treatments [82]. This approach will further enhance our understanding of the effects of diverse ultrasound conditions on flavor substances.

4.4 *Lipid oxidation*

Meat and meat products are rich in lipids, making them prone to deterioration caused by lipid oxidation during storage and processing. Lipids are susceptible to changes in temperature, light, water, and other variables that can modify their chemical properties. Lipid oxidation is a complex phenomenon that involves various biochemical reactions. This process primarily involves the initiation of oxidation of unsaturated fatty acids through free radicals, resulting in the decomposition or formation of small molecules. This complex process significantly influences the content of unsaturated fatty acids as well as the flavor, color, tenderness, and other characteristics of the product [83]. A specific level of lipid oxidation can generate unique compounds that enhance the flavor of meat products; however, excessive oxidation may result in spoilage, nutrient degradation, and even the formation of detrimental substances, such as hydrogen peroxide, ultimately compromising product quality [80].

Lipid oxidation encompasses both free and enzymatic oxidation processes. Ultrasonic treatment not only promotes free oxidation but also promotes enzymatic oxidation. In the process of ultrasonic curing, the cavitation effect of ultrasonic waves causes the particles to collide violently, and the water molecules produce hydroxyl free radicals, which undergo strong oxidation [84]. The effect of ultrasound on the free oxidation stability of lipids depends on the intensity, frequency, and duration of ultrasonic treatment. Optimizing the ultrasonic process parameters can enhance meat product quality; however, exceeding a certain threshold in ultrasonic power may have detrimental effects. Bao *et al*., [67] studied the meat quality and nutrient composition of dry-cured yak that was pretreated with varying ultrasonic power levels. The results revealed an increase in saturated fatty acid content in the meat as the ultrasonic power increased, which had a detrimental impact on both color and flavor, while simultaneously enhancing tenderness. By investigating the impact of ultrasound on the characteristic flavor profile of unsmoked bacon, Zhang *et. al*., [79] demonstrated that ultrasonic treatment significantly augmented lipase activity, facilitated the synthesis of polyunsaturated fatty acids, enhanced product oxidation levels, and promoted the production of distinctive flavor compounds, such as aldehyde-esters and acids.

In conclusion, ultrasonic treatment influences lipid oxidation during meat processing, which is important theoretical information for the use of ultrasonication in industrial production. Further comprehensive investigations are required to determine the optimal parameters for ultrasonic treatment.

4.5 *Protein structure*

Muscle structure is mainly composed of collagen and myofibrillar proteins. Myofibers are composed of myofibrils, which are fundamental units of muscles. Myofibrils are composed primarily of myofibrillar proteins. Meat products consist primarily of myofibrillar proteins, such as myosin, actin, and troponin, as well as structurally stable proteins. Collagen is found mainly in connective tissue and forms the supporting skeleton of muscles [60].

Currently, there is insufficient evidence to support the notion that ultrasound induces alterations in the primary structure of proteins [85]. Nevertheless, ultrasonic treatment can induce changes in secondary and tertiary structures, thereby affecting overall protein functionality. Zhang *et al*., [86] investigated the effects of ultrasound-assisted tumbling curing on the physicochemical properties of pork myofibrillar proteins. Their findings revealed that ultrasonic treatment led to a reduction in α-helix content, an increase in β-sheet content, disruption of protein secondary structure, and expansion of the myofibrillar protein structure with exposed hydrophobic groups on its surface. Kang *et al*., [87] found that ultrasonic treatment reduced the content of total sulfhydryl groups in beef and increased the surface hydrophobicity and content of free sulfhydryl residues in protein. Fourier transform infrared spectroscopy (FTIR) was used to determine the β-sheet and α-helix contents, and the results indicated that the secondary structure of the protein was changed. Wang *et al*., [85] demonstrated that 20 kHz ultrasonic treatment effectively disrupted some hydrogen bonds in myofibrillar proteins, leading to the unfolding of protein molecular chains within a short duration (15 min). This process resulted in a reduction in the α-helix and β-sheet contents, accompanied by an increase in the number of β-turns. In addition, sonication exposes hydrophobic groups encapsulated within protein molecules, thereby increasing their hydrophobicity, which is associated with tertiary structural changes in proteins. Liu *et al.*, [88] and Li [89] reported similar findings in their investigations of myofibrillar proteins in the porcine longissimus muscle and golden threadfin bream, respectively. Arredondo-Parada *et al.*, [90] demonstrated that ultrasound treatment at a frequency of 20 kHz induced structural alterations in the three-dimensional conformation of giant squid proteins, resulting in increased hydrophobicity attributed to enhanced exposure of hydrophobic groups. Tang *et al.*, [91] employed light microscopy to examine the microstructure of actomyosin in *Oreochromis niloticus* subjected to high-intensity ultrasound, revealing that ultrasound treatment induced significant changes in the shape and filament length of actomyosin aggregates, with a direct correlation between higher ultrasound power and shorter filaments.

