

Review

Application of Ultrasound in Proteins: Physicochemical, Structural Changes, and Functional Properties with Emphasis on Foaming Properties

José Ramón Antunez-Medina ¹, Guadalupe Miroslava Suárez-Jiménez ¹, Víctor Manuel Ocano-Higuera ², Iván de Jesús Tolano-Villaverde ³, José de Jesús Ornelas-Paz ⁴, Wilfrido Torres-Arreola ^{1,*} and Enrique Márquez-Ríos ^{1,*}

¹ Departamento de Investigación y Posgrado en Alimentos, Universidad de Sonora, Boulevard Luis Encinas y Rosales, Hermosillo 83000, Sonora, Mexico; miroslava.suarez@unison.mx (G.M.S.-J.)

² Departamento de Ciencias Químico Biológicas, Universidad de Sonora, Boulevard Luis Encinas y Rosales, Hermosillo 83000, Sonora, Mexico; victor.ocano@unison.mx

³ Department of Food Technology Engineering, Universidad Estatal de Sonora, Campus Hermosillo, Ley Federal del Trabajo s/n, Hermosillo 83100, Sonora, Mexico; jesus.tolano@ues.mx

⁴ Coordinación de Fisiología y Tecnología de Alimentos de la Zona Templada, Centro de Investigación en Alimentación y Desarrollo, Av. Río Conchos, Parque Industrial, Cuauhtémoc 31570, Chihuahua, Mexico; jornelas@ciad.mx

* Correspondence: wilfrido.torres@unison.mx (W.T.-A.); enrique.marquez@unison.mx (E.M.-R.)

Abstract: Proteins have the ability to form foam, which is a system consisting of a gas phase dispersed within a continuous phase, either liquid or solid. In certain types of food, the incorporation of gas is important for maintaining quality and sensory attributes. However, foam is a thermodynamically unstable system, and its stabilization is a highly researched area. In recent years, there has been growing interest in the application of ultrasound not only to improve foaming properties, but also to alter physicochemical and structural characteristics of proteins, making it an environmentally friendly and versatile technology. Ultrasound can enhance formation and stability by inducing conformational changes through the cavitation phenomenon. However, the benefits of this technology depend on the inherent characteristics of the proteins and the conditions applied during its use, such as frequency, time, amplitude, energy, protein concentration, volume, and medium conditions. This review aims to explore how ultrasound influences the physicochemical properties, induces structural modifications, and consequently enhances functional characteristics such as foaming capacity.

Keywords: ultrasound; protein functionality; foaming properties; structural changes; physicochemical properties



Academic Editors: Monika Krzywicka, Zbigniew Kobus and Anna Pecyna

Received: 1 April 2025

Revised: 3 May 2025

Accepted: 20 May 2025

Published: 23 May 2025

Citation: Antunez-Medina, J.R.; Suárez-Jiménez, G.M.; Ocano-Higuera, V.M.; Tolano-Villaverde, I.d.J.; Ornelas-Paz, J.d.J.; Torres-Arreola, W.; Márquez-Ríos, E. Application of Ultrasound in Proteins:

Physicochemical, Structural Changes, and Functional Properties with Emphasis on Foaming Properties.

Processes **2025**, *13*, 1646.

<https://doi.org/10.3390/pr13061646>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Proteins are essential macromolecules in food systems, providing structure, texture, and nutritional value to a variety of products. Their functional properties, such as solubility, emulsification, and foaming, are critical in determining the texture and quality of food products. Traditional methods for modifying protein functionality, such as thermal treatment, chemical modification, and enzymatic hydrolysis—have been widely used to enhance solubility, emulsification, and foaming properties. However, these approaches often present notable drawbacks. Heat treatments can lead to protein denaturation and aggregation, adversely affecting solubility and causing undesirable textural changes. Chemical modifications may involve the use of reagents that raise safety and regulatory concerns,

while enzymatic processes can be costly, time-consuming, and highly sensitive to processing conditions. In contrast, ultrasound technology offers a non-thermal, cleaner, and more energy-efficient alternative [1,2].

Ultrasound technology uses high-frequency sound waves to induce mechanical and thermal effects in food materials, including proteins. The primary mechanism behind ultrasound's interaction with proteins is cavitation, the formation of microbubbles that rapidly collapse, generating shear forces and microjets. These forces can disrupt protein structures, leading to changes in protein solubility, viscosity, and functional behavior, such as foaming capacity. Studies have shown significant improvements in the functional properties of various protein sources through ultrasound treatment [3,4]. Ultrasound treatment has been shown to alter the secondary and tertiary structures of proteins, increasing surface hydrophobicity and reducing particle size, which enhances their emulsifying and foaming abilities [5].

The application of ultrasound in protein processing has been explored for a wide range of purposes, including enhancing protein solubility in aqueous solutions, improving emulsifying properties, and modifying foaming characteristics. For instance, studies indicate that ultrasonic processing can result in a notable increase in the foaming capacity and stability of proteins, making them more effective as stabilizing agents in various food products, such as whipped toppings and baked goods [4,6]. Moreover, this technology can lead to improvements in the quality of food products, including dairy, meat, and plant-based alternatives, as well as the development of novel protein-based materials for non-food applications [7].

As the demand for high-quality, minimally processed food products continues to rise, further research is needed to optimize ultrasound parameters, assess long-term stability, and understand consumer acceptance of ultrasound-treated foods [8]. This review will explore the main effects of ultrasound technology on proteins, as understanding these effects is essential for optimizing its application in industrial processes and advancing food product design. This has the potential to lead to significant advancements in the food industry, particularly in the efficient processing and enhancement of protein-based products. While previous reviews have addressed the impact of ultrasound on protein functionality, this manuscript presents a more integrated and comparative perspective. It links physicochemical and structural changes with specific improvements in functional properties, particularly foaming capacity. The review also incorporates recent findings not yet covered in the earlier literature and provides a clear connection between ultrasound-assisted extraction and downstream protein functionality.

2. Mechanism of Ultrasound

Ultrasound refers to sound waves with frequencies above the audible range for humans, typically between 20 kHz and several MHz. The application of ultrasound in protein processing relies on the propagation of these high-frequency sound waves through a medium, typically a liquid, such as a protein solution or food matrix. These waves cause mechanical vibrations in the medium, leading to localized pressure variations [9]. The main mechanisms through which ultrasound interacts with proteins include mechanical vibration, cavitation, and thermal effects. Mechanical vibration occurs as sound waves create alternating high- and low-pressure zones, generating rapid compression and expansion that produce shear forces, disrupting protein molecular structures [10]. Cavitation involves the formation, growth, and collapse of microbubbles within the liquid; as pressure drops below a threshold, small vapor bubbles form and collapse, releasing energy in the form of shock waves and microjets, which can significantly affect protein molecules [11]. Although ultrasound is often classified as a non-thermal process, it also generates localized

heat, especially during cavitation, where the collapse of bubbles creates intense heat and shear forces, leading to localized temperature rises that can affect protein structure and reactivity [12].

3. Effects of Ultrasound on Physicochemical Properties of Proteins

The physicochemical properties of proteins, such as solubility, viscosity, foaming properties, and their ability to aggregate or denature, are crucial in determining their behavior in solutions and food matrices. Ultrasound, by inducing structural changes in proteins, can significantly modify these properties (Figure 1). Through partial denaturation, exposure of hydrophobic groups, and the reduction of protein aggregates, ultrasound can enhance the functionality of proteins in various applications, such as foam production, improving food texture, and creating more soluble and homogeneous protein solutions. Understanding these effects enables researchers and food technologists to optimize the use of ultrasound in protein processing to improve the quality and functionality of food products [13,14].

