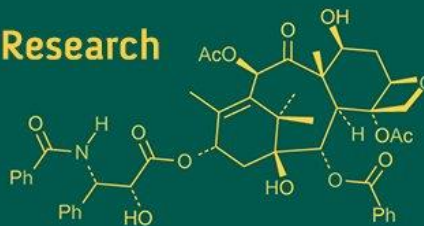


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Ultrasound technology in fish and seafood processing: A review of principles, applications and challenges

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Abstract

Ultrasound technology has emerged as a promising non-thermal processing technology for the fish and seafood industry because of its ability to improve product quality, processing efficiency, and food safety while minimizing thermal damage. This review summarizes the principles, mechanisms, applications, advantages, and limitations of use of ultrasound in seafood processing. The technology primarily works on acoustic cavitation, which generates localized high pressure, temperature, and shear forces that enhance mass transfer, modify tissue structure, and inactivate microorganisms. Recent studies demonstrate that ultrasound significantly improves marination and curing by accelerating salt diffusion, enhances drying process by improving moisture migration, and also helps in efficient extraction of valuable bioactive compounds such as astaxanthin and proteins from seafood by-products. Furthermore, ultrasound-assisted freezing and thawing produce smaller ice crystals, thereby reduces structural damage, and preserve the physicochemical, nutritional, and sensory properties of seafood. Its application in microbial inactivation, emulsification, and quality assessment also contributes in extending the shelf life and development of value-added seafood products. Despite these advantages, challenges including high equipment costs, limited industrial-scale implementation, lack of standardized processing parameters, and potential quality deterioration under excessive treatment remain barriers to commercialization. Overall, ultrasound represents a sustainable and versatile technology with significant potential to modernize fish processing and support the production of safe, high-quality seafood products.

Keywords: Ultrasound technology, fish processing, thermal food processing, acoustic cavitation, seafood preservation

1. Introduction

Fish is one of the most nutritious but also most perishable foods. It is rich in protein, essential amino acids, and omega-3 fatty acids, but its high moisture content and active enzymatic and microbial systems spoil it quickly if not processed and preserved properly (Sireesha *et al.*, 2022; Ekonomou & Bozaris, 2021) [27, 9]. Traditional preservation methods such as chilling, freezing, drying, salting, and heat treatment remain widely used; however, they may involve certain quality-related trade-offs. In particular, thermal treatments can cause losses of heat-sensitive nutrients and undesirable changes in sensory attributes such as taste and colour (Ravikumar *et al.*, 2017) [22]. This has pushed the seafood industry to look more seriously at non-thermal alternatives.

Ultrasound is one of the technologies gaining ground here. It works using sound waves above 20 kHz, applied through a liquid medium (Saklani *et al.*, 2021; Singh *et al.*, 2023) [23]. Depending on the frequency and power used, it's grouped into low-intensity (used mainly for diagnostics/quality checks) and high-intensity or "power" ultrasound, which is what drives the physical and chemical changes useful in processing (Singh *et al.*, 2023). The key mechanism behind these effects is cavitation, tiny bubbles form in the liquid and then collapse violently, creating brief bursts of high pressure, heat, and shear forces at a microscopic level. This is what speeds up mass transfer and breaks down structures in the food (Saklani *et al.*, 2021; Prempeh *et al.*, 2025) [23, 18].

In fish processing specifically, this has translated into several uses pre-treatment before drying, salting and curing, freezing and thawing, and more recently, extraction of bioactive compounds and non-destructive quality checks (Prempeh *et al.*, 2025)^[18]. Bai *et al.*, (2023)^[2] showed that ultrasound-assisted curing of sea bass improved salt diffusion and gave better texture and flavor than conventional curing. Beyond individual studies like this, ultrasound pre-treatment more broadly tends to shorten processing time and improve physicochemical and sensory quality without hurting nutritional value (Sireesha *et al.*, 2022)^[27].

Even so, ultrasound is still not a mainstream tool in commercial fish processing, especially in developing countries. Cost of equipment, lack of standard operating protocols, and difficulty scaling up from lab to industry remain real barriers. This review looks at how ultrasound works, what it's been used for in fish processing so far, and where the gaps are.