On the basis of current research findings, ultrasonic treatment of meat products leads to complex alterations in protein structure, which are influenced by the intensity, frequency and duration of ultrasonic exposure (Table 2). Regarding the mechanism by which ultrasound affects protein structure, it is commonly suggested that ultrasonic cavitation leads to the decomposition of water molecules, generating highly reactive free radicals and oxidizing susceptible amino acid residues [86]. However, based on these findings, we can confidently speculate that there are potential mechanisms that warrant further investigation. Consequently, future investigations should focus on comprehensive analysis and synthesis of these structural changes, while also exploring the underlying reaction mechanisms by incorporating other techniques.

Table 2: Effects of ultrasound-assisted treatment on proteins.

Meat Type	Conditions	Results	Ref.
Sausage	Frequency: 25 kHz Intensity: 128 W	1. Ultrasound treatment increased the levels of serine, methionine, phenylalanine, glutamate, and arginine. 2. Ultrasound affected protein hydrolysis and the formation of lipid oxidation derivatives.	[11]
Pork	Frequency: 20 kHz Intensity: 0,100, 300 and 500 W Time: 60 and 120 min	Ultrasound-assisted vacuum tumbling treatment induced protein oxidation and altered the physicochemical properties of myofibrillar proteins.	[86]
Pork	Frequency :20 kHz Intensity: 100, 300, 500 and 700 W Time:30, 60, 90 and 120 min.	After ultrasonic treatment at 300 W or 500 W for 120 min, protein extraction was considerably increased, enhancing the quality of pork.	[92]
Ham	Intensity:300 and 1000 W Temperature:40and 50 °C Frequency:25 kHz	1. Ultrasonic treatment increased the release of cathepsin and accelerated the degradation of sarcoplasmic and skeleton proteins. 2. Ultrasonic treatment improved the overall taste quality and decreased the bitterness of defective dry-cured ham.	[13]
Black pork	Frequency: 40 kHz Intensity:200 W Time: 20 min	Ultrasonic treatment increased the solubility of myofibrillar proteins, disrupted muscle fiber structure, and enhanced the characteristics of myofibrillar proteins.	[44]
Beef	Power: 400 W Frequency: 25 kHz	Ultrasonic treatment increased the degradation of myosin light chains and troponin T, reduced the contents of β-turns and β-sheets, and promoted protein oxidation and hydrolysis.	[93]
Chicken	Power: 500 W Frequency: 40 kHz	1. Ultrasonic treatment enhanced the surface hydrophobicity, SH content, and absolute ζ-potential value of the myofibrillar proteins. 2. Ultrasonic treatment improved the emulsifying properties and physical stability of myofibrillar protein emulsions.	[94]

4.6 *Moisture*

Ultrasonic-assisted curing can enhance the water content of meat products and improve their water holding capacity and meat yield while reducing cooking loss. The water holding capacity of meat is influenced by the contents of free water and immobilized water. A decrease in the free water content indicates more pronounced water binding, suggesting the conversion of additional free water into immobilized water. During cooking, meat primarily loses free water, while a small portion of immobilized water may be expelled from the muscle fiber structure. Ultrasonic-assisted curing leads to a reduction in free water and an increase in immobilized water within the meat, thereby reducing cooking losses and enhancing water holding capacity [95]. Sun *et al.*, [96] applied ultrasonication to porcine myosin in a 0.3% NaCl solution and observed that the gel water holding capacity in the low-salt solution reached 84.5% after

6 min of treatment, exhibiting a linear increase with prolonged ultrasonic exposure time; these results demonstrated the effective enhancement of protein water holding capacity through ultrasonic treatment.

Ultrasonic treatment disrupts the network structure of myofibrils, facilitating rapid penetration of the curing solution into meat pores and ensuring a more uniform distribution within the meat, thereby enhancing the water holding capacity of myofibrillar proteins [97]. Kang *et al.*, [98] demonstrated that ultrasound-assisted curing significantly reduces beef cooking loss via cavitation-induced disruption of the beef myofibril structure, enabling enhanced water retention by myofibrillar proteins. Furthermore, ultrasonic-assisted curing facilitates penetration of the salting solution into the meat and promotes protein degradation and swelling through reactions with proteins. This process leads to increased binding between protein side chains and water molecules, ultimately improving the water holding capacity [99]. Zou *et al.*, [100] revealed that ultrasonic treatment disrupts the structure of myofibrillar proteins, leading to the release of a substantial amount of salt-soluble proteins and facilitating their accumulation on the meat surface. This phenomenon enhances the ability of muscles to prevent water spillover, thereby reducing water loss during cooking and resulting in a significant improvement in cooking yield. There are also contrasting perspectives suggesting that sonication may diminish water holding capacity, potentially because of variations in ultrasound intensity and processing techniques [30]. However, these viewpoints do not undermine our affirmative stance on the potential of ultrasound to enhance water holding capacity.