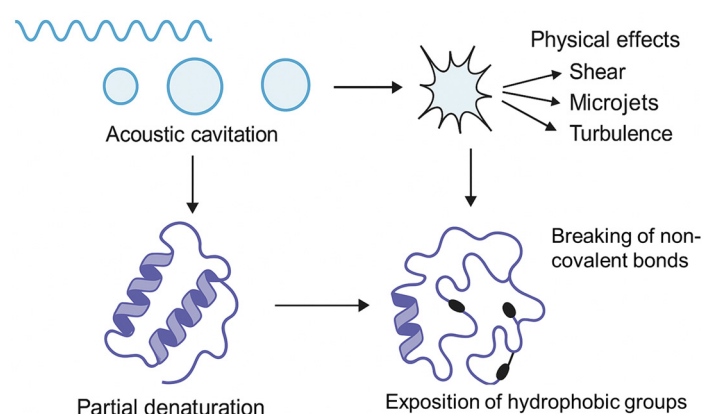


Figure 1. Mechanism of ultrasound on proteins.

3.1. Protein Solubility

Solubility refers to a protein's ability to dissolve in water or aqueous solutions and is directly related to its three-dimensional structure. Ultrasonic treatment can increase protein solubility by inducing partial denaturation or fragmentation of protein aggregates. This occurs due to the breaking of non-covalent interactions that maintain proteins in a compact structure. When proteins are subjected to ultrasound, the interactions that limit the exposure of hydrophilic groups are destabilized, making the proteins more soluble in aqueous solutions. This improvement in solubility can be particularly useful in liquid food products or the production of protein-based beverages [8]. In a study by Wang et al. [15], 100–600 W of power were applied for 5 min to aggregates of oxidized soy protein, with the 500 W treatment resulting in the most significant improvement in solubility. This was attributed to the weakening of the reaggregation effect, which enhanced solubility. Additionally, Malik et al. [16] applied high-intensity ultrasound (HIU) to 10% sunflower protein isolate dispersions at frequencies of 20 kHz (using an ultrasound probe) and 40 kHz (using an ultrasound bath), with treatment times of 5, 10, 20, and 30 min. The 20 min probe treatment was the most effective in improving solubility. This effect was attributed to conformational changes in the protein and the formation of more soluble protein aggregates from insoluble ones. Similarly, Resendiz-Vazquez et al. [17] evaluated the effect of ultrasound on a 10% jackfruit seed (*Artocarpus heterophyllus*) protein solution at 200 W, 400 W, and 600 W, finding that the control (0 W) showed a solubility of 0.06 mg/mL, while after ultrasonic treatment, the solubility increased to 0.66, 0.38, and 0.57 mg/mL at

200, 400, and 600 W, respectively. The largest increase in solubility at 200 W was likely due to conformational changes induced by the ultrasound treatment. It has been reported that ultrasound can reduce the tendency of proteins to aggregate, which is linked to improved solubility, as the breakdown of large protein aggregates into smaller units favors greater dispersion in solution [18]. Finally, Huang et al. [19] applied HIU (0, 125, 250, 375, and 500 W for 20 min) to ormosia protein, significantly enhancing protein solubility. This was attributed to cavitation effects that broke non-covalent bonds, reduced particle size, and altered the secondary and tertiary protein structures, leading to lower surface tension and improved solubility. As observed, ultrasound proves to be an effective tool for enhancing protein solubility. Several studies indicate that this technology can significantly increase the solubility of proteins from various sources by promoting conformational changes and disaggregating protein clusters, which increases hydrophilic group exposure. However, these effects are highly dependent on treatment conditions and protein source.

3.2. Viscosity of Protein Solutions

The viscosity of protein solutions depends on concentration and molecular interactions, and it is an important measurement in food and pharmaceutical applications. Ultrasound can modify the viscosity of a protein solution by breaking protein aggregates through cavitation and mechanical forces, benefiting products like sauces and soups. However, in some cases, viscosity could increase due to the formation of smaller interacting aggregates [20]. In a study carried out by Yolandi et al. [21], the effect of ultrasound at different frequencies (20, 28, 35, 40, 50 kHz) on hydrolyzed soy protein (12% hydrolysis degree) at 14% (*w/v*) was evaluated. The study found that applying low-frequency ultrasound (20 kHz) reduced viscosity by 12.05%. The researchers argued that low frequency ultrasound more easily penetrates highly viscous fluids, promoting acoustic cavitation, which causes the disruption of aggregates and molecular bonds. Similarly, a study by Mao et al. [22] investigated the effect of ultrasound at powers of 0 W, 180 W, 360 W, and 540 W for 3 min. The results showed that treatments with 180 W and 360 W, combined with an increase in pH, increased the apparent viscosity of chicken liver proteins. The study also indicated that excessive ultrasound treatment can affect the protein structure and thus decrease viscosity. Likewise, Kang et al. [23] exposed soy protein to different pH levels (3.0, 5.0, 9.0, and 11.0) for 1 h and then adjusted the pH to 7.0, followed by the application of HIU at 20 kHz with different power (200, 300, and 400 W) for 10 min. The study demonstrated that, without ultrasound treatment, viscosity decreased at pH 5.0 and 9.0, while it increased at pH 3.0 and 11.0. When ultrasound was applied (at any pH level), a decrease in viscosity was observed, particularly when 300 W was used. The researchers noted that the decrease in viscosity caused by ultrasound treatment could be due to the mechanical forces generated by ultrasound cavitation, which disrupted interactions between protein molecules, causing them to align along the flow field and exhibit lower resistance to flow [24]. As can be noticed, ultrasound can either alter or improve the viscosity of proteins in solution. In general, its application leads to a reduction in viscosity due to the fragmentation of molecular structures or protein aggregates, along with increased protein solubility. These changes promote improved alignment of proteins within the flow field, resulting in lower resistance to flow caused by the action of sound waves on the proteins. This response is characteristic of pseudoplastic materials, where apparent viscosity declines as shear rate increases. The cavitation and mechanical forces generated by ultrasound contribute to the disruption of protein networks, thereby reducing the formation of gel-like structures. However, ultrasound can also temporarily increase viscosity if it induces the formation of smaller aggregates that interact with each other. Studies suggest that, when applied in

moderate doses, ultrasound is effective in decreasing viscosity, while excessive treatments may alter protein structure and have counterproductive effects.