This review draws on peer-reviewed journal articles retrieved primarily through Google and Google Scholar, using search terms such as "ultrasound," "ultrasonication," "acoustic cavitation," "fish processing," "seafood preservation," and "shrimp," combined with specific application areas including "drying," "extraction," "thawing," "freezing," and "emulsification." Full-text versions of relevant articles were downloaded and reviewed in detail. The literature covered spans mostly 2020-2026, reflecting recent developments in ultrasound-based seafood processing, along with a small number of earlier foundational studies included to explain core mechanisms. In total, this review synthesizes findings from 33 peer-reviewed studies covering ultrasound applications in drying, bioactive compound extraction, microbial inactivation, freezing/thawing, and emulsification in fish and seafood processing.

2. Non-thermal processing technologies in fish processing

Fish spoils quickly because of its high-water content, active enzymes, and vulnerability to microbial growth. Thermal methods like pasteurization and sterilization control this well, but they come at a cost, protein denaturation, lipid oxidation, softer texture, and loss of heat-sensitive nutrients (Zhao *et al.*, 2019; Arumugam *et al.*, 2026)^[31, 1]. As demand grows for fresh-like, minimally processed seafood, non-thermal processing technologies (NTPTs) have become an active area of research, since they inactivate microbes and enzymes using pressure, electric fields, radiation, or acoustic energy instead of heat, which helps preserve the product's natural quality (Ekonomou & Boziaris, 2021)^[9].

2.1 Major non-thermal technologies used in fish processing

- High Hydrostatic Pressure (HHP) applies pressures roughly in the range of 100–600 MPa to inactivate microorganisms and enzymes while keeping sensory and nutritional quality largely intact. It's already used commercially for shellfish shucking, extending shelf life, and controlling pathogens (Ekonomou & Boziaris, 2021)^[9].

- Pulsed Electric Field (PEF) uses short bursts of high voltage to disrupt microbial cell membranes. It works best on liquid or semi-liquid foods, but in fish processing it's being explored to improve mass transfer during drying or extraction (Zhao *et al.*, 2019)^[31].
- Cold plasma generates reactive ions, electrons, and free radicals that inactivate microbes on food surfaces. It's promising for decontaminating fish surfaces without affecting the product internally (Ekonomou & Boziaris, 2021)^[9].
- Ozone treatment is a strong oxidizer effective against bacteria, viruses, and fungi, and it removes odors without leaving harmful residues, useful for seafood decontamination (Arumugam *et al.*, 2026)^[11].
- Ultrasound uses sound waves above 20 kHz to create acoustic cavitation, which improves mass transfer, disrupts microbial cells, and speeds up processing. In fish specifically, it's been applied to marination, extraction, drying, freezing, and quality evaluation (Sireesha *et al.*, 2022; Prempeh *et al.*, 2025)^[27, 18].

2.2 Advantages and limitations

Overall, NTPTs retain nutritional and sensory quality better than thermal methods, use less energy, cut processing time, and improve safety and shelf life. Their main drawback is practical rather than technical high equipment cost, limited industrial-scale uptake, and a lack of standardized protocols mean most of these methods are still more common in research settings than in commercial plants. Among these, ultrasound stands out for being relatively low-cost, versatile, and easy to combine with other processing steps which is why the rest of this review focuses on it in detail.

3. Principle and mechanism of ultrasound in fish processing

Ultrasound refers to sound waves above 20 kHz beyond the range of human hearing that travel through a medium as alternating compression and rarefaction cycles, transferring energy and triggering physical, chemical, and biological changes in food (Saklani *et al.*, 2021; Singh *et al.*, 2023)^[23]. Based on frequency and power, it's split into low-intensity ultrasound, used mainly for analysis and quality checks, and high-intensity ultrasound, which is what drives actual processing effects (Singh *et al.*, 2023). As a pre-treatment, its main value lies in opening up microscopic channels in tissue, which speeds up moisture diffusion and cuts down processing time and energy use during drying and other operations.

