Sustainable Food Technology

ROYAL SOCIETY OF CHEMISTRY

REVIEW

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Cite this: Sustainable Food Technol., 2026, 4, 1411

Unravelling the impact of high-intensity ultrasound on the water mobility of meat products by LF-NMR

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Received 15th August 2025
Accepted 27th December 2025

DOI: 10.1039/d5fb00477b

rsc.li/susfoodtech

High-intensity ultrasound (HIUS) is a green, cost-effective, and safe non-thermal technology that has been widely studied for the processing of meat and meat products, including brining, freezing, thawing, and cooking. It's based on acoustic waves applied through a liquid medium that generates cavitation bubbles, which implode, causing thermal, mechanical, and chemical damage to the food matrix. Given that the muscle is composed mainly of water, it's expected that HIUS can modify the water distribution in meat. This review aims to evaluate the effects of high-intensity ultrasound (HIUS) on water mobility in meat products using low-field NMR (LF-NMR) technology. To this end, articles that applied HIUS directly to the meat matrix and used LF-NMR technology to assess changes in water distribution and mobility were considered. Following a systematic search in the Scopus, Embase, and Web of Science databases, 57 articles were selected after screening, and 7 were added manually, totaling 64 articles. The results were divided based on the process evaluated in each article, which includes the application of HIUS. Thus, the following processes were evaluated: curing, freezing, thawing, heating, fermentation, bacterial inactivation, and quality improvement (HIUS only). The results demonstrated that the effects of HIUS on water retention depend mainly on operational parameters, such as time, power, and frequency, and can also be influenced by the nature of the matrix, the equipment, the process itself, and the application method. Furthermore, the possibilities of applying HIUS to meat products and their challenges were also discussed.

Sustainability spotlight

The water mobility and distribution in meat products is a good indicator of structural changes in these products. Low-field nuclear magnetic resonance (LF-NMR) is a cheap and fast technique often utilized for this. HIUS is an environmentally friendly, low-cost and safe non-thermal technology, which causes several physicochemical changes in meat tissue, which can affect the water mobility and its distribution in these products. The aim of this review is to understand the effects of high-intensity ultrasound (HIUS) on the water mobility of meat products. This study can contribute to the formation of a more environment-friendly food industry, as both techniques (LF-NMR and HIUS) are recognized as green technologies. This work is aligned with the Sustainable Development Goals 7 (affordable and clean energy) and 9 (industry, innovation and infrastructure).

1 Introduction

The growing world population is driving the demand for high-quality meat.[1,2] Meat is fundamental to human nutrition, as it is a rich source of energy and essential nutrients such as proteins, zinc, iron, and vitamin B_{12}.[1] However, its high nutritional value combined with its high water content makes the product highly perishable.[3] Given this scenario, the meat industry has been

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using several traditional methods for food preservation, such as heating, freezing, and drying, to provide high-quality, safe, and durable products.[3] On the other hand, these methods cause nutritional and sensory deterioration, do not ensure the complete inactivation of foodborne pathogens, are costly, energy-intensive, and have negative environmental impacts.[4,5] Therefore, low-cost and environmentally friendly processes that ensure microbial safety, quality, and shelf-life, and maintain the nutritional and sensory attributes of meat and meat products are desirable.[6] In this scenario, non-thermal preservation technologies (NTTs), such as ultraviolet type C (UV-C), gamma radiation, high hydrostatic pressure (HPP), alternative chemical compounds (ACC), and high-intensity ultrasound (HIUS), are effective alternatives for meat processing, capable of maintaining or improving the quality and shelf-life of meat and meat products.[7] Among these methods, HIUS has attracted attention for its results on meat tenderization and for the possibilities of application in different meat processes, such as curing, freezing, and thawing.[8,9]

Ultrasound is an environmentally friendly, economical, and safe NTT for food processing based on acoustic waves greater than 20 kHz. Ultrasound can be classified as low-intensity (<100 kHz; < 1 W cm^{-2}) and high-intensity (20–500 kHz; >1 W cm^{-2}) ultrasound, and can be applied directly using a probe or by immersing the product in an ultrasonic bath.[10,11] Whereas the bath system is more cost-effective, as it can process several samples per batch, the probe system is more potent due to its smaller application area and direct contact with the sample, in addition to having lower acoustic energy losses, as it directly contacts the sample.[11] Furthermore, the propagation of the ultrasonic waves is irregular in the bath system due to their reflection in the bath walls. In contrast, in the probe system, the release of the metal that constitutes the probe can occur, contaminating the treated sample.[12] Another important aspect of the HIUS application is the application mode, which can be continuous or pulsed. The first one, although it is better in terms of microbiological inactivation, causes an increase in temperature.[12] The HIUS, when it is applied in a liquid medium, causes the cavitation phenomenon, generating bubbles that expand and contract continuously until they reach the critical volume and implode. The implosion of the cavitation bubbles causes the formation of micro-jets, free radicals, reactive oxygen species (ROS), and hot spots.[7] The increase in pressure and temperature due to the implosion of the cavitation bubbles breaks down the water molecules, generating H^+ and OH^-, thus promoting chemical reactions and modifying other molecules. Furthermore, the bubbles attract each other, generating microstreaming that can improve the diffusion of reactants, enhance mass and heat transfer, and cause damage to solid surfaces.[13] Thus, HIUS processing can cause significant structural changes in meat proteins, affecting important quality parameters, including water holding capacity (WHC), water distribution within the meat structure, juiciness, tenderness, and general appearance.[5]

Therefore, HIUS can cause changes on both microscopic and macroscopic scales when applied to biological tissues and may have positive effects on meat processing, such as accelerating and improving curing, drying, and tenderization.[14,15] However, it is worth noting that the effects of HIUS application on the

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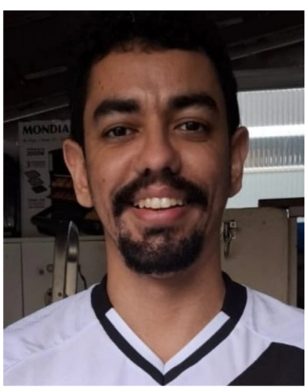

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physicochemical properties of the meat products are often contradictory, depending on the intensity, time, frequency, application system, and the matrix itself.[5,14] Some of the adverse effects of the cavitation induced by the HIUS include thermal damage and macromolecule depolymerization, even in the absence of bubble implosion, in addition to the oxidative stress resulting from the free radicals (ROS) and the local overheating, thus impairing the product quality.[14] From this, it can be seen that the effects of the HIUS application on the physicochemical properties of meat and meat products are, to some extent, difficult to control, which is a significant challenge for this technology.

Given that muscle tissue is composed mostly of water, primarily within the myofibrils, the structural changes induced by HIUS in the muscle structure result in alterations in water mobility and distribution.[16] In fact, as reviewed by Kang *et al.*,[5] the HIUS application is capable of improving the gel-forming ability and the solubility of the proteins, and, consequently, the WHC of the meat, when operational parameters such as intensity, frequency, and time are correctly chosen. Hence, the changes in the physicochemical properties of the meat induced by the ultrasound application were the premise of the work by Stadnik *et al.*,[17] who evaluated the effects of HIUS application on beef during ageing by evaluating its WHC, water mobility, and distribution. Additionally, considering the complex structure of the muscle, which is composed mainly of proteins and connective tissue, water, a small molecule, can accumulate at various levels within it. Therefore, evaluating the mobility and distribution of the water in meat can provide important information about its structure.

The Low-Field Nuclear Magnetic Resonance (LF-NMR) technology is an effective tool for this purpose. The LF-NMR technology is a cost-effective, rapid, and non-invasive technique widely used for determining the distribution and mobility of water in foods.[18,19] It is based on the absorption of resonance radiofrequency pulses by protons aligned with an external magnetic field, B_0.[20] The absorption of this energy causes the protons to rotate in a plane perpendicular to B_0. When the pulses cease, relaxation occurs, involving two phenomena. (I) The protons return to rotate in their original direction, aligned with B_0. This is the longitudinal (or spin–lattice) relaxation, and its characteristic constant time is T_1. This is the result of the energy change between the protons and their surroundings (lattice). (II) Randomization (or the loss of phase coherence) of the protons occurs in the plane perpendicular to B_0. This is the transversal (or spin–spin) relaxation, and is governed by the constant time T_2. The proton interactions cause differences in local magnetic fields, leading to different T_2 values.[21] According to the diffusive and chemical exchange model, the water molecules diffuse to the biopolymer surface and exchange with the biopolymer protons, thus providing information about the morphological state of the biopolymers.[21] Therefore, under this model, the proton populations can be classified based on their transversal relaxation time, T_2, as follows. (i) T_{2b}, with the lowest relaxation time and the lowest relative population, P_{2b}, assigned to protein protons and water closely associated with proteins. This proton population is commonly recognized as "bound water".[21] (ii) T_{21}, with intermediate relaxation time and the highest relative population, P_{21}, relative to water entrapped by intermolecular interactions, such as hydrogen bond and steric effects, and related to sarcomere lengths, juiciness, and taste. This proton population, in meat products is often called "immobilized water".[22,23] (iii) T_{22}, with the highest relaxation time, and relative population P_{22}, assigned to water weakly associated with the matrix, between fiber bundles, in the sarcoplasmic area which can be easily lost and utilized by microorganisms. This water population is often recognized as "free water".[24,25] Therefore, LF-NMR can provide several information about the meat morphology. However, this technology has some limitations, including low sensitivity and data that are difficult to process and interpret. Besides this, the algorithm used to process the data and the sample processing can affect the results, and there are still controversies about the relationship between water mobility and its distribution in meat and meat products.[16,20,21] Furthermore, the T_2 relaxation patterns can vary depending on several factors such as the species, muscle type, slaughter procedure, pH, and temperature.[16]

Thus, this systematic review aims to discuss the changes induced by HIUS on water mobility and distribution in meat and meat products, as well as the main mechanisms described in the literature. To this end, the effects of HIUS applied alone and in combination with other processes are evaluated, as well as its synergistic effects on water mobility using LF-NMR technology. Furthermore, the relationships between water mobility and other quality parameters, as well as the challenges and gaps in the literature regarding the HIUS application, are also discussed.