3.3. Particle Size

Protein aggregation is an important process that can be modified by ultrasound. The ability of proteins to form aggregates or lose their native structure is key to determining their functional applications in food. When proteins are denatured under ultrasound, their tertiary structures are altered, and exposed hydrophobic surfaces can induce interactions between molecules, promoting aggregation. These aggregates can form a three-dimensional network that alters the physical properties of food products. In some cases, these aggregates can improve texture characteristics, as seen in products such as tofu or textured soy protein, where protein aggregation is desirable [25,26]. In a study conducted by Jambrak et al. [27], whey protein isolate (WPI) suspensions were treated with ultrasound using a probe (20 kHz for 15 and 30 min) and an ultrasonic bath (40 kHz for 15 and 30 min). It was found that both treatments decreased particle size, but the application of HIU using the probe (20 kHz) was much more effective, reducing particle size from 126.75 μm (without HIU) to 22.03 and 90.29 μm for 15 and 30 min, respectively. In contrast, the treatment with the ultrasonic bath (40 kHz) resulted in a reduction to 116.6 μm (15 min) and an increase in particle size when the treatment was extended to 30 min (1030 μm). This led to the conclusion that ultrasound can be useful in reducing particle size, but prolonged exposure can even promote the formation of aggregates. In another study by Hong et al. [28], HIU (40 kHz) was applied at different power (0, 130, 260, 390, 520 W) to silver carp myofibrillar protein (MP) for 30 min. A reduction in particle size from 1589 (control) to 181 nm was observed when 390 W was used. The authors suggest that this may be due to the shear force and turbulence generated by ultrasound cavitation, which causes intense agitation and collision of protein aggregates, leading to the disruption of non-covalent interactions between proteins. However, when the power was increased to 520 W, the particle size increased to 213 nm, which could be attributed to excessive HIU causing the reaggregation of the MP particles. In another study by Zhao et al. [29], pH changes, ultrasound, and pH/HIU treatments were applied to pea protein and whey proteins, both individually and mixed. It was found that the particle size increased with a change in pH, while it decreased with ultrasound and the combined approach. This was attributed to the fact that ultrasound reduces particle size through cavitation, which increases the surface area. Authors argued that cavitation is capable of breaking up agglomerates, aggregates, and even smaller particles, disrupting Van der Waals forces. Hence, HIU can affect particle size, either decreasing it or promoting the formation of protein aggregates. The results indicate that a reduction in particle size generally improves the functional properties of proteins. Therefore, standardizing process conditions is crucial to achieving this goal, as failure to do so may result in the formation of protein aggregates.

3.4. Thermal Denaturation

Protein denaturation is a process in which the secondary, tertiary, or quaternary structure is altered, causing the protein to lose its functional shape. While ultrasound is typically less aggressive than heat in inducing denaturation, it can still significantly modify proteins, altering their functional properties. However, ultrasound-induced denaturation can lead to a loss of functionality, such as reduced gelation or emulsification capacity, depending on the process conditions [30]. In this regard, in a study conducted by Duan et al. [31], the effect of HIU applied for 20 min at different power levels (0, 100, 200, 300, 400, and 500 W) on the physicochemical properties of beef liver peptides was investigated. For this, 2–5 mg of protein was placed in aluminum pans under oxygen flow. The researchers found

that the thermal denaturation temperature decreased slightly, from 139.0 °C (control) to 138.6 °C and 138.0 °C at 100 and 200 W, respectively. However, it increased when 300, 400, and 500 W were applied, with values of 140.1 °C, 140.4 °C, and 142.5 °C, respectively. The authors noted that the samples treated at 400 W were thermodynamically more stable, as indicated by a lower enthalpy value, meaning that less energy was required for their denaturation. In another study, Frydenberg et al. [32] investigated the impact of high-intensity ultrasound (HIU) (24 kHz, 300 W/cm², 2078 J/mL) on the thermal behavior of whey protein isolates. They used 10–20 mg of protein, which were heating from 5 to 120 °C. Their findings revealed that ultrasound application reduces the denaturation enthalpy of whey proteins. This effect was attributed to changes in the bonding pattern, where a protein conformation with fewer or weaker bonds requires less energy to unfold, leading to a reduction in enthalpy. Similarly, Farahnak et al. [33] examined the effect of HIU on the thawing process of mushrooms (*Agaricus bisporus*), focusing on thawing rate and protein denaturation. Ultrasound was applied using both a water bath system (20 kHz, 16.65 W/kg of water) and a probe-type system (28 kHz, 21.35–49.50 W/cm²). Differential scanning calorimetry (DSC) results demonstrated that thawing with a water bath ultrasound system, probe-type ultrasound (250 W), and refrigeration resulted in lower protein denaturation due to a reduced denaturation enthalpy. Additionally, mushrooms treated with probe-type ultrasound (250 W) exhibited higher water retention capacity and greater firmness, which was associated with less structural damage to their proteins. As can be seen, protein denaturation induced by the use of ultrasound is a complex process influenced by power levels and application methods, while HIU can reduce denaturation enthalpy, making proteins more thermodynamically stable. This results in a lower energy requirement for breaking intramolecular bonds, making it easier to form new interactions. These modifications are essential in various agri-food processes, such as foam formation, emulsification, gelation, and even enhancing protein solubility, ultimately improving their functional properties in food applications.

4. Structural Changes Induced by Ultrasound

Ultrasound, when interacting with proteins, induces a series of structural changes that alter their physical and functional properties. The action of ultrasound, particularly its ability to generate cavitation (Figure 2), can induce modifications at the secondary, tertiary, and quaternary structure levels of proteins. These structural alterations are essential for understanding how ultrasound can modify the behavior of proteins in solutions and food matrices [34].

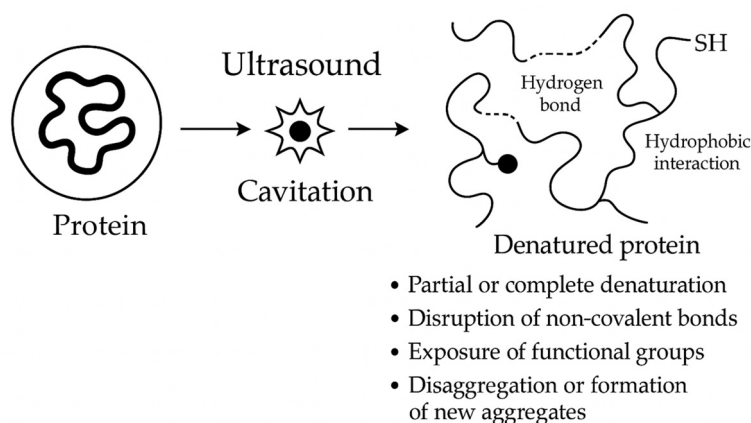


Figure 2. Structural changes induced by ultrasound.

4.1. Effects on Secondary Structure of Proteins

The secondary structure of proteins refers to the local configurations adopted by the polypeptide chains, such as α -helices, β -sheets, and random coil structures. These structures are stabilized by hydrogen bonds between the hydrogen atoms of the amide groups and the oxygen atoms in the polypeptide backbone. The mechanical forces generated by ultrasonic waves, combined with thermal and cavitation effects, can disrupt the hydrogen bonds that stabilize the α -helices and β -sheets. As a result, these ordered structures can transition into disordered or random configurations, increasing the proportion of polypeptide chains in the form of a random coil [35]. The loss of ordered secondary structures can make the protein more flexible and less compact. This altered flexibility can change the interactions of the protein with other molecules, which may be advantageous in applications such as emulsification and foam formation [30]. In a study by Li et al. [36], HIU (20 kHz) was applied to meat protein suspensions at 7.5% (*w/w*) for different times (1, 3, and 6 min) and an amplitude of 60%. An effect on the secondary structure of the protein was found, inducing the unfolding of the α -helical region and consequently the formation of β -sheets, β -turns, and disordered structures. This contrasts with findings by Hu et al. [37], who evaluated the effect of HIU (20 kHz) on 10% soy protein solutions at different energies (200, 400, and 600 W) and times (15 and 30 min). These researchers reported that increasing the energy and duration of HIU application resulted in an increase in α -helical conformations and a decrease in β -sheet and disordered structures. In another study, Vanga et al. [35] applied HIU (20 kHz) to almond milk protein at various times (1, 4, 8, 12, and 16 min), reporting that the content of α -helices and β -sheets remained unchanged. Meanwhile, the content of random coils increased from 14.34% to 27.16% in the first 4 min, after which no significant changes were observed. Additionally, Zheng et al. [30] subjected proteins to different ultrasonic powers (100 W, 320 W, and 640 W) for a period of 60 min. At the end of the study, it was revealed that the cavitation phenomenon induced by HIU disrupted intermolecular hydrogen bonds and promoted protein degradation, contributing to the conversion of ordered protein to a disordered state. As seen, HIU can modify the secondary structure of proteins, altering ordered configurations such as α -helices and β -sheets, and promoting their conversion into disordered or “random coil” structures. This structural change is a result of the mechanical forces, thermal effects, and cavitation induced by ultrasonic waves, which break the stabilizing hydrogen bonds. The transition to a higher proportion of disordered structures increases the flexibility of the proteins, which can be beneficial for applications such as emulsification and foam formation. However, these effects vary depending on factors such as ultrasound intensity, exposure time, and energy applied. Moreover, studies have shown contradictory results, with some indicating an increase in disordered conformations and others showing an increase in ordered structures, highlighting the need to optimize sonication conditions for protein systems.