3.1 Acoustic cavitation: The core mechanism

The effects of ultrasound in food processing come down to one central phenomenon acoustic cavitation. During the rarefaction phase of the sound wave, negative pressure causes tiny gas bubbles to form in the liquid; during compression, these bubbles collapse violently. This collapse produces intense, localized conditions temperatures reaching roughly 5000 K and pressures up to about 1000 atm, along with shock waves, microjets, and shear forces (Saklani *et al.*, 2021; Knorr *et al.*, 2004)^[23, 12]. It's these micro-scale extremes that drive the structural and chemical changes seen in treated food. Fig 1 explains mechanism of Cavitation and Its Associated Effects.

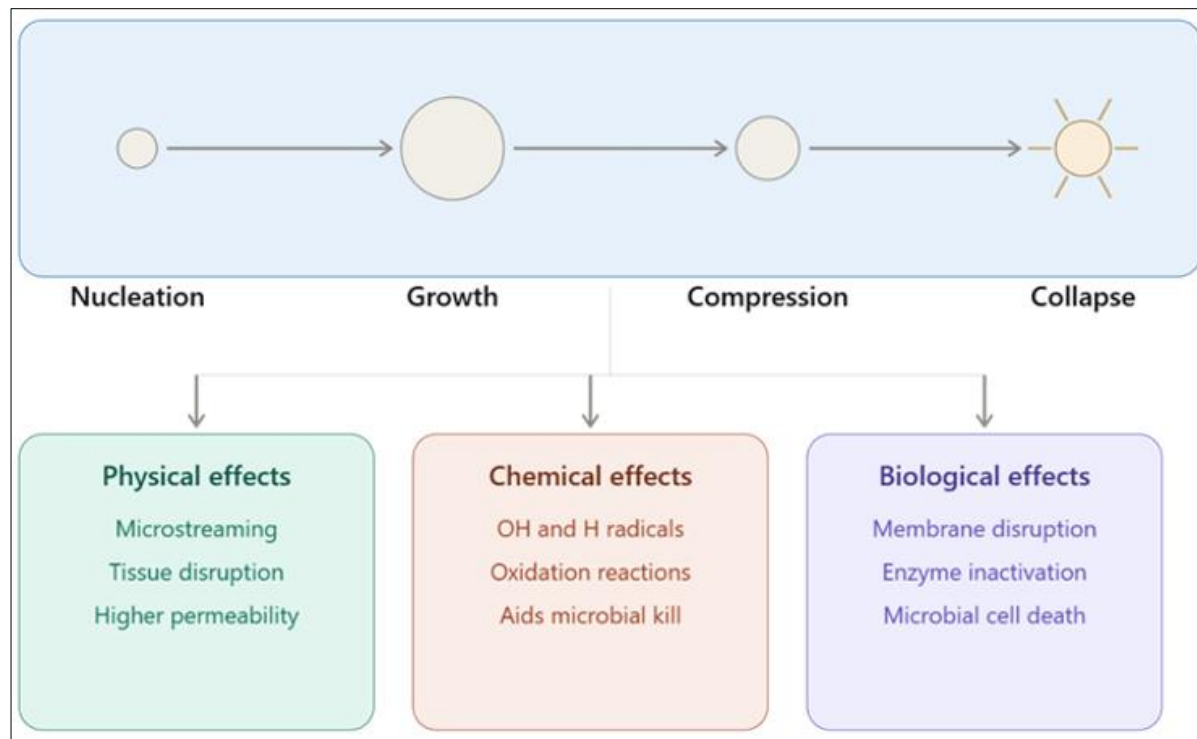


Fig 1: Mechanism of cavitation and its associated effects

- **Physical effects:** Cavitation creates microstreaming and turbulence that improve heat and mass transfer, breaks down muscle tissue structure to help solutes diffuse, and increases the tissue's permeability to salt, water, and other additives. Together, this speeds up marination, curing, and drying (Prempeh *et al.*, 2025) ^[18].
- **Chemical effects:** The extreme conditions during bubble collapse can split water molecules into free radicals such as $\bullet\text{OH}$ and $\bullet\text{H}$. These radicals help inactivate microbes, but if not controlled, the same reactions can also drive unwanted lipid oxidation (Saklani *et al.*, 2021) ^[23].
- **Biological effects:** Shear forces disrupt microbial cells and damage cell membranes, while the associated chemical effects inactivate spoilage-related enzymes together improving safety and extending shelf life (Sireesha *et al.*, 2022) ^[27].
- **Effect on fish muscle:** In fish specifically, ultrasound disrupts muscle fibers and opens microchannels in the tissue, increasing water diffusivity. This translates into practical gains in texture, tenderness, and rehydration capacity (Bai *et al.*, 2023) ^[2].