2 Materials and methods

2.1 Systematic search

The systematic search was completed in June 2024 in the following databases: Web of Science, Scopus, and Embase. The search string was obtained through the PICO (Population, Intervention, Comparison, and Outcomes) methodology. The search aimed to answer the following question: what is the effect of ultrasound on water mobility in meat products? For this, all studies that applied the HIUS directly to meat products (*in natura* or derivatives), alone or combined with other preservation technologies, were considered.

Thus, the search terms were: "pork", "meat", "chicken", "fish", "beef" (population), "ultrasound" (intervention), "moisture", "water", "distribution", "compartmentalization", "migration", and "mobility" (context). The final search string was obtained by the combination of these blocks using the appropriate Boolean operators: [("moisture" OR "water") AND ("distribution" OR "compartmentalization" OR "migration" OR "mobility") AND ("pork" OR "meat" OR "chicken" OR "fish" OR "beef") AND "ultrasound"].

2.2 Eligibility criteria

The articles included in this review were selected following the PRISMA (Preferred Reporting Items for Systematic Reviews and

Table 1 Inclusion and exclusion criteria[a]

Inclusion criteria	Exclusion criteria
Use of LF-NMR as an approach to evaluate water mobility Application of HIUS as processing technology Meat and meat products as population	Review articles; meta-analysis; book chapters; annals; conference papers, abstracts, theses and dissertations Articles not written in English

[a] HIUS: high-intensity ultrasound, LF-NMR: low-field nuclear magnetic resonance.

Meta-Analyses) methodology.[26] The removal of duplicated articles and the further screening processes were carried out using the *StArt*© (State of the Art through Systematic Review) software. Only articles written in English were included in the review, with no restriction on the publication date. The inclusion and exclusion criteria are listed in Table 1.

2.3 Risk of bias

This work may have a potential source of bias, including language, the chosen databases, inclusion and exclusion criteria, the period of the systematic search, and the impact of missing data.

3 Results and discussion

3.1 Search results

The search returned 347 articles (Web of Science: 141; Embase: 80; and Scopus: 126), of which 136 were duplicates. From the remaining 211 articles, 115 were excluded after reading titles and abstracts, and 39 were excluded after full reading because they did not fit with the eligibility criteria, totaling 57 articles included in the review (Fig. 1). Furthermore, seven papers were added manually. The reviewed articles are organized in Table 2 according to the application of HIUS in each work: curing (20), freezing (11), thawing (22), quality improvement (4), bacterial inactivation (1), fermentation (2), and heating (4) (Fig. 2). The following matrices were analyzed: fish (23), pork (19), chicken (13), beef (8), mollusks (2), and mutton (1). The meat matrices by treatment are presented in Fig. 3. The findings were expressed based on the LF-NMR results of each article, and the fundamental aspects of the processes were compiled, considering aspects such as the equipment (probe or bath), the variables assessed, and the groups studied, using the same labels as the authors.

3.2 Cure

Traditional curing methods have some challenges, such as (i) the high salt content in meat, needing a posterior desalting process, (ii) possible cross-contamination due to manipulation and handling, and (iii) textural damage.[5] The HIUS technology may be applied in the curing process for the improvement of the mass transfer of salt to meat, thus reducing the cure time and resulting in a product with less salt than traditional methods.[5,14] Additionally, HIUS is suggested to reduce microbial load and improve or maintain product texture when applied as a brining-assisted technology, thereby avoiding the limitations of traditional curing methods.[11,15]

Recent studies reported that ultrasound-assisted curing improved the WHC of meat products (Table 2). The mechanism used to explain these results involves the swelling of myofibrils and the extraction of soluble proteins, caused by the increased mass transfer of brine in meat induced by HIUS.[15] The salt ions can bind to myofibrillar proteins, causing electrostatic repulsion and increasing the space between them.[27] The enhanced gaps allow the exposition of protein side chains that can bind to water molecules.[28] LF-NMR measurements carried out by Xiong *et al.*[29] found that HIUS-assisted cure of chicken breast decreased T_{21} values, indicating that the immobilized water is more tightly bound to the matrix and its conversion to free water is impaired; meanwhile, Kang *et al.*[30] reported that at high ultrasonic powers (250 W or 300 W) and treatments above 120 min, T_{21} values increased in beef *longissimus dorsi*. This is in accordance with the study by McDonnell *et al.*,[31] which did not observe a significant difference in bound and free water constant times in HIUS-treated samples but found that 19 W cm^{-2} treatments increased T_{21} values.

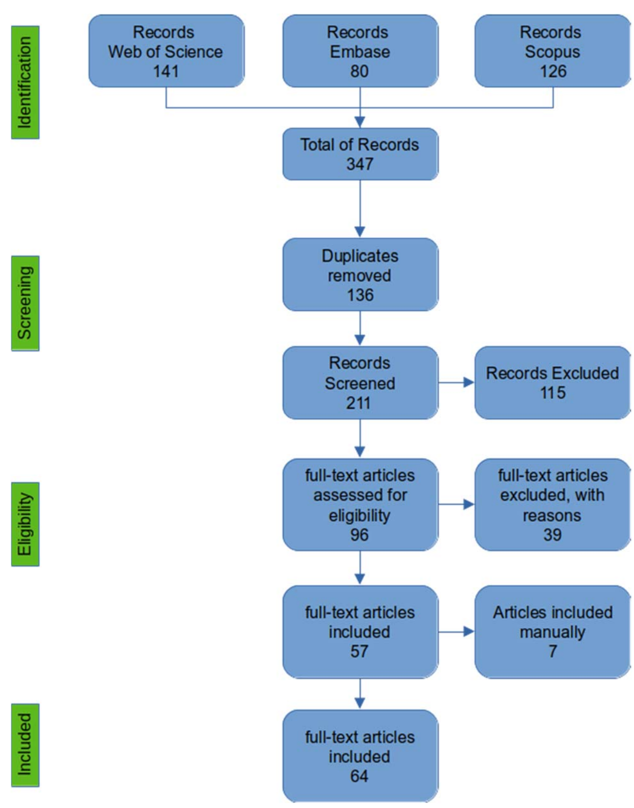

Fig. 1 PRISMA flowchart of the systematic review search.

Table 2 Water mobility effects of high-intensity ultrasound in meat processing[a]

Processing	Matrix/product	Parameters US (W; W mL^{-1}; W cm^{-2}; W L^{-1}; Hz; kHz; min; h)	Process	Findings	References
Curing	Reduced-salt pork batter (*Mesoglutaeus*)	40 kHz; 192 W; 0–60 min	• 25 g NaCl, 0 g $NaHCO_3$; 0 min • 20 g NaCl and 2 g $NaHCO_3$; 0 min • 20 g NaCl and 2 g $NaHCO_3$; 30 min • 20 g NaCl and 2 g $NaHCO_3$; 60 min • The prepared batter was vacuum packaged and then sonicated using an ultrasonic machine	• Increase in the content of P_{21} and decrease of P_{22} on addition of sodium bicarbonate and increase of HIUS time • T_{21} and T_{22} values decreased with addition of sodium bicarbonate and increased with increase of HIUS time	Kang *et al.*[25]
	Chicken meat breast batter (*Pectoralis major*)	40 kHz; 300 W; 10, 20, 30 and 40 min	• Meat batters with varying salt content % (w/w): 1.0%, 1.5% and 2.0%	• The 20 and 40 min treatments did not change T_2 constant times significantly, for any salt level	Li *et al.*[87]
			• Ultrasonic bath	• The samples treated with HIUS for 20 min had a higher proportion of immobilized water and lower proportion of free water	
	Pork (*M. semitendinosus*)	20 kHz; 9.0 and 54.9 W cm^{-2}; 120 min	• The HIUS treatment was performed using an ultrasonic probe in 1000 mL of 50 g L^{-1} brine solution (NaCl or salt replacer(SR))	• Decrease in T_{21} and increase in T_{22} values after 120 min of brine for NaCl and SR • Decrease of P_{21} with the increase of ultrasonic power • Lower water retention than control • Greater water exudation with increasing ultrasonic intensity	Ojha *et al.*[34]
	Beef (*longissimus dorsi*)	20 kHz; 150, 200, 250 and 300 W; 30 and 120 min	• HIUS-assisted brine	• The 150 and 200 W treatments did not significantly affect T_{21} values	Kang *et al.*[30]
			• Ultrasonic probe	• The treatments of 250 and 300 W led to an increase in T_{21} values • Treatments lasting more than 120 min showed higher T_{21} values	
			• Brine (w/v): sucrose (1.5%), sodium tripolyphosphate (0.16%), sodium pyrophosphate (0.16%) and sodium hexametaphosphate (0.8%)	• P_{21} increased with increase of power and treatment time	
	Chicken breast (*pectoralis major*)	20 kHz; 200 W; 15.6 W cm^{-2}; 5 min	• Ultrasonic probe (12 mm diameter)	• The HIUS treatment improved water retention in treated samples (UDW and UCP)	Zou *et al.*[68]
			• UDW: HIUS treatment and immersion of the sample in deionized water for 55 min, 4 °C		
			• UCP: HIUS treatment and later immersion of the sample in collagen peptide solution from chicken cartilage (CCCP) for 55 min, 4 °C		