4.2. Effects on Tertiary Structure of Proteins

The tertiary structure of proteins refers to the three-dimensional arrangement of polypeptide chains, determined by interactions between the R groups of amino acids. These interactions include disulfide bonds, hydrophobic interactions, ionic interactions, and hydrogen bonds. The stability of this structure is crucial for the biological function of proteins. Ultrasonic waves induce mechanical and shear forces that can break the interactions maintaining the protein in its compact form. As a result, proteins may adopt a more extended or less structured conformation, affecting their functionality. This can lead to the exposure of hydrophobic regions, an increase or decrease in SH groups, or the formation and disruption of disulfide bonds, potentially influencing the protein's ability to form emulsions or foams [38]. In a study by Xue et al. [39], ultrasound was applied to a

20% (*w/v*) chicken meat protein solution using a frequency of 20 kHz, with 450 W of energy and an amplitude of 60% for 6 min. The researchers observed that ultrasonic treatment favored the exposure of hydrophobic amino acid residues, such as tyrosine, tryptophan, and phenylalanine. Additionally, a decrease in SH groups was found, possibly due to the formation of disulfide bonds or oxidation of thiol groups resulting from hydrogen peroxide formation. In another study, Wang et al. [18] subjected myofibrillar protein to ultrasonic treatment (20 kHz) with 500 W of power for periods of 0.2, 4, 6, 8, and 10 min. They observed protein unfolding, indicated by an increase in the exposure of hydrophobic groups, the rupture of disulfide bonds, and a consequent increase in SH groups. On the other hand, Chen et al. [38] compared traditional thermal treatment with HIU application on goat milk. They used ultrasound (400 W, 500 W, and 600 W) for 10 min and found that the thermal treatment caused protein aggregation, associated with a decrease in the Z potential. In contrast, samples subjected to HIU (500 W and 600 W) showed an increase in the absolute value of the Z potential, as well as a decrease in particle size. The authors concluded that sonication could break fat globules and protein aggregates, generating particles with a greater specific surface area, which increases the exposure of charged groups, leading to more stable protein conformations. Similarly, Wang et al. [40], in their study on microgel preparation using whey protein with heat and HIU (160, 320, 480, and 640 W/cm²), reported an increase in hydrophobicity after HIU application, as well as an increase in the absolute Z potential value, detecting a value of −13.8 for the control and −18.8 for the samples treated at 640 W/cm². Furthermore, they reported an increase in SH groups from 9.0 to 33.6 μmol/g for control and sonicated protein at 640 W/cm², respectively. These changes resulted in improvements in foam capacity and stability, with the best ultrasound treatment being 320 W/cm². For the above, HIU alters the tertiary structure of proteins by inducing changes in molecular interactions that affect their conformation and functionality. This favors the exposure of hydrophobic residues and SH groups, which can enhance the protein's functional properties. These modifications depend on the frequency, power, and duration of the ultrasonic treatment, allowing the process to be tailored to the specific needs.

5. Foaming Properties of Proteins

Protein foamability plays a crucial role in various food products such as bread, ice cream, and beverages [41]. Foam formation typically proceeds through three main stages: dispersion, stabilization, and coarsening. Initially, proteins unfold and incorporate air into a liquid or semi-solid matrix, generating bubbles. Once dispersed, these bubbles must be stabilized to prevent them from merging or collapsing. Over time, some smaller bubbles may combine into larger ones in a phenomenon called coarsening. The quality and durability of foam are determined by the balance among these three stages. Protein foaming behavior is commonly evaluated through two parameters: foaming capacity (FC) and foaming stability (FS) [42]. FC reflects the ability of a protein to generate foam under specific processing conditions, including pH, temperature, and protein concentration, while FS indicates the foam's ability to retain its volume over time. Various factors such as protein orientation, surface hydrophobicity, molecular size, degree of denaturation, and homogenization affect a protein's foaming performance [43]. These factors determine how well a protein can generate and maintain foam in different food applications. Due to the importance of this functional property, food technologists have been actively seeking alternatives to improve it. To achieve this, both physical and chemical methods have been proposed. One of the most recently studied approaches is modification using physical methods, with ultrasound being among the most investigated due to its potential to enhance not only foaming properties but also other functional characteristics [44].

The cavitation bubbles produced during sonication are typically not numerous enough to generate foam. However, foam formation can be achieved by positioning the sonication horn at the air–liquid interface, allowing air bubbles to become incorporated into the mixture as the sonication continues [45]. Foaming properties of proteins stem from their ability to create and stabilize foams by adsorbing at the gas–liquid interface, preventing bubble coalescence. Ultrasound enhances this capability by partially denaturing proteins, exposing hydrophobic regions that reinforce foam structure. This effect is particularly valuable in products like whipped cream and meringues, where a stable, long-lasting foam is desired [46]. Table 1 presents findings on the effects of ultrasound treatment on various protein sources. Singh et al. [47] evaluated the impact of high-intensity ultrasound (20 kHz, at 30, 40, 50, 60, and 70% amplitude for 10, 15, 20, 25, and 30 min) on squid ovary protein (*Loligo formosana*) at a 4% (*w/v*) concentration. Results showed an increase in foaming capacity with higher amplitude (70%) and longer ultrasound exposure (30 min). This improvement was attributed to increased surface hydrophobicity associated with protein unfolding. In another study, Amiri et al. [24] treated a 3% (*w/v*) beef protein (*Longissimus dorsi*) solution with ultrasound (20 kHz, 100 and 300 W) for 10, 20, and 30 min. They observed that both foaming capacity and stability improved under all treatment conditions. This was attributed to protein unfolding and the exposure of hydrophobic groups at the gas–liquid interface, enhancing absorption due to increased surface contact caused by particle size reduction. Similarly, Stefanović et al. [48] applied HIU at 20 kHz and 40% amplitude for 0, 2, 5, 10, 15, and 20 min to a 10% (*w/v*) egg white protein solution for foam production. They found that 5 min or more of HIU treatment was sufficient to improve foaming capacity and stability; however, further improvements were negligible beyond this point. Morales et al. [49] studied the foaming capacity of a 6% (*w/v*) soy protein solution treated with HIU (20 kHz, 20% amplitude) for 20 min. They reported a significant increase in foaming capacity due to ultrasound treatment, although no changes were observed in foam stability across all conditions. On the other hand, Xiong et al. [50] evaluated the foaming capacity of pea protein (5% *w/v*) solution treated with HIU (20 kHz) at different amplitudes (30, 60, and 90%) for 30 min. Their findings showed an increase in foaming capacity from 145.6 to 200%, along with improved foam stability from 58 to 73.3%. This effect was attributed to protein unfolding caused by ultrasound, which enhanced protein adsorption at the air–water interface, improving their viscoelastic properties and resulting in greater foam stability. Similarly, Flores-Jimenez et al. [51] investigated the foaming capacity and stability of canola protein isolate (2% *w/v*) treated with HIU (40 kHz) for 15 and 30 min. After ultrasound application, the pH was adjusted to 2, 4, 6, 8, and 10 using 0.1 M HCl or NaOH. The foaming capacity of the 30 min treatments at pH 4, 6, and 8 increased significantly compared to the control, while foam stability significantly improved at pH 6 and 8. These enhancements in foaming properties were likely due to ultrasound-induced denaturation, which resulted in a more flexible protein structure, leading to stronger interactions at the air–water interface. In another study, Kang et al. [3] evaluated the effect of HIU (200, 400, and 600 W) on the foaming properties of chickpea protein (6%, *w/v*) for 10, 15, and 30 min. The application of 200 W for 15 min resulted in a significant improvement in foaming capacity, while no significant changes were observed in the other treatments, even in some treatments it decreased. Regarding foam stability, all treatments exhibited improvements except for 400 W for 30 min. These results were attributed to the partial denaturation of proteins, which enhanced the exposure of hydrophobic groups, thereby improving protein adsorption at the air–water interface.