Ultrasonic intensity plays a crucial role in the water holding capacity of meat products. Siro *et. al.*, [99] applied ultrasonic treatment to porcine tissue and observed that the water holding capacity increased with increasing treatment time under low-intensity ultrasonication of less than 2.5 W cm^{-2}. However, within an ultrasonic intensity range of 3–4 W cm^{-2}, protein denaturation resulted in a decrease in water holding capacity with prolonged treatment time.

5 Limitations of Ultrasonic-Assisted Curing

Due to its convenience and safety to humans, ultrasonic technology has been widely applied in the field of meat processing. Although ultrasound-assisted curing has significant benefits, potential drawbacks must be considered. For example, Bao *et al.*, [67] showed that excessive ultrasonic power can have negative effects on the color and odor of dry-cured yak meat. In addition, increased hardness was observed in low-salt meat products treated at high power levels, indicating the need for careful optimization of ultrasound parameters in practical production [101]. Therefore, balancing power and intensity is crucial for maximizing benefits while minimizing adverse effects. In industrial production, due to the complex structure of meat products and variations in types, cuts, sizes, etc., different ultrasound conditions are required. Bianka *et al.*, [9] found that smaller muscle samples (3 cm^3) exhibited a higher salt content and weight gain compared to larger samples (5 cm^3) when different ultrasonic conditions were used for curing. This suggests that adjusting the ultrasound parameters may be necessary to achieve similar results for different-sized samples.

Due to differences in ultrasound parameters and production conditions, there may be significant variations in the ultrasonic-assisted curing process between the laboratory and industrial scales. These differences can affect the efficiency of curing and its influence on parameters such as salt absorption, weight changes, and meat quality. Inguglia *et al.*, [42] reported that high-power ultrasound at different frequencies (25 kHz, 45 kHz, and 130 kHz) significantly increased sodium absorption in chicken breast meat without adverse effects on quality parameters. However, these results may not directly translate to larger scales if the frequency and treatment time are not carefully optimized. Additionally, variations in yield during the curing process are influenced by processing conditions such as brine concentration and storage time; these variations cannot be ignored in industrial production. In anchovy fillets, the greatest weight changes occurred early in the curing process, indicating that industrial processes must consider these dynamics to optimize yield and quality [102].

Although laboratory research provides valuable insights into the curing process, expanding laboratory-scale results to industrial production requires careful consideration of differences in ultrasound parameters and processing conditions to ensure stable quality and efficiency on a large scale. Additionally, developing industrial ultrasound equipment and ensuring its feasibility for practical production are challenges that need to be overcome in the industrialization process. However, some advanced curing techniques, such as breathing ultrasonic tumbling, have shown promise in improving curing efficiency and meat quality by enhancing absorption and tenderness. These technologies provide alternatives for expanding curing methods while maintaining quality attributes [103].

6 Conclusions

Meat products are prone to spoilage and are often cured to extend their shelf life. Traditional curing methods are inefficient and produce meat products with unstable quality, so new technologies have been developed to improve curing efficiency and product quality. Ultrasonication is an emerging technology that is widely applied and studied in the meat industry. The application of ultrasonic waves during curing can effectively enhance the curing efficiency and change the texture, color, flavor compounds, lipid oxidation, protein structure, and moisture content of the product. Notably, appropriate ultrasonication conditions can effectively improve meat product quality, but inappropriate conditions can damage product morphology, leading to the generation of harmful substances or the loss of nutrients. In addition, current research has been conducted under laboratory conditions, where the parameters may not necessarily apply to large-scale production. Therefore, specific processing parameters need to be designed and optimized on the basis of individual product characteristics as well as the production scale to achieve the desired results. In the future, with further research and development as well as the application of omics techniques and other methods, the impact of ultrasound on meat product quality and its regulatory mechanisms will become clearer. The development and improvement of ultrasound equipment and the integration of ultrasonication with other novel technologies will highlight the unique advantages of ultrasound-assisted processing in the meat industry.

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Author Contributions

Y.H.: conceptualization, investigation, reviewing and editing, methodology, research design, writing an original draft, funding acquisition, project administration; S. A., R. K., W. C., N. W., P. Y.: conceptualization, data curation, writing—reviewing and editing; Q.S.: investigation, methodology. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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