Table 2 (*Contd.*)

Processing	Matrix/product	Parameters US (W; W mL^{-1}; W cm^{-2}; W L^{-1}; Hz; kHz; min; h)	Process	Findings	References
	Chicken breast (*pectoralis major*)	20 kHz; 300 W; 50 min (5 s on/5 s off)	• 40 mm × 30 mm × 10 mm pieces weighing about 20 ± 1 g • USC: HIUS combined with sodium bicarbonate-assisted curing (solution with 6% salt and 2% sodium bicarbonate) • (5 cm × 4 cm × 3 cm), 50 g ± 2 g pieces	• UCP samples had the highest P_{21} values for the same storage time • Increase in time constants of bound water	Xiong *et al.*[29]
	Pork (*m. longissimus thoracis et lumborum*)	20 kHz; 4.2, 11.0 and 19.0 W cm^{-2}; 10, 25 and 40 min	• 6-mm ultrasonic probe (2 cm away from the meat) • Cylindrical samples (35ϕ × 4.2 mm), weighing 4.2 ± 0.5 g	• Decrease of T_{21} and T_{22} values • The treatment does not affect the bound and free water populations significantly	McDonnell *et al.*[31]
	Chicken breast (*pectoralis major*)	40 kHz; 300 W; 10, 20, 40 and 80 min	• Ultrasonic probe • 65 mL brine solution (5.7% (w/w) NaCl) • HIUS treatment (UT) (80 min, only) • HIUS-assisted enzyme (UET-10, 20, 40 and 80 min) • UET samples were injected with 1/10 of their weights with papain 45 U g^{-1} • Ultrasonic bath at 30 °C	• The 19 W cm^{-2} treatments increased T_{21} values • UT and UET treatments shortening T_{2b} values • UT and UET-10, 20 and 40 samples showed increase of P_{21} and decrease of P_{22} values • UET treatment decreased T_{22} values compared to enzyme treatments without HIUS	Cao *et al.*[32]
	Surimi (*Nemipterus virgatus*)	40 kHz; 150 W; 20 min	• 30 mm × 30 mm × 20 mm pieces weighing 9.00 ± 0.50 g • The HIUS was applied with and without curdlan gum 0.4% (w/w)	• HIUS treatments less than 20 min longer showed positive effects on WHC • HIUS and curdlan alone and HIUS-combined curdlan showed higher immobilized content and the lowest free water content	Zhang *et al.*[88]
	Chicken meat paste (*pectoralis major*)	20 kHz; 300 W; 1 min, 3 times (2 s on/4 s off)	• Sonicated samples: UT: 1% salt (NaCl); CAR-UT: 1% salt and 0.3% carrageenan; CUD-UT: 1% salt and 0.3% curdlan	• HIUS-treated samples showed decreased P_{2b}, without significant difference for P_{21} and P_{22} compared to control • CAR-UT showed lower P_{2b} than the CAR group • The CUD-UT group showed higher T_{21} and T_{22} values compared to the CUD group	Zhao *et al.*[89]
	Chicken breast (*pectoralis major*)	40 kHz; 300 W; 60 min; 7.84 W cm^{-2}	• Ultrasonic probe • The samples were marinated with 2% complex phosphate at 4 °C for 30 min and then sonicated	• Decrease of T_{2b} • Increase of T_{21} and P_{21} • T_{22} and P_{22} disappeared compared to deionized water curing	Tong *et al.*[90]
	Sea bass (*Lateolabrax japonicus*)	20 kHz; 600 W; 10 min	• HIUS in distilled water (UA); HIUS in 1% chitosan-grafted-chlorogenic acid solution (GUA)	• GUA samples had higher P_{21} and lower P_{22} values	Yang *et al.*[91]
	Silver carp surimi (*Hypophthalmichthys molitrix*)	120, 150, 180, 210 and 240 W; 10, 15, 20 and 30 min	• 150 g samples sealed in a 160 × 240 × 0.2 mm polyethylene bag	• Low-salt (0–0.5%) samples treated by HIUS, had lower P_{22} and higher P_{21} values than control	Gao *et al.*[92]

Table 2 (*Contd.*)

Processing	Matrix/product	Parameters US (W; W mL^{-1}; W cm^{-2}; W L^{-1}; Hz; kHz; min; h)	Process	Findings	References
	Beef (*m. semitendinosus*)	20 kHz; 300 W; 15.6 W cm^{-2}; 5 min	• Ultrasonic bath varying salt contents • UDW: HIUS pretreatment and further marination in deionized water for 55 min • UMH: HIUS pretreatment and further marination in L-histidine (1.5 g L^{-1}) solution for 55 min • 50 mm × 20 mm × 10 mm samples, weighing about 30 ± 1 g	• HIUS treatment decreased T_{22} values in any salt level • HIUS-treated samples had lower T_{21} values • UDW and UMH samples had higher P_{21} and P_{22} than control	Shi *et al.*[93]
	Pork loin (*longissimus*)	25 kHz; 320 W; 30 min; 10 s on/5 s off	• Ultrasonic probe • HIUS combined with glycerol-mediated curing in different concentrations • 50 × 40 × 10 mm^3 pieces (50 ± 1 g)	• Decrease of T_{21} and T_{22} values	Gu *et al.*[94]
	Snakehead fish (*Channa argus*)	40 kHz; 216 W; 10 min	• Ultrasonic probe • HIUS-assisted impregnation with a cryoprotectant solution	• Conversion of immobilized water into bound water and decrease of P_{22} • Lower moisture loss	Zheng *et al.*[95]
	Reduced-sodium bacon (pork belly)	20 kHz; 300 and 800 W; 30 and 60 min; 3 s on/3 s off	• Ultrasonic bath • HIUS-assisted dry curing (UDC) • 120 × 90 × 30 mm samples weighing 200 ± 20 g	• The (300 W/60 min) and (800 W/30 min) treatments increased T_{21} values	Pan *et al.*[96]
	Pork (*longissimus dorsi*)	20, 40, and 60 kHz; 20/40 kHz, 20/60 kHz, and 40/60 kHz; 20 + 40 kHz, 20 + 60 kHz, and 40 + 60 kHz; 50 W L^{-1}. 20 + 40 kHz, 20 + 60 kHz, 40 + 60 kHz, and 20 + 40 + 60 kHz; 100 W L^{-1}	• Ultrasonic probe • HIUS-assisted brine in different frequency modes (mono-, dual-) And tri-frequency) in sequential (SEU) and simultaneous modes (SIU) • Ultrasonic bath	• Samples treated by HIUS had higher T_{2b} and T_{21} values, but lower T_{22} than control samples	Guo *et al.*[97]
	Yellowfin tuna (*Thunnus albacares*)	20 kHz; 540 W; 30 min	• HIUS-assisted salting • 3 × 3 × 1 cm^3 samples weighing 11 ± 1 g	• Samples treated with HIUS showed better water retention than the control group	He *et al.*[98]
	Pork (*longissimus dorsi*)	20 + 40 kHz; 400 W; 5 min	• Ultrasonic bath • Dual-frequency HIUS combined with L-lysine treatment • 10 cm × 4 cm × 2 cm samples weighing 50 g ± 2 g	• Higher P_{2b} and P_{21} values, and lower P_{22} values	Xu *et al.*[99]
Freezing	Prepared ground pork (boneless pork leg)	20 kHz; 80 W L^{-1}; 10 s on/15 s off	• HIUS-assisted immersion freezing (UIF)	• The samples treated with HIUS showed the smallest changes in the immobilized water population and the lowest P_{22} values after 90 days of storage among treated samples	Wu *et al.*[100]

Table 2 (*Contd.*)