Foam formation at the air–water interface involves the transport, penetration, and rearrangement of protein molecules. These processes are affected by factors such as surface hydrophobicity, protein orientation, degree of denaturation, as well as protein size and

structural flexibility [43]. Sonication has been shown to increase surface hydrophobicity and reduce protein particle size, both of which enhance foaming by promoting protein adsorption at the interface [16]. Several studies have reported that when protein solutions undergo ultrasonication, their foaming capacity increases up to an optimal point, after which prolonged treatment leads to a decline [16,43]. This reduction is attributed to excessive sonication or higher power inputs causing protein aggregation, which in turn shields hydrophobic groups from interacting with the interface. As can be seen, HIU effectively enhances the foaming properties of proteins by partially denaturing their structure, increasing surface hydrophobicity, and improving gas–liquid interface absorption. However, intensity and time of ultrasound application are fundamental, since these must be defined for each protein system, making ultrasound a valuable tool for food applications requiring durable foams.

Table 1. Effect of ultrasound application on foaming properties in different protein sources.

Protein Source	Frequency (kHz)	Treatment	Results	Reference
Egg white	20	2, 5, 10, 15, and 20 min; 40% amplitude	At 15 min the capacity (60.6%) and foaming stability (193.3%) increased.	Stefanović et al. [48]
Chicken meat	20	6 min, 450 W; 60% amplitude		Xue et al. [39]
Beef	20	10, 20, and 30 min; 100 and 300 W	Decrease in particle size and conformational changes	Amiri et al. [26]
Wheat	20 y 40	15 and 30 min; 43–48 W/cm ²		Jambrak et al. [27]
Soy	20	5, 10, 15, and 20 min; 20% amplitude	Foaming capacity: Without ultrasound (153.3%) After 5 min with ultrasound (248.3%) After 20 min with ultrasound (268.2%)	Morales et al. [49]
Squid ovary (<i>Loligo formosana</i>)	20	30 min; 70% amplitude	Foaming capacity: Without ultrasound (244%) With ultrasound (320%)	Singh et al. [47]
Pea	20	30 min; 30, 60, and 90% amplitude	HIU at 90% amplitude for 30 min showed an increase in foaming capacity (from 145.6% to 200%) and foaming stability (from 58% to 73.3%).	Xiong et al. [50]
Chickpea	-	10, 15, and 30 min; 200, 400 and 600 W	The foaming properties increased significantly with the treatment of 200 W power and 15 min	Kang et al. [3]
Ormosia	-	20 min; 0, 125, 250, 375, and 500 W	Increasing ultrasound power (0, 125, 250, 375, and 500 W) improved different properties and characteristics such as solubility, particle size, FC, and FS.	Huang et al. [19]
Squid mantle	20	0–5 min; 20–40% amplitude	The application of 40% amplitude for 1 min showed the best foaming capacity, while the best stability was achieved using 40% amplitude for 5 min.	Arredondo-Parada et al. [4]
Whey protein	20	160, 320, 480, and 640 W	The 480 W application showed better foaming ability, while the low energy use (160 and 320 W) presented better stability.	Wang et al. [40]
Cricket protein	20	20 min; 90% amplitude	The effect of the protein extraction method on its main functional properties was studied. Ultrasonic extraction was found to have the best foaming capacity and stability.	Cruz-López et al. [8]

6. Challenges and Limitations of Ultrasound Application in Food Industry

Although ultrasound has proven to be a promising tool for enhancing various food properties and optimizing industrial processes, its application in the food industry is not without challenges and limitations [52]. The use of ultrasound can lead to protein unfolding and denaturation, resulting in structural modifications that may be either beneficial or detrimental depending on the protein type and the ultrasound processing parameters [53]. At elevated intensity levels, ultrasound may also generate reactive oxygen species, potentially inducing protein oxidation. The cavitation effect promotes the formation of free radicals, which can trigger several changes such as the conversion of sulfhydryl (SH) groups to disulfide (SS) bonds, the formation of carbonyl groups, and the hydroxylation of aromatic residues [54]. Therefore, to enable the commercial-scale application of this technology, it is essential to carefully evaluate processing parameters such as temperature, treatment duration, ultrasound probe configuration, and duty cycle.

On the other hand, the generation of acoustic waves necessitates substantial energy input, particularly to achieve modifications in proteins and other food components. In large-scale applications, inefficient parameters of optimization such as frequency, amplitude, and exposure time can further exacerbate operational costs [55]. Therefore, the high energy requirements and considerable cost of the equipment necessary for the effective implementation of ultrasound technology in the food industry is one of the main challenges today. Furthermore, the industrial scale of ultrasonic systems requires regular maintenance and precise calibration to ensure consistent performance, increasing overall operating costs. These factors can limit its use for small and medium sized enterprises, potentially hindering a broader industrial implementation [56,57].

7. Future Perspectives and Research Directions

Ultrasound has shown great potential for enhancing the functional properties of proteins. However, several challenges still limit its large-scale application. The future of ultrasound in the food industry will be driven by technological advancements, the search for more efficient methods, and the expansion of its applicability to a wider range of food products [58]. One of the key areas for future development of ultrasound technology in the food industry is the optimization of process parameters for different food types, particularly considering the characteristics of proteins and other ingredients. Therefore, enhancing the customization of ultrasound parameters for each specific food product will be crucial. Currently, ultrasound parameters such as frequency, amplitude, time, and power vary depending on the physical and chemical properties of the food matrix. Future research should focus on developing predictive models that allow precise adjustment of these parameters to improve process efficiency without compromising the product quality. For instance, the ultrasound settings that enhance protein solubility in liquid systems may differ from those required for gel formation or emulsion stabilization in more viscous products [59].