Processing	Matrix/product	Parameters US (W; W mL^{-1}; W cm^{-2}; W L^{-1}; Hz; kHz; min; h)	Process	Findings	References
			• The sample was treated using an ultrasonic probe in a constant temperature tank, filled with a mixture of 95% ethanol/5% fluoride	• T_{21} values of UIF samples had minor changes	
			• The treatment was interrupted when the center temperature reached −18 °C	• The T_{2b} values showed lower increase between the days 30 and 90 of storage. No significant changes for P_{2b} values	
	Chicken breast (*pectoralis major*)	30 kHz; 125, 165, 205, and 245 W; 8 min (30 s on/30 s off)	• HIUS-assisted immersion freezing (UF) • Ultrasonic bath • 7-cm-long pieces with 110 ± 6 g • Temperature kept at −25 ± 0.5 °C, using 95% ethanol/5% fluoride (v/v) as the coolant with a continuous flow of 1.5 L min^{-1}	• There were no significant differences in T_{2b} and P_{2b} values • UF-165 treatment had lower water mobility and T_{21} values	Zhang *et al.*[41]
			• The HIUS was applied when the central temperature of samples reached 0 °C	• UF-245 treatment led to a decrease in P_{21} and increase in P_{22} values	
	Common carp (*Cyprinus carpio*)	30 kHz; 175 W; 9 min (30 s on/30 s off)	• 5-cm-long pieces with 210 ± 15 g • HIUS-assisted immersion freezing (UIF) • Temperature: −25 ± 0.5 °C, 95% ethanol/5% fluoride as the coolant • The treatment was performed until the core temperature reached −18 °C • −18 ± 1 °C for 180 days storage after treatments	• Lower T_{2b}, T_{21} and T_{22} values, during storage than air freezing and immersion freezing methods	Sun *et al.*[101]
	Porcine (*longissimus lumborum*)	30 kHz; 120, 180, 240, and 300 W; 8 min (30 s on/30 s off)	• HIUS-assisted immersion freezing (UIF) • Ultrasonic bath	• The UIF-180 treatment had lower T_{21} and T_{22} values • UIF-180 showed lower water mobility	Zhang *et al.*[40]
			• 95% ethanol/5% fluoride coolant with continuous flows of 1.5 L min^{-1}		
			• 30-mm-thick slices weighed 120 ± 2 g	• The UIF-300 samples had high T_{21} values	
	Porcine (*longissimus lumborum*)	30 kHz; 180 W; 8 min (30 s on/30 s off)	• HIUS-assisted immersion freezing (UIF) performed as described by Zhang *et al.*[40] • 3-cm-thick chops (120 ± 2 g) • The samples were stored at −18 ± 1 °C for 0, 30, 60, 90,	• Lowest T_{2b} values after day 30 • Low water mobility • Lower T_{21} values • Higher P_{21} values • Minor changes in free water	Zhang *et al.*[102]

Table 2 (*Contd.*)

Processing	Matrix/product	Parameters US (W; W mL^{-1}; W cm^{-2}; W L^{-1}; Hz; kHz; min; h)	Process	Findings	References
			120, 150, and 180 days after treatments		
	Common carp (*Cyprinus carpio*)	30 kHz; 125, 150, 175, 200, and 225 W; 30 s on/30 s off; 9 min	• HIUS-assisted immersion freezing (UIF) • 95% ethanol as the coolant • 5-cm chops (210 ± 15 g) • When the central temperature of samples reached approximately −18 °C, they were stored at −18 ± 1 °C for 24 h • Ultrasonic bath	• The UIF-175 samples had the lowest T_{21} value • T_{21} value decreased at low ultrasonic power and increased at higher power levels	Sun *et al.*[103]
	Chicken breast (*pectoralis major*)	30 kHz; 125, 165, 205 and 245 W; 8 min	• UF: HIUS-assisted immersion freezing • 7 cm shops weighing about 110 ± 6 g • HIUS treatment was started when the center temperature of the samples reached 0 °C • The process was stopped when the center temperature of the samples reached −18 ± 0.5 °C • Ultrasonic bath	• UF-165 group had lower T_{21} than IF group • UF-165-treated samples had higher P_{21} and lower P_{22} than IF-treated samples	Zhang *et al.*[104]
	Yellow croaker (*Pseudosciaena crocea*)	25 kHz; 200 W; 30 s on/45 s off	• HIUS-assisted freezing (UIF) • The process was stopped when the center temperature of samples reached −18 °C • After that, the samples were subjected to 5 freeze–thaw cycles • Ultrasonic bath	• The UIF process reduced the loss of immobilized water and the increase of free water	Li *et al.*[73]
	Yellow croaker (*Pseudosciaena crocea*)	28 kHz; 160 W, 175 W and 190 W; 0.800 W L^{-1}, 0.875 W L^{-1} and 0.950 W L^{-1}	• The samples were subjected to vacuum immersion with water (W) and potassium alginate solution (PA) and then to HIUS-assisted freezing (UAF) • The process was stopped when the central temperature of the samples reached −18 °C • 10 cm × 5 cm × 1 cm samples • Ultrasonic bath	• PA-UAF-175 treatment showed the highest T_{21} and P_{21} values • Samples treated at 175 W showed better moisture results, while treatments at 190 W had higher free water contents	Cheng *et al.*[105]
	Chicken breast (*pectoralis major*)	165 W; 8 min; 30 s on 30 s off	• HIUS-assisted immersion freezing (UF) • 7.0 ± 0.2-cm samples weighing 104 ± 5 g • The process was stopped when the temperature of the sample geometric centre was −18 ± 0.5 °C • Ultrasonic bath	• Small increase of T_2 values • P_{21} values higher than air freezing and immersion freezing processes	Zhang *et al.*[106]
	Common carp (*Cyprinus carpio*)	30 kHz; 125, 150, 175, 200 and 225 W; 9 min; 30 s on/30 s off	• HIUS-assisted freezing at different power levels (UF) • 5-cm samples of 210 ± 15 g • Ultrasonic bath	• T_{21} reached the minimum values at 175 W and the maximum at 225 W among HIUS-treated samples • 175 W had the lowest increase of T_{22}	Sun *et al.*[107]

Table 2 (*Contd.*)

Processing	Matrix/product	Parameters US (W; W mL^{-1}; W cm^{-2}; W L^{-1}; Hz; kHz; min; h)	Process	Findings	References
Thawing	Mirror carp (*Cyprinus carpio* L.)	200 W	• HIUS-assisted saline thawing (UST) and HIUS thawing (UT) • The UST treatment was carried out using varying salt contents (0.05%, 0.10% and 0.20%) • Treatments with HIUS until the center temperature of the sample reached 4 °C	• The samples with 0.10% salt content showed the smallest increase in T_{21} value	Li *et al.*[42]
	Common carp (*Cyprinus carpio*)	30 kHz; 100, 300, and 500 W	• HIUS-assisted thawing (UT) • The samples were frozen until the core temperature reached −18 °C • 5-cm-long pieces and 4-cm-thick • The treatment was stopped when the core temperature of the sample reached 4 °C • Ultrasonic bath with distilled water (20 ± 0.5 °C)	• The UT-300 group had the lowest T_{21} values among thawed samples, while the UT-500 group had higher T_{21} values • UT-300 showed the lowest increase in T_{22} values	Sun *et al.*[43]
	Red seabream (*Pagrus major*)	40 kHz; 200 W	• HIUS-assisted thawing (UT) and HIUS-assisted vacuum thawing (UVT) • Ultrasonic bath • Temperature: 10 °C • 8 cm long × 4 cm wide pieces, weighed approximately 100 g	• The UT and UVT treatments showed lower conversion of immobilized water to free water and higher immobilized water content	Cai *et al.*[108]
	Prepared ground pork	20 kHz; 20 s on/25 s; 90, 120 and 150 W L^{-1}	• HIUS-assisted thawing (UIT) • Ultrasonic probe • The process was stopped when the center temperature reached 4 °C • The samples were thawed after 30 days of storage	• The UIT-120 samples had the lowest T_{21} and T_{22} values; and the highest P_{21} value and the lowest P_{22} value • The UIT-150 samples showed increased T_{21} and T_{22} values compared to other HIUS-treated samples	Wu *et al.*[109]
	Frozen beef (sirloin)	22, 33 and 40 kHz; 22/33, 22/40, and 33/40 kHz; 22/33/40 kHz; 100 W L^{-1}	• The samples were thawed using HIUS in different frequency modes (mono-, di- and tri-) • 10 × 10 × 1 cm (about 150 g) • Ultrasonic bath	• The samples treated with 22 and 22/33 kHz modes had lower T_{21} than control • The 22 kHz treatment had higher P_{2b}, P_{21} and P_{22} than control	Wu *et al.*[110]
	Chicken breast (*pectoralis major*)	40 kHz; 200 W	• HIUS-assisted thawing with water (WUT) • Slightly acidic electrolyzed water (SAEW) thawing (EUT) • 3 × 3 × 3 cm^3 (64 ± 5 g) samples	• P_{22} of the EUT group was not significantly different from the control	Kong *et al.*[111]

Table 2 (*Contd.*)

Processing	Matrix/product	Parameters US (W; W mL^{-1}; W cm^{-2}; W L^{-1}; Hz; kHz; min; h)	Process	Findings	References
			• The process was stopped when the center temperature reached 0 °C • Ultrasonic bath		
	Cuttlefish	53 kHz; 200 W	• HIUS water thawing (UWT) • Samples weighing about 1100 ± 50 g • The process was stopped when the center temperature of samples reached 4 °C	• UWT samples had lower T_{21} and T_{22} values than control	Lv & Xie[74]
	Chicken breast (*pectoralis major*)	40 kHz; 200 W	• WUT: HIUS-assisted water thawing • EUT: HIUS-assisted SAEW thawing • 3 cm × 3 cm × 3 cm samples weighing about 64 ± 5 g • Ultrasonic bath	• T_{21} values for EUT-treated samples was not significantly different from the control group • P_{21} values of EUT and WUT groups was not significantly different from the control group	Kong *et al.*[112]
	Red drum (*Sciaenops ocellatus*)	40 kHz; 400 W	• HIUS-assisted thawing (UT) • HIUS combined with microwave thawing (UMT) • Ultrasonics combined far infrared thawing (UIT) • 30 g samples • Ultrasonic bath	• UT, UMT and UIT samples had higher P_{21} values than fresh samples, and UMT was the highest among them • UT samples had highest T_2 values and greater conversion of bound water into immobilized water	Cai *et al.*[113]
	Yellow croaker (*Pseudosciaena crocea*)	28 kHz, 40 kHz and 28/40 kHz; 200 W	• HIUS-assisted thawing in different frequency modes (mono and dual) • The process was stopped when the center temperature of samples reached 4 °C • Ultrasonic bath	• The samples treated with dual-frequency mode treatment had the highest T_{2b} and T_{21} values and WHC	Cheng *et al.*[114]
	Pompano (*Trachinotus ovatus*)	200 W; 33 min	• HIUS-assisted thawing • The process was stopped when the temperature of samples reached 0 °C • Ultrasonic bath	• Free water content was not significantly affected	Lan *et al.*[115]
	Largemouth bass (*Micropterus salmoides*)	40 kHz; 200 W	• Vacuum combined with HIUS thawing • The process was stopped when the temperature of samples reached 0 °C • 3 × 3 × 2 cm^3 samples weighing about 20 g • Ultrasonic bath	• Samples thawed with HIUS had T_{2b} and T_{21} values higher than fresh samples • Decrease of T_{22} • Decrease of P_{21} and increase of P_{22}	Cai *et al.*[116]
	Chicken breast (*pectoralis major*)	30 kHz; 200, 300, 400, and 500 W; 30 s on/30 s off	• HIUS-assisted immersion thawing (UT) • 7-cm long chops weighing 106 ± 3 g • The process was stopped when the geometric center temperature of the samples reached 4 ± 0.5 °C • Ultrasonic bath	• UT-300 samples had the lowest T_{2b}, T_{21} and T_{22} values • UT-300 samples had the highest P_{2b} and P_{21} values and the lowest P_{22} values • Among the HIUS-treated samples, UT-500 group had the highest T_{2b}, T_{21} and T_{22} values • UT-500 treatment decreased P_{21} and increased P_{22} values	Zhang *et al.*[44]
	Large yellow croaker (*Pseudosciaena crocea*)	40 kHz; 200, 240, 280, and 320 W	• HIUS-assisted thawing	• T_{2b} values decreased at 240 W and increased at 320 W	Chu *et al.*[117]

Table 2 (*Contd.*)

Processing	Matrix/product	Parameters US (W; W mL^{-1}; W cm^{-2}; W L^{-1}; Hz; kHz; min; h)	Process	Findings	References
			• The process was stopped at 0 °C • Ultrasonic bath	• The 240 and 280 W groups had the lowest P_{22} values among treated samples • 320 W group had the highest P_{22} value	
	Tuna (*Thunnini*)	40 kHz; 11.63 W cm^{-2}; (280 W; 6, 12, 18, and 24 min); (160, 280, and 400 W; 12 min)	• HIUS-assisted thawing • Ultrasonic bath	• Increase of T_{2b} compared to the control group • T_{21} and T_{22} values increased with treatment time • T_{21} increased with power levels • The 280 W; 12 min treatment had the highest T_{2b} and P_{21} values • P_{21} decreased at 400 W	Ma *et al.*[118]
	Small yellow croaker (*Larimichthys polyactis*)	26, 28 and 30 kHz; 60 W L^{-1}	• HIUS thawing with a fixed frequency at 28 kHz (FFUT) • HIUS-assisted thawing with a sweep frequency of 28 ± 2 kHz (SFUT) • 16 ± 0.5 cm samples weighing 30 ± 0.5 g • Ultrasonic bath	• T_{2b} values of the FFUT group increased, but was not significantly changed in the SFUT group, when compared to the control group • SFUT samples showed higher P_{2b} and P_{21} and lower P_{22} values than the FFUT group	Wang *et al.*[119]
	Large yellow croaker (*Larimichthys crocea*)	20 kHz; 20/28 kHz; 20/28/40 kHz; 0.9 W L^{-1}	• HIUS-assisted thawing in different frequency modes (mono-, di- and tri-) • 30 ± 5 cm samples weighing 500 ± 20 g • The process was stopped when the central temperature of samples reached 4 ± 1 °C • Ultrasonic bath	• P_{2b}, P_{21} and P_{22} values of samples treated with multiple frequencies were not significantly different from fresh samples • For the mono-frequency group, P_{2b} and P_{21} values were lower than those of fresh samples, but P_{22} values were higher	Bian *et al.*[120]
	Chicken breasts (*pectoralis major*)	30 kHz; 200, 300, 400, and 500 W; 30 s on/30 s off	• HIUS-assisted thawing at different power levels • 7-cm-long chops (106 ± 3 g) • The process was stopped when the central temperature of the samples reached 4.0 ± 0.5 °C • Ultrasonic bath	• Samples treated at 300 W had the lowest T_{21} and the highest P_{21} values • 500 W treatments increased T_{21} and decreased P_{21} values	Zhang *et al.*[45]
	Pork (*longissimus lumborum*)	500 W; 20 min	• HIUS-assisted thawing • Samples weighing 100 ± 0.1 g • Ultrasonic bath	• Increase of T_{21}, T_{22} and P_{22}, and decrease of P_{21} compared to fresh samples	Wang *et al.*[121]
	Yellowtail (*Seriola quinqueradiata*)	40 kHz; 200 W	• HIUS-assisted thawing (UT) and microwave combined with HIUS thawing (MUT) • 250 ± 30 g samples • The process was stopped when the central temperature reached 0 °C • Ultrasonic bath	• Decrease of P_{22} in samples treated with HIUS • MUT samples had the best water retention	Shen *et al.*[72]
	Pork (*longissimus dorsi*)	500 W; 45 min	• HIUS-assisted thawing • 100 ± 0.1 g samples • Ultrasonic bath	• Lower T_{21} values	Wang *et al.*[122]
	Pork, beef and mutton (tenderloin)	45 kHz; 300 W; 9–10 min	• HIUS-assisted thawing • 3 × 3 × 3 cm samples • Ultrasonic bath	• Highest values of P_{2b} and P_{21}	Gan *et al.*[123]
Quality improvement	Pork loin	20 kHz; 200, 400 and 600 W; 15, 30 and 45 min	• Ultrasonic bath in ice varying the power and temperature	• When the time of treatment was 15 min and 30 min, the group of 600 W showed higher P_{21} and lower P_{22} values	Luo *et al.*[124]

Table 2 (*Contd.*)

Processing	Matrix/product	Parameters US (W; W mL^{-1}; W cm^{-2}; W L^{-1}; Hz; kHz; min; h)	Process	Findings	References
			• 9 cm × 6 cm × 3 cm samples weighting about 110 g	• For 45 min treatment, the 600 W group showed the lowest P_{21} values and the higher P_{22} values	
	Beef (*M. semimembranosus*)	45 kHz; 2 W cm^{-2}; 2 min	• Ultrasonic bath with cold water	• The sonicated samples showed higher T_{21} values after 48, 72 and 96 h of ageing • sonicated samples had lower T_{22} values compared to control samples at 24 and 72 h *post mortem* • The sonicated samples showed better WHC values	Stadnik *et al.*[17]
	Unsmoked bacon	20 kHz; 250, 500 and 750 W; 60 min	• HIUS treatment was applied in dry-cured (3% NaCl and 0.01% $NaNO_2$ (w/w)) bacon samples before ageing • Ultrasonic bath	• HIUS-treatment increased P_{21} and decreased P_{22} of samples, improving their WHC	Zhang *et al.*[125]
	Frankfurter-type sausages (pork (lean and back-fat))	25 kHz; 240 W; 15, 20, 25, 30, and 35 min	• Ultrasonic bath	• 25 min-treatment increased P_{21} and decreased P_{22}	Zhang *et al.*[126]
Heating	Silver carp surimi (*Hypophthalmichthys molitrix*)	40 kHz; 270 W; 50 min	• HIUS-assisted water bath heated at 40 °C with addition of extra virgin olive (EVO) oil, the samples then were heated in a water-bath at 90 °C for 30 min	• Sonicated samples with less than 3% (w/w) EVO showed increase of T_{2b} and P_{2b} and decrease of P_{21} • Samples with more than 3% of oil treated by HIUS showed decreased P_{2b} and increased P_{21} • Sonicated samples had lower P_{22}	Lu *et al.*[50]
	Defective Jinhua ham (*Biceps femoris*)	25 kHz; 300 and 1000 W; 6 h	• 300 W/40 °C; 300 W/50 °C; 1000 W/40 °C; 1000 W/50 °C treatments • Ultrasonic bath	• HIUS-treated samples had increased T_{2b}, T_{21} and T_{22} • P_{2b} decreased with increase of HIUS power; for the same ultrasonic power, temperature did not significantly affect P_{2b} • HIUS-treated samples had lower P_{21} and higher P_{22} than control • Increase of T_{2b}, T_{21} and T_{22}	Zhou *et al.*[54]
	Beef (anterior tendon)	28 kHz; 60 W; 37 min	• HIUS-assisted sous-vide cooking (USV) at different cooking times • 8 cm × 6 cm × 3 cm samples weighing 150 ± 5 g • The samples were cooked at 71 °C • Ultrasonic bath	• Highest proportion of immobilized water in USV samples cooked for 60 and 80 min	Wang *et al.*[51]
	Pork meatballs (hind legs)	20 kHz; 150, 300, 450, 600, and 750 W; 10 min	• HIUS-assisted cooking • 2.5-cm-diameter samples weighing about 30 g	• Samples cooked at 450 W had the highest P_{21} and the lowest P_{22} values	Zhao *et al.*[52]