Ultrasound has proven to be a good technology to improve functional properties of proteins from various sources, such as soy, peas, and dairy proteins, among others. However, the exploration of new protein sources and their application in functional foods remains a promising area of research. With the growing demand for plant-based foods, ultrasound could play a significant role in improving plant-derived proteins from legumes, seeds, and other unconventional crops. Future research will focus on how ultrasound can enhance the solubility, digestibility, and bioavailability of these proteins, particularly in the production of plant-based meat products, such as burgers or sausages, which require specific functional properties [60]. On the other hand, advances in ultrasound technology

are crucial for making this technique a more efficient, cost-effective, and accessible tool for the food industry. The development of more powerful and efficient transducers is a key direction for the future. Currently, the ultrasound transducers available for the food industry are limited by their size, penetration ability, and energy efficiency. Future research could focus on the development of smaller devices that are easier to integrate into production lines, providing greater uniformity in ultrasound application and a more efficient use of energy [45].

8. Conclusions

Ultrasound has become a valuable tool for various applications in the food industry, from improving protein extraction to enhancing their functional properties. This is attributed to the phenomenon of cavitation, which leads to the continuous growth and collapse of microbubbles, inducing the unfolding of the tertiary and secondary structure of proteins. This exposes their hydrophobic and hydrophilic regions, allowing for greater interaction and stability in a colloidal system such as foam. In most cases, this results in increased solubility, decreased particle size, viscosity, surface tension, among others. Additionally, its use in food preservation and the extraction of bioactive compounds highlights its versatility and potential in creating healthier, more sustainable, and high-quality products in the food industry.

Although this technology has enormous potential to improve food production and quality, its application in the food industry faces several challenges, such as high energy and equipment costs, as well as difficulties in its use in high-viscosity media. Nevertheless, its implementation in the food industry is promising and offers numerous innovative opportunities, such as broadening its application to alternative protein sources. In this way, advancements in ultrasound technology and its integration with sustainable practices will shape the next stage of this technology in the food industry.

Author Contributions: Conceptualization, W.T.-A. and J.R.A.-M.; methodology, E.M.-R.; validation, J.d.J.O.-P.; formal analysis, G.M.S.-J.; resources, V.M.O.-H.; data curation, I.d.J.T.-V.; writing—original draft preparation, W.T.-A.; writing—review and editing, E.M.-R.; visualization, J.R.A.-M.; supervision, G.M.S.-J.; funding acquisition, E.M.-R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by project USO313009084, and the APC was funded by the Department of Research and Graduate Studies in Food Science and the Interdisciplinary Faculty of Biological and Health Sciences at the University of Sonora.

Data Availability Statement: The data from this study can be requested from the corresponding author by sending an e-mail to enrique.marquez@unison.mx.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Małecki, J.; Muszyński, S.; Sołowiej, B.G. Proteins in food systems—Bionanomaterials, conventional and unconventional sources, functional properties, and development opportunities. *Polymers* **2021**, *13*, 2506. [[CrossRef](#)] [[PubMed](#)]
2. Yousefi, N.; Abbasi, S. Food proteins: Solubility & Thermal stability improvement techniques. *Food Chem. Adv.* **2022**, *1*, 100090. [[CrossRef](#)]
3. Kang, S.; Zhang, J.; Guo, X.; Lei, Y.; Yan, M. Effects of Ultrasonic Treatment on the Structure, Functional Properties of Chickpea Protein Isolate and Its Digestibility In Vitro. *Foods* **2022**, *11*, 880. [[CrossRef](#)] [[PubMed](#)]
4. Arredondo-Parada, I.; Torres-Arreola, W.; Suárez-Jiménez, G.M.; Ramírez-Suárez, J.C.; Juárez-Onofre, J.E.; Rodríguez-Félix, F.; Marquez-Rios, E. Effect of ultrasound on physicochemical and foaming properties of a protein concentrate from giant squid (*Dosidicus gigas*) mantle. *LWT-Food Sci. Technol.* **2020**, *121*, 108954. [[CrossRef](#)]
5. Kavimughil, M.; Dutta, S.; Moses, J.A.; Anandharamakrishnan, C. Sonication of egg and its effect on foaming behavior. *Sustain. Food Technol.* **2023**, *1*, 511–527. [[CrossRef](#)]