Table 2 (*Contd.*)

Processing	Matrix/product	Parameters US (W; W mL^{-1}; W cm^{-2}; W L^{-1}; Hz; kHz; min; h)	Process	Findings	References
			• The samples were cooked until the central temperatures reached 75 °C		
Bacterial inactivation	Oyster (*Crassostrea gigas*)	20 kHz; 300 W; 7.5 W mL^{-1}; 12.5 min	• Ultrasonic bath • The samples were inoculated with *Vibrio parahaemolyticus* and placed in a beaker with 0.85% NaCl solution and sonicated using an ultrasonic probe with 10 mm of diameter • After the treatment, the samples were stored at 4 °C for 5 days	• Small decrease in the content of immobilized water after 5 days of cold storage	Ma *et al.*[65]
Fermentation	Beef (*Semitendinosus*)	30 kHz; 300 W; 30 min	• US: HIUS treatment • US-BP: HIUS treatment combined with inoculation of *P. acidilactici* BP2 • (2 cm × 2 cm × 10 cm) strips	• HIUS-treated samples had higher P_{2b} values • US and US-BP delayed values of time constants T_{2b}, T_{21} and T_{22} compared to control • HIUS treated samples showed increase of P_{21} and decrease of P_{22}	Hu *et al.*[58]
	Beef (*m. semitendinosus*)	25, 33 and 45 kHz; 65 W; 30 min	• The samples were pre-treated with ultrasound before curing • 10 cm length 10 cm, 4 cm width and 0.2 cm thickness slices	• Uncultured pre-treated samples at 25 and 45 kHz had lower P_{21} decrease • Cultured samples pre-treated at 25 kHz and 33 kHz had lower P_{21} decrease	Ojha *et al.*[59]

[a] CAR-UT: HIUS treatment and 1% salt and 0.3% carrageenan; CCCP: collagen peptide solution from chicken cartilage; SR: salt replacer; CUD-UT: HIUS treatment and 1% salt and 0.3% curdlan; EUT: SAEW thawing; EVO: extra virgin olive; FFUT: HIUS thawing with fixed frequency at 28 kHz; GUA: HIUS in 1% chitosan-grafted-chlorogenic acid solution; HIUS: high-intensity ultrasound; MUT: microwave combined with HIUS thawing; PA: potassium alginate; P_{2b}: bound water population; P_{21}: immobilized water population; P_{22}: free water population; SAEW: slightly acidic electrolyzed water; SEU: HIUS-assisted brine in different frequency modes (mono-, dual- and tri-frequency) in sequential mode; SFUT: HIUS-assisted thawing with a sweep frequency of 28 ± 2 kHz; SIU: HIUS-assisted brine in different frequency modes (mono-, dual- and tri-frequency) in simultaneous mode; T_{2b}: transversal relaxation time constant of bound water; T_{21}: transversal relaxation time constant of immobilized water; T_{22}: transversal relaxation time constant of free water; UA: HIUS in distilled water; UAF: HIUS-assisted freezing; UCP: HIUS treatment and later immersion of the sample in collagen peptide solution from chicken cartilage (CCCP); UDC: HIUS-assisted dry curing; UDW: HIUS treatment and immersion of the sample in deionized water for 55 min, 4 °C; UET: HIUS-assisted enzyme; UF: HIUS-assisted immersion freezing; UIF: HIUS-assisted immersion freezing; UIT: ultrasonics combined far infrared thawing/HIUS-assisted thawing; UMH: HIUS pretreatment and further marination in L-histidine (1.5 g L^{-1}) solution for 55 min; UMT: HIUS combined with microwave thawing; US: HIUS treatment; US-BP: HIUS treatment combined with inoculation of *P. acidilactici* BP2; USC: HIUS combined with sodium bicarbonate-assisted curing; UST: HIUS-assisted saline thawing; USV: HIUS-assisted sous-vide cooking; UT: HIUS thawing/HIUS-assisted thawing/HIUS-assisted immersion thawing/HIUS treatment and 1% salt (NaCl)/HIUS-treated samples; UVT: HIUS-assisted vacuum thawing; UWT: HIUS water thawing; W: water; WUT: HIUS-assisted water thawing.

Cao *et al.*[32] found that the ultrasound-assisted enzymatic treatments improved the WHC of samples compared to the treatments without HIUS. They explained that the improvements may be the result of the action of enzymes and the cavitation phenomenon caused by ultrasound on myofibrils, which improved their capacity to retain water. However, treatments longer than 40 min had negative effects on WHC. This can be explained by the ultrasound-induced rupture of muscle cells during prolonged treatments.[33] On the other hand, Ojha *et al.*[34] found an increase in the free water population and a decrease in immobilized water in ultrasound-treated samples. Meanwhile, their results can be attributed to the increased salt content in meat, which leads to structural changes in meat proteins and osmotic dehydration. The HIUS technology showed suitable results in the curing process, increasing the WHC of the samples, when operational parameters such as power, time, and salt concentration are appropriately chosen. Nevertheless, as pointed out by Kang *et al.*,[5] the changes in meat proteins, in HIUS-assisted curing, also depend on the type and geometry of the equipment and of the sample and the distance between the sample and the transducer; therefore, these factors still need further studies for a better understanding of the effects of HIUS on water mobility in the curing process.

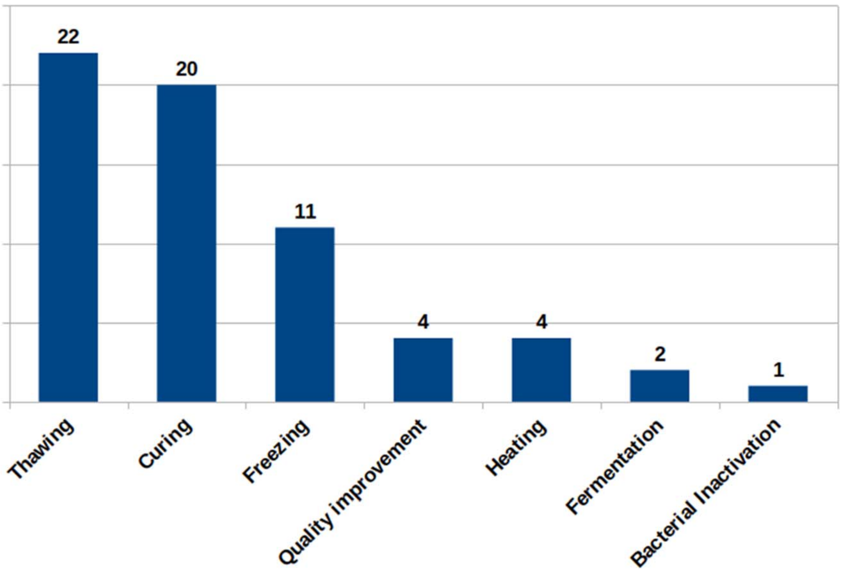

Fig. 2 Division of the reviewed articles according to the treatments involving the use of HIUS. The group "Quality Improvement" consists of studies in which HIUS was the only treatment applied to the meat matrix. These data can help to understand the current state of the HIUS application in meat product processing and of the use of LF-NMR for the analysis of water mobility and distribution in each food process, highlighting potential knowledge gaps in the literature.

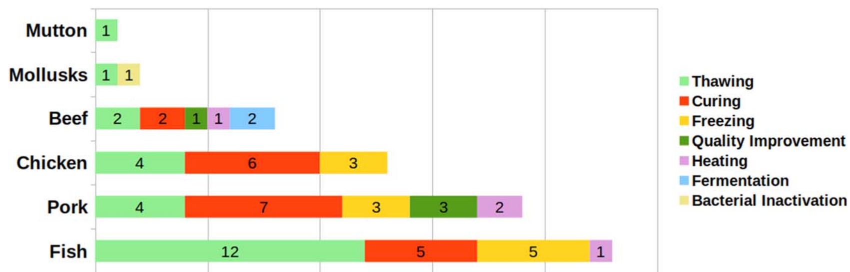

Fig. 3 Meat matrix types used in the reviewed articles and their distribution per treatment. This visualization may provide insights for further studies exploring the use of HIUS in new meat matrices and treatments and the use of LF-NMR for the study of water behavior in meat products.

Considering that studies applying HIUS with high time and power have shown contradictory results, it is reasonable to consider that, in addition to the experimental parameters of HIUS, external factors such as the matrix, the type, and the concentration of the salt used can be determining factors for WHC results. This is based on the fact that different salts have different kinetics and possibly different behaviors under the HIUS effects. However, the studies analyzed here vary in several fundamental aspects, such as the type of meat and muscle, operational conditions, and the method of application. Thus, studies evaluating the effects of these variables individually and their potential interactions are necessary.