6. Higuera-Barraza, O.A.; Toro-Sánchez, C.L.; Ruiz-Cruz, S.; Márquez-Ríos, E. Effects of High-energy ultrasound on the functional properties of proteins. *Ultrason. Sonochem.* **2016**, *31*, 558–562. [\[CrossRef\]](#)
7. Darsana, K.; Sivakumar, P. Potential of ultrasound in food processing: An overview. *Curr. J. Appl. Sci. Technol.* **2023**, *42*, 14–34. [\[CrossRef\]](#)
8. Cruz-López, S.O.; Escalona-Buendía, H.B.; Martínez-Arellano, I.; Domínguez-Soberanes, J.; Alvarez-Cisneros, Y.M. Physicochemical and techno-functional characterization of soluble proteins extracted by ultrasound from the cricket *Acheta domesticus*. *Heliyon* **2024**, *10*, e40718. [\[CrossRef\]](#)
9. Zhu, X.; Das, R.S.; Bhavya, M.L.; Garcia-Vaquero, M.; Tiwari, B.K. Acoustic cavitation for agri-food applications: Mechanism of action, design of new systems, challenges and strategies for scale-up. *Ultrason. Sonochem.* **2024**, *105*, 106850. [\[CrossRef\]](#)
10. Yang, H.; Carrascal, C.A.; Xie, H.; Shamdassani, V.; Anthony, B.W. 2-D ultrasound shear wave elastography with multi-sphere-source external mechanical vibration: Preliminary phantom results. *Ultrasound Med. Biol.* **2020**, *46*, 2505–2519. [\[CrossRef\]](#)
11. Tan, W.K.; Cheah, S.C.; Parthasarathy, S.; Rajesh, R.P.; Pang, C.H.; Manickam, S. Fish pond water treatment using ultrasonic cavitation and advanced oxidation processes. *Chemosphere* **2021**, *274*, 129702. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Bucur, M.; Radulescu, M.; Radu, G.L.; Bucur, B. Cavitation-effect-based treatments and extractions for superior fruit and milk valorisation. *Molecules* **2023**, *28*, 4677. [\[CrossRef\]](#)
13. Xiong, Y.; Li, Q.; Miao, S.; Zhang, Y.; Zheng, B.; Zhang, L. Effect of ultrasound on physicochemical properties of emulsion stabilized by fish myofibrillar protein and xanthan gum. *Innov. Food Sci. Emerg. Technol.* **2019**, *54*, 225–234. [\[CrossRef\]](#)
14. Rajasekaran, B.; Singh, A.; Ponnusamy, A.; Patil, U.; Zhang, B.; Hong, H.; Benjakul, S. Ultrasound treated fish myofibrillar protein: Physicochemical properties and its stabilizing effect on shrimp oil-in-water emulsion. *Ultrason. Sonochem.* **2023**, *98*, 106513. [\[CrossRef\]](#)
15. Wang, Y.; Li, B.; Guo, Y.; Liu, C.; Liu, J.; Tan, B.; Guo, Z.; Wang, Z.; Jiang, L. Effects of ultrasound on the structural and emulsifying properties and interfacial properties of oxidized soybean protein aggregates. *Ultrason. Sonochem.* **2022**, *87*, 106046. [\[CrossRef\]](#)
16. Malik, M.A.; Sharma, H.K.; Saini, C.S. High intensity ultrasound treatment of protein isolate extracted from dephenolized sunflower meal: Effect on physicochemical and functional properties. *Ultrason. Sonochem.* **2017**, *39*, 511–519. [\[CrossRef\]](#)
17. Resendiz-Vazquez, J.; Ulloa, J.; Urías-Silvas, J.; Bautista-Rosales, P.; Ramírez-Ramírez, J.; Rosas-Ulloa, P.; González-Torres, L. Effect of high-intensity ultrasound on the technofunctional properties and structure of jackfruit (*Artocarpus heterophyllus*) seed protein isolate. *Ultrason. Sonochem.* **2017**, *37*, 436–444. [\[CrossRef\]](#)
18. Wang, H.; Wang, P.; Shen, Q.; Yang, H.; Xie, H.; Huang, M.; Zhang, J.; Zhao, Q.; Luo, Q.; Jin, D.; et al. Insight into the effect of ultrasound treatment on the rheological properties of myofibrillar proteins based on the changes in their tertiary structure. *Food Res. Int.* **2022**, *157*, 111136. [\[CrossRef\]](#)
19. Huang, D.; Xu, Y.; Zhang, W.; Liu, Y.; Zhang, T.; Liu, H.; Jiang, Y.; Li, D. Enhancement of foaming property of ormosia protein: Insights into the effect of high-intensity ultrasound on physicochemical properties and structure analysis. *Food Hydrocoll.* **2024**, *152*, 109902. [\[CrossRef\]](#)
20. Higuera-Barraza, O.A.; Torres-Arreola, W.; Juárez-Onofre, E.J.; Carrillo-Torres, R.C.; Suárez-Jiménez, G.M.; Ruíz-Cruz, S.; Márquez-Ríos, E. Ultrasound treatment improved the emulsifying property of a protein concentrate obtained from giant squid. *Fisheries Sci.* **2024**, *90*, 1035–1042. [\[CrossRef\]](#)
21. Yolandani, Ma, H.; Li, Y.; Liu, D.; Zhou, H.; Liu, X.; Wan, Y.; Zhao, X. Ultrasound-assisted limited enzymatic hydrolysis of high concentrated soy protein isolate: Alterations on the functional properties and its relation with hydrophobicity and molecular weight. *Ultrason. Sonochem.* **2023**, *95*, 106414. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Mao, R.; Xiong, G.; Zheng, H.; Qi, J.; Zhang, C. Effect of ultrasound on the functional properties and structural changes of chicken liver insoluble proteins isolated by isoelectric solubilization/precipitation. *Ultrason. Sonochem.* **2025**, *112*, 107165. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Kang, Z.; Zhang, S.; Kong, Y.; Wu, Z.; Li, Y.; Liu, T.; Xie, F. Modification of soybean protein isolate by pH-shifting combined with ultrasonic treatment: Structural, viscosity, and functional properties. *Food Struct.* **2024**, *42*, 100383. [\[CrossRef\]](#)
24. Amiri, A.; Sharifian, P.; Soltanizadeh, N. Application of ultrasound treatment for improving the physicochemical, functional and rheological properties of myo fi brillar proteins. *Int. J. Biol. Macromol.* **2018**, *111*, 139–147. [\[CrossRef\]](#)
25. Yanjun, S.; Jianhang, C.; Shuwen, Z.; Honguan, L.; Jing, L.; Lu, L.; Uluko, H.; Yanling, S.; Wenming, C.; Wupeng, G.; et al. Effect of power ultrasound pre-treatment on the physical and functional properties of reconstituted milk protein concéntrate. *J. Food Eng.* **2014**, *124*, 11–18. [\[CrossRef\]](#)
26. Mao, J.; Gao, Y.; Ye, W.; Meng, Z. Impact of high-intensity ultrasound on interfacial protein adsorption of non-dairy whipping cream: Whipping properties and foam stabilization model. *Int. J. Biol. Macromol.* **2025**, *286*, 138466. [\[CrossRef\]](#)
27. Jambrak, A.R.; Mason, T.J.; Lelas, V.; Paniwnyk, L.; Herceg, Z. Effect of ultrasound treatment on particle size and molecular weight of whey proteins. *J. Food Eng.* **2014**, *121*, 15–23. [\[CrossRef\]](#)

28. Hong, Z.; Kong, Y.; Guo, R.; Huang, Q. Stabilizing effect of silver carp myofibrillar protein modified by high intensity ultrasound on high internal phase emulsions: Protein denaturation, interfacial adsorption and reconfiguration. *Int. J. Biol. Macromol.* **2024**, *265*, 130896. [\[CrossRef\]](#)
29. Zhao, R.; Fu, W.; Li, D.; Dong, C.; Bao, Z.; Wang, C. Structure and functionality of whey protein, pea protein, and mixed whey and pea proteins treated by pH shift or high-intensity ultrasound. *J. Dairy Sci.* **2023**, *107*, 726–741. [\[CrossRef\]](#)
30. Zheng, H.; Huang, C.; Liu, S.; Chen, X.; Wang, X.; Hu, P. Effect of ultrasound treatment on the oxidation and conformational structure of myofibrillar protein of beef marinated in red sour soup. *Meat Sci.* **2025**, *224*, 109779. [\[CrossRef\]](#)
31. Duan, Y.; Yang, X.; Deng, D.; Zhang, L.; Ma, X.; He, L.; Zhu, X.; Zhang, X. Effects of ultrasonic waves of different powers on the physicochemical properties, functional characteristics, and ultrastructure of bovine liver peptides. *Ultrason. Sonochem.* **2024**, *110*, 107031. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Frydenberg, R.P.; Hammershøj, M.; Andersen, U.; Greve, M.T.; Wiking, L. Protein denaturation of whey protein isolates (WPIs) induced by high intensity ultrasound during heat gelation. *Food Chem.* **2016**, *192*, 415–423. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Farahnak, R.; Nourani, M.; Riahi, E. Ultrasound thawing of mushroom (*Agaricus bisporus*): Effects on thawing rate, protein denaturation and some physical properties. *LWT-Food Sci. Technol.* **2021**, *151*, 112150. [\[CrossRef\]](#)
34. Lai, Y.; Zhu, Y.; Li, X.; Zhang, G.; Lian, J.; Wang, S. Ultrasound-induced structural changes in partial nitrification sludge: Unravelling the mechanism for improved nitrogen removal. *Environ. Res.* **2024**, *261*, 119637. [\[CrossRef\]](#)
35. Vanga, S.K.; Wang, J.; Orsat, V.; Raghavan, V. Effect of pulsed ultrasound, a green food processing technique, on the secondary structure and in-vitro digestibility of almond milk protein. *Food Res. Int.* **2020**, *137*, 109523. [\[CrossRef\]](#)
36. Li, K.; Kang, Z.L.; Zhao, Y.Y.; Xu, X.L.; Zhou, G.H. Use of high-intensity ultrasound to improve functional properties of batter suspensions prepared from pse-like chicken breast meat. *Food Bioprocess Technol.* **2014**, *7*, 3466–3477. [\[CrossRef\]](#)
37. Hu, H.; Wu, J.; Li-Chan, E.C.; Zhu, L.; Zhang, F.; Xu, X.; Fan, G.; Wang, L.; Huang, X.; Pan, S. Food Hydrocolloids Effects of ultrasound on structural and physical properties of soy protein isolate (SPI) dispersions. *Food Hydrocoll.* **2013**, *30*, 647–655. [\[CrossRef\]](#)
38. Chen, X.; Wei, L.; Mao, Y.; Zhao, A.; Pu, M.; Liu, Y.; Wang, B. A Comparative study of ultrasound and thermal processing: Effects on stability and protein structure in goat milk. *J. Dairy Sci.* **2025**, *in press*. [\[CrossRef\]](#)
39. Xue, S.; Xu, X.; Shan, H.; Wang, H.; Yang, J.; Zhou, G. Effects of high-intensity ultrasound, high-pressure processing, and highpressure homogenization on the physicochemical and functional properties of myofibrillar proteins. *Innov. Food Sci. Emerg. Technol.* **2018**, *45*, 354–360. [\[CrossRef\]](#)
40. Wang, Z.; Zhao, H.; Tao, H.; Yu, B.; Cui, B.; Wang, Y. Ultrasound improves the physicochemical and foam properties of whey protein microgel. *Front. Nutr.* **2023**, *10*, 1140737. [\[CrossRef\]](#)
41. Chen, W.; Ma, H.; Wang, Y.Y. Recent advances in modified food proteins by high intensity ultrasound for enhancing functionality: Potential mechanisms, combination with other methods, equipment innovations and future directions. *Ultrason. Sonochem.* **2022**, *85*, 105993. [\[CrossRef\]](#)
42. Ampofo, J.; Ngadi, M. Ultrasound-assisted processing: Science, technology and challenges for the plant-based protein industry. *Ultrason. Sonochem.* **2022**, *84*, 105955. [\[CrossRef\]](#) [\[PubMed\]](#)
43. Mir, N.A.; Riar, C.S.; Singh, S. Physicochemical, molecular and thermal properties of high-intensity ultrasound (HIUS) treated protein isolates from album (*Chenopodium album*) seed. *Food Hydrocoll.* **2019**, *96*, 433–441. [\[CrossRef\]](#)
44. Zhang, W.; Boateng, I.D.; Xu, J. How does ultrasound-assisted ionic liquid treatment affect protein? A comprehensive review of their potential mechanisms, safety evaluation, and physicochemical and functional properties. *Compr. Rev. Food Sci. Food Saf.* **2024**, *23*, e13261. [\[CrossRef\]](#)
45. Chavan, P.; Sharma, P.; Sharma, S.R.; Mittal, T.C.; Jaiswal, A.K. Application of High-Intensity Ultrasound to Improve Food Processing Efficiency: A Review. *Foods* **2022**, *11*, 122. [\[CrossRef\]](#)
46. Tan, M.C.; Chin, L.N.; Yusof, Y.A.; Taip, F.S.; Abdullah, J. Characterisation of improved foam aeration and rheological properties of ultrasonically treated whey protein suspension. *Int. Dairy J.* **2015**, *43*, e7–e14. [\[CrossRef\]](#)
47. Singh, A.; Benjakul, S.; Kijroongrojana, K. Effect of ultrasonication on physicochemical and foaming properties of squid ovary powder. *Food Hydrocoll.* **2018**, *77*, e286–e296. [\[CrossRef\]](#)
48. Stefanović, A.B.; Jovanović, J.R.; Dojčinović, M.B.; Lević, S.M.; Nedović, V.A.; Bugarski, B.M.; Knežević-Jugović, Z.D. Effect of the controlled high-intensity ultrasound on improving functionality and structural changes of egg white proteins. *Food Bioprocess Technol.* **2017**, 1224–1239. [\[CrossRef\]](#)
49. Morales, R.; Martínez, K.D.; Ruiz-Henestrosa, V.M.P.; Pilosof, A.M.R. Modification of foaming properties of soy protein isolate by high ultrasound intensity: Particle size effect. *Ultrason. Sonochem.* **2015**, *26*, 48–55. [\[CrossRef\]](#) [\[PubMed\]](#)
50. Xiong, T.; Xiong, W.; Ge, M.; Xia, J.; Li, B.; Chen, Y. Effect of high intensity ultrasound on structure and foaming properties of pea protein isolate. *Food Res. Int.* **2018**, *109*, 260–267. [\[CrossRef\]](#)

51. Flores-Jiménez, N.T.; Ulloa, J.A.; Urías Silvas, J.E.; Ramírez Ramírez, J.C.; Rosas Ulloa, P.; Bautista Rosales, P.U.; Silva Carrillo, Y.; Gutiérrez Leyva, R. Effect of high-intensity ultrasound on the compositional, physicochemical, biochemical, functional and structural properties of canola (*Brassica napus* L.) protein isolate. *Food Res. Int.* **2019**, *121*, 947–956. [[CrossRef](#)] [[PubMed](#)]
52. Arruda, T.R.; Vieira, P.; Silva, B.M.; Freitas, T.D.; Amaral, A.J.B.D.; Vieira, E.N.R.; Leite Júnior, B.R.C. What are the prospects for ultrasound technology in food processing? An update on the main effects on different food matrices, drawbacks, and applications. *J. Food Process Eng.* **2021**, *4*, e13872. [[CrossRef](#)]
53. Saran, V.; Pavithra, R.; Koli, V.; Dattatrya, P.A.; Nikashini, T.; Ashika, R.; Gowda, N.A.N.; Sunil, C.K. Ultrasound modification of techno-functional, structural, and physico-chemical properties of legume proteins: A review. *Food Biosci.* **2024**, *60*, 104456. [[CrossRef](#)]
54. Jadhav, H.B.; Das, M.; Das, A.; Geetha, V.; Choudhart, P.; Annapure, U.; Alaskar, K. Enhancing the functionality of plant-based proteins with the application of ultrasound-A review. *Meas. Food* **2024**, *13*, 100139. [[CrossRef](#)]
55. Lei, Y.; Hou, J.; Fang, C.; Tian, Y.; Naidu, R.; Zhang, J.; Zhang, X.; Zeng, Z.; Cheng, Z.; He, J.; et al. Ultrasound-based advanced oxidation processes for landfill leachate treatment: Energy consumption, influences, mechanisms and perspectives. *Ecotoxicol. Environ. Saf.* **2023**, *263*, 115366. [[CrossRef](#)]
56. Knorr, D.; Zenker, M.; Heinz, V.; Lee, D.U. Applications and potential of ultrasonics in food processing. *Trends Food Sci. Technol.* **2004**, *15*, 261–266. [[CrossRef](#)]
57. Gallo, M.; Ferrara, L.; Naviglio, D. Application of ultrasound in food science and technology: A perspective. *Foods* **2018**, *7*, 164. [[CrossRef](#)]
58. Awad, T.S.; Moharram, H.A.; Shaltout, O.E.; Asker, D.; Youssef, M.M. Applications of ultrasound in analysis, processing and quality control of food: A review. *Food Res. Int.* **2012**, *48*, 410–427. [[CrossRef](#)]
59. Bhargava, N.; Mor, R.S.; Kumar, K.; Sharanagat, V.S. Advances in application of ultrasound in food processing: A review. *Ultrason. Sonochem.* **2021**, *70*, 105293. [[CrossRef](#)]
60. Nazari, B.; Mohammadifar, M.A.; Shojaee-Aliabadi, S.; Feizollahi, E.; Mirmoghtadaie, L. Effect of ultrasound treatments on functional properties and structure of millet protein concentrate. *Ultrason. Sonochem.* **2018**, *41*, 382–388. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.