3.3 Freezing

Freezing is a traditional method for food preservation that renders the components necessary for microbiological metabolism unusable, thereby slowing down the spoilage process. Therefore, frozen foods are recognized for having improved shelf-life.[35] However, the ice crystals formed during the freezing process cause physical damage to the food structure, leading to quality losses.[36] In meat products, this phenomenon increases the exudation of the water of meat during thawing.[37] Thus, rapid and cost-effective freezing processes, which maintain as many as possible of the original characteristics of the matrix, are desirable. Immersion freezing is a freezing method in which the packaged food is immersed in a cryogen or a fluid refrigerant. The advantages of this method include its short time, uniform temperature, and non-contact between the food and the liquid medium.[38] The combined use of immersion-freezing and HIUS has been studied because ultrasound technology increases the freezing rate and generates the smallest ice crystals, thus decreasing the physical damage caused to food when thawing.[37]

Several authors have demonstrated that ultrasound-assisted immersion freezing, under appropriate conditions, improves the water retention of meat samples (Table 2). These results are confirmed by WHC and LF-NMR measurements. HIUS causes the formation of small, evenly distributed ice crystals through the cavitation effect. The cavitation bubbles formed by sonication act as ice nuclei, thus increasing the number of ice nuclei. Moreover, ice crystals broken when hit by ultrasonic waves lead to shortening of the ice crystals.[39] Notwithstanding, Zhang *et al.*[40] and Zhang *et al.*[41] found that ultrasonic treatments, under some conditions (30 kHz; 300 W; 8 min; porcine longissimus muscles, and 30 kHz; 245 W; 8 min; chicken breast, respectively), increased water mobility and decreased the WHC of samples. The authors explained that these results are due to the high powers of ultrasound, which destroy the protein structure, thereby reducing the ability of proteins to retain water. Therefore, despite the promising application of HIUS as a freezing-assisted technology, there is a need to optimize parameters, such as power and time, to enhance the cavitation effects positively.

Most of the studies evaluated in this review assessed the effects of HIUS on the thawing of various samples, using application times ranging from 8 to 9 minutes. Overall, a trend can be observed suggesting that high power levels decrease water retention in the samples. However, this hypothesis disregards other parameters such as the application mode, equipment, and matrix used. Thus, it is worth highlighting that the application mode (continuous or pulsed) and the equipment (bath or probe) can affect the results due to ultrasonic efficiency, homogeneity, and temperature control, meaning that even favorable time and power conditions may not lead to the expected result.

3.4 Thawing

Thawing is the opposite of freezing and is the processing step during which the major loss of sensory and nutritional qualities, as well as damage to the muscle tissue of meat, occurs. Although slow thawing times are better for meat products, HIUS can achieve good results when correctly applied in the thawing process.[5] Several authors have found that ultrasound-assisted thawing improves the retention of water in meat products (Table 2). The principal explanation for these results is that the HIUS reduces protein damage, thereby delaying drip loss.[14] Li *et al.*[42] reported that the use of salt at a 0.10% concentration helps to avoid osmotic dehydration in mirror carp (*Cyprinus carpio* L.), as shown by the lower increase in T_{21} values among the analyzed samples. Meanwhile, Sun *et al.*[43] found that the HIUS treatment at 500 W disrupted the muscle cell structure through ultrasonic waves, as indicated by the increase in T_{21} values, suggesting that the muscle's capacity to bind water was impaired and the interactions between water and proteins were weakened. Their results are in accordance with the studies of Zhang *et al.*[44] and Zhang *et al.*[45] (Table 2), which present similar trends for T_{21} values in chicken breast muscle thawed using HIUS, and that samples with decreased T_{21} values had higher P_{21} values, and *vice versa*. They explained that, under appropriate conditions, the HIUS can slow down the degradation of muscle tissue, strengthening the interactions between water and meat proteins, and increasing the WHC of the meat. As explained by Leygonie *et al.*,[46] the decrease in thawing time may be related to the reduction of exudation of water, caused by the reabsorption of water by the fiber cells after the melting of the ice crystals in the extracellular space. This depends on the relationship between the amount of water available and the capacity of fiber muscles to absorb this water.

HIUS-assisted thawing is a promising approach that can promote higher thawing rates, decreasing the damage suffered by meat proteins during thawing. These beneficial effects can be observed by LF-NMR as a decrease in T_{21} values and/or an increase in P_{21} values, indicating less damaged myofibrils. Nevertheless, the application of HIUS in the thawing process still presents some challenges, as pointed out by Soltani Firouz *et al.*[47] and Kang *et al.*,[5] such as the heat generated by cavitation bubbles induced by HIUS can overheat the surface of the matrix while the inner layer is less heated. This can cause sensory and nutritional losses of the meat, requiring optimized parameters for its application in meat thawing.

Thus, it is possible to assume that the power and application time of HIUS are determining factors in this process. Furthermore, another factor that cannot be overlooked is the sample format, which, if chosen appropriately, can reduce the application time and the effects of surface overheating. Furthermore, as discussed earlier, the equipment and application method, which can have important effects on temperature and efficiency, should be considered. Additionally, the frequency can also affect the results, as depicted in Table 2.

3.5 Heating

Heat has been widely used in food processes such as pasteurization, sterilization, drying, evaporation, and cooking.[48] However, the food is exposed to high temperatures for a long time to reach the required quality and safety parameters, promoting chemical reactions responsible for color changes, and loss of odor, taste, and nutrients during and after the thermal processing.[49] Therefore, processes that decrease the damage caused to myofibrillar proteins are desirable, because their functional properties are directly related to the quality of meat products.[5] Thus, HIUS-assisted heating is a worthy alternative, since HIUS can improve the heat transfer, reducing the processing time and the damage caused to the muscle tissue, resulting in faster cooking, higher water retention, and lower cooking losses.[14]

In our review, four studies about heating processing assisted by HIUS were assessed (Table 2). In the studies of Lu *et al.*,[50] Wang *et al.*,[51] and Zhao *et al.*,[52] samples treated with HIUS showed an increase in P_{21} values under appropriate conditions (Table 2). They explained that heat treatment assisted by HIUS can solubilize and partially denature the myofibrillar proteins, resulting in the formation of a complex gel structure that retains water. This is in accordance with the work of Saleem & Ahmad,[53] which found that HIUS facilitated the denaturation and aggregation of myofibrillar proteins in chicken breast (*pectoralis major*), forming a more homogeneous network of gels. On the other hand, the HIUS-assisted heat treatment of Jinhua ham (25 kHz; 300 and 1000 W; 6 h) increased the amount of free water and decreased the immobilized water content, possibly due to the denaturation of proteins and shortening of myofibrils, which caused the exudation of water into the extra myofibrillar space.[54] The application of HIUS in thermal processing can improve the water retention in meat and meat products, when operational parameters are properly chosen. Moreover, the limited number of studies and the significant variations in time (50 min–6 h) and power (60–1000 W) make it challenging to comprehend their effects on water mobility in these matrices.

3.6 Fermentation

Fermented meat and meat products have an extended shelf life, distinct flavor, color, and texture, and their consumption has increased over the last few years.[55] The fermentation process is made by microorganisms or enzymes and requires specific conditions of temperature and humidity to occur.[56] The fermentation can be carried out by the natural microbiota present in the raw material, or by the use of a starter culture such as lactic acid bacteria (LAB) and coagulase-negative *Staphylococci* (CNS).[57] During the fermentation process with LAB, protein degradation in meat is caused by enzymes of the meat and produced by the bacteria, improving several parameters such as texture, flavor, and nutritional composition.[55,56]

Hu *et al.*[58] and Ojha *et al.*[59] studied the production of beef jerky by the fermentation of beef (*semitendinosus*) with *P. acidilactici* BP2 and *L. sakei*, respectively, using HIUS as pre-treatment. In the work of Hu *et al.*[58] fermented samples treated with HIUS and inoculated with LAB had the lowest T_{21} and T_{22} values, but did not have significantly different water populations. They explained that the improvement in water retention is a result of the synergic effect of cavitation caused by HIUS and the hydrolysis of muscle proteins caused by LAB. Ojha *et al.*[59] observed that the pre-treated samples, under appropriate conditions (Table 2), had fewer changes in the immobilized water population. The effects of HIUS and inoculation of a starter culture on T_2 values can be explained by the possible increase in substrate availability for fermentative bacteria caused by HIUS-induced cavitation on meat proteins.[47] In this context, despite the lack of studies on water migration of HIUS-treated fermented meat products, we can hypothesize that HIUS and starter cultures present an additive or synergistic effect in promoting water retention; however further studies are needed to assess the extent of this combined effect on the physicochemical, functional, and sensory properties and propose the appropriate conditions for using these technologies.

3.7 Bacterial inactivation

Meat and fish products are highly susceptible to bacterial spoilage due to their composition, nutritional value, higher water activity, and high moisture content, which have negative consequences for the economy and public health.[60,61] Traditional food preservation methods, such as heating and the use of chemical compounds, present several issues, including high energy costs, incomplete inactivation of microorganisms, the formation of harmful compounds that affect human health, higher acidity and salt content, and final products with poor nutritional and sensory attributes.[62,63] Thus, the use of HIUS technology for bacterial inactivation is a viable alternative to conventional methods, as it can inactivate microorganisms and clear surfaces through the cavitation effect, without impairing the nutritional and textural properties of the meat matrix; however, the degree of decontamination depends on the nature of the microorganism.[7,64] Ma *et al.*[65] compared the HIUS with heat treatment in the decontamination of oysters (*Crassostrea gigas*) inoculated with *Vibrio parahaemolyticus*. Their results showed that the sonicated samples had lower loss of immobilized water than thermal treatment after five days of storage. The results can be explained by the difference in protein denaturation induced by the different treatments. They explained that heat caused the denaturation and shrinkage of myofibrillar proteins, allowing water to be extruded between them. Nevertheless, the cavitation effect produced by HIUS can modify the structure of proteins, increasing the protein–water interactions and, thus, the WHC of the meat matrix.[5] Therefore, HIUS seems to be a promising alternative to achieve a safe meat product with improved technological properties. On the other hand, the literature lacks data on water mobility regarding the inactivation of foodborne pathogens in red meat matrices.

3.8 Quality parameters

Quality parameters such as pH, WHC, color, tenderness, juiciness, flavor, and appearance affect the overall quality and consumer's acceptance of meat and meat products.[66] Thus, the application of HIUS on meat processing has been intensively studied due to its promising results without harming the quality of the final product.[62] According to the results previously discussed, HIUS, when applied alone, shows good results on water retention in different meat and meat products. The main explanation for this is the implosion of cavitation bubbles, causing the disruption of protein aggregates in the myofibrils, decreasing particle size and increasing the superficial area, improving the protein–water interactions and WHC.[67]

There is no clear relationship between texture parameters and water mobility and distribution. Kang *et al.*[25] found that the samples with higher P_{21} values had higher hardness in pork meat batters of mesoglutaeus, in contrast with the study of Zou *et al.*,[68] which showed lower hardness in samples with the highest P_{21} in chicken breast meat. Ojha *et al.*[34] stated that samples of pork (*m. semitendinosus*) with lower WHC had lower Warner–Bratzler shear force (WBSF) values, indicating a higher tenderization in samples with lower P_{21} and T_{21} values. On the other hand, Zhao *et al.*[52] reported a negative relationship between P_{21} values and the hardness of pork meatballs. In fact, this discordance has already been discussed by Pearce *et al.*,[16] who suggested that this divergence may be a result of differences in intramuscular fat or glycogen contents of meat. Moreover, it's worth mentioning that Tasoniero *et al.*[69] found a correlation between hardness and T_{2b}, $T_{21,}$ and T_{22} relaxation times only in wooden-breast chicken meat, but not in normal breast muscle.

Furthermore, the relationship between color and LF-NMR measurements remains unclear. Kang *et al.*[25] demonstrated an increase in yellowness (b*) and a decrease in redness (a*) values, accompanied by an increase in ultrasonic time (*i.e.*, an increase in P_{21}); however, the same parameter did not significantly affect lightness (L^*) values in pork meat batters. Nevertheless, Zhao *et al.*[52] found that the samples of pork meatballs with the highest P_{21} values showed both decreased L^*, a^*, and b^* values, and Cao *et al.*[32] showed that chicken breast samples with increased P_{21} had increased L^* and b^* values, and decreased a^* values. Thus, it is not possible to state that the changes in the color of meat are direct results of changes in water mobility and distribution, because the color of meat and meat products is affected by several factors, such as pH, age, muscle type, species, pre- and postmortem conditions, and myoglobin contents.[70,71]

The results for the changes in pH are discrepant. Zhang *et al.*[40] and Sun *et al.*[43] found no significant differences among samples with different T_{21} values, whereas Shen *et al.*[72] reported that samples with higher P_{21} values had higher pH levels, and *vice versa*. This is in accordance with Pearce *et al.*,[16] who said that the reason for this is unknown.

Regarding the protein and lipid oxidation, the results are diverse. Li *et al.*[73] did not observe significant differences in protein oxidation among samples with different P_{21} values; however, lipid oxidation was lower in samples with higher P_{21} values. In contrast, the work of Lv & Xie,[74] observed significantly different protein oxidation results in samples with similar P_{21} values, but samples with higher P_{21} values presented a higher degree of lipid oxidation. The effect of protein oxidation on water mobility is dependent on the degree of oxidation, which can increase the swelling of the myofilaments, enhancing the WHC, or increase the number of cross-linked structures between proteins, impairing the ability of myofibrils to swell, decreasing the WHC.[75] These contradictory results indicate that the relationship between the results provided by LF-NMR and important quality parameters of meat, such as pH, color, and texture, needs to be better understood. Since the studies differ greatly from one another, our ability to formulate hypotheses becomes limited. However, it is still reasonable to assume that the type of meat (*e.g.*, beef, chicken, pork, or fish), the type of muscle fiber (*e.g.*, type I or type II), and the post-mortem time have a significant impact on the results. This is important because such factors are closely related to glycogen and fat content, pH, and also to the amount of myoglobin and, consequently, the meat's response to oxidative stress caused by the HIUS application. The effects of these parameters on the water distribution and mobility were discussed by Pearce *et al.*[16] Also, a detailed discussion of the relationship between muscle fiber type and meat quality parameters can be found in the article by Picard & Gagaoua.[76] Thus, it is reasonable to assume that the type of meat and muscle fiber may have caused such discrepancies in the results after the application of HIUS.

4 Challenges and perspectives

The HIUS is an emergent technology with great potential for meat and meat product processing. The studies assessed in this review generally showed promising results. Nevertheless, given their diverse nature in terms of equipment, operational parameters, and samples, it's not possible to determine the causes of the differences among them. This was considered by Soltani Firouz *et al.*[47] as a challenge to the industrial application of HIUS. Moreover, it's worth mentioning that no article included in this review applies HIUS to alternative meat products. This indicates the scarcity of this type of work. However, it is worth mentioning that HIUS can be applied in the processing of edible insects and plant proteins, for example, increasing their solubility, extraction, and modifying the texture when applied appropriately, as reviewed by Sengar *et al.*[77] and Ojha *et al.*[78] Meat alternatives are meat-free products that try to emulate the sensory and nutritional attributes of conventional meat, and include plant-based, legumes, edible mushrooms, lab-grown meat, and edible insects.[79–81] For example, plant proteins are constituted mainly by globular proteins, which makes the structure of plant-based products different from traditional meat; moreover, the presence of carbohydrate polymers also affects the WHC of these products.[82,83] Also, given that the effects of HIUS can vary depending on the amino acid composition,[14] it is expected that HIUS will yield different results in food products containing different species of edible insects. Thus, the effects of HIUS on this matrix type and, consequently, on parameters such as WHC, water distribution, juiciness, and texture still need to be understood. Furthermore, based on these results, it is possible to say that the standardization of parameters and the inconsistency of results are the primary challenges for implementing HIUS on an industrial scale. This is because the limited knowledge of the effects of HIUS on different matrices reduces the predictability and reproducibility of the results. Furthermore, as some reviews point out, HIUS faces additional challenges, including low energy efficiency, limited microbiological inactivation, limited information regarding food safety, and regulatory issues.[47,84,85] Additionally, as noted by Monteiro *et al.*,[86] misinformation on the part of consumers can also be a barrier to the market. Another aspect that should be considered is that, although HIUS may be potentially advantageous and safer when compared to traditional food preservation methods, it may not be so in relation to other non-thermal methods such as HPP and UV-C, for example, as discussed by Yaya-González *et al.*[85] Finally, it is worth highlighting that HIUS equipment can also be highly noisy, potentially posing an occupational hazard. Therefore, there is still a long way to go in optimizing and scaling HIUS for industrial use.

5 Conclusion

Our review assessed water mobility in meat products undergoing HIUS-assisted processes, such as curing, freezing, and thawing, and discussed the main mechanisms and discrepancies in the results. From the results discussed, it was possible to note that the effects of HIUS application on water retention in meat products are contradictory and closely related to the extent of damage caused to muscle tissue. Thus, T_2 values measured by LF-NMR serve as an indicator of the structural changes undergone by the meat, such as an increase in the space between myofibrils. It was observed that, under optimized power, temperature, and frequency conditions, HIUS can alter the hydrophobicity of proteins, thereby increasing protein–water interactions and favoring the formation of thinner and more homogeneous gels that retain more water. However, outside of these conditions, at high times and power levels, for example, HIUS can favor the formation of hydrophobic protein–protein interactions, expel water, and even destroy muscle structure, decreasing WHC. The possibilities of applying HIUS to alternative meat products were also discussed. Although studies have applied HIUS in the processing of alternative proteins, information on its applications in hybrid products, such as beef patties, is lacking. Finally, the implementation of these technologies (LF-NMR and HIUS) still faces several challenges. For LF-NMR, the difficulty in interpreting and processing the data hinders the technique's widespread use. As for HIUS, the lack of standardization, low energy efficiency, and lack of data regarding the safety of treated foods hinder the scaling up of this technology to an industrial scale.

Author contributions

Davi S. Santos: conceptualization, methodology, investigation, writing – original draft; Yago A. A. Bernardo: conceptualization, methodology, writing – review & editing, supervision; Carlos A. Conte-Junior: resources, writing – review & editing, supervision, funding acquisition.

Conflicts of interest

The authors declare that they have no conflict of interest.

Data availability

There were no generated data.

Acknowledgements

The authors are thankful for the financial support provided by the Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ) Brazil – grant numbers [E-26/200.891/2021 and E-26/200.060/2024], and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) – grant numbers [313119/2020-1 and 139777/2024-5].

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