3.2 Factors affecting ultrasound efficiency

How well ultrasound performs depends on frequency and intensity, treatment time, temperature, the properties of the medium (viscosity, density), and the structure of the fish tissue itself. Getting the best results without compromising quality means optimizing these variables for each specific application rather than using one fixed protocol.

3.3 Types of ultrasonic apparatus

Ultrasonic systems used in food and related processing applications can be broadly classified into bath-type and probe-type systems. Bath-type units generally operate at relatively low intensities (approximately 10–40 W/L), with ultrasonic energy distributed through the treatment medium,

whereas probe-type systems can provide much higher intensities ($\geq 20,000$ W/L) directly at the sample, resulting in stronger and more localized ultrasonic effects. Probe diameter also influences the intensity and nature of ultrasonic treatment; larger-diameter probes generally produce greater thermal effects, whereas smaller probes can provide more localized treatment. Consequently, probe systems are generally more suitable for rapid and intensive applications such as emulsification and particle-size reduction, whereas ultrasonic baths are more appropriate for relatively gentle applications such as equipment cleaning and degassing. Beyond food processing, ultrasonication has also been investigated as an intensification technique in nanofluid preparation, where appropriate sonication can improve nanoparticle dispersion and stability (Sandhya *et al.*, 2021) ^[24].

3.4 Applications of ultrasound in fish processing

Ultrasound's versatility in fish processing comes down to its core mechanism i.e. cavitation drives better mass transfer, structural change, and microbial control, all of which translate into real processing gains (Sireesha *et al.*, 2022; Prempeh *et al.*, 2025) ^[27, 18].

3.4.1 Ultrasound-assisted marination and curing

Bai *et al.* (2023) ^[2] tested ultrasound-assisted low-salt curing on sea bass fillets ($5 \times 3 \times 1$ cm³, 20 g), treating them in 5% brine at 100, 300, or 500 W (20.5 kHz) for 30, 60, 90 minutes. Ultrasound consistently improved salt diffusion over static marination, most strikingly, just 30 minutes at 500 W achieved 1.3 times more NaCl uptake than 90 minutes of static marination, showing how much cavitation speeds up salt penetration.

The same study found benefits for flavor too. Moderate treatment (300 W, 60 min) raised total free amino acid content from 5.62 to 6.24 mg/g and boosted desirable flavor compounds like aldehydes and esters, improving overall taste and sensory scores.

3.4.2 Ultrasound-assisted drying

Ultrasound pre-treatment before drying works by disrupting tissue structure and opening up channels for moisture to escape, which speeds up drying and improves product quality. Castañeda-López *et al.*, (2021)^[4] pre-treated white shrimp in 10% salt solution at 4 °C for 15 and 30 minutes (130 W, 40 kHz ultrasonic bath) before hot-air drying at 35±2 °C. This cut dehydration time by 15.6% and 12.1% for

the two treatments, respectively, with the Page model best describing the drying kinetics. Effective moisture diffusivity rose from 4.68×10^{-10} m²/s in untreated samples to 6.24×10^{-10} m²/s in ultrasound-treated ones i.e. 34% increase, which the authors linked to cavitation-induced surface damage and the formation of irregular cavities that let moisture escape more easily. Ultrasound also lowered water activity, raised ash content, and improved rehydration.

Table 1: Ultrasound pre-treatment effects on drying of seafood products

Author (Year)	Species/Material	Ultrasound Conditions	Key Findings
Castañeda-López <i>et al.</i> , (2021) ^[4]	<i>Litopenaeus vannamei</i> shrimp	130 W, 40 kHz, treated for 15–30 minutes	Drying time down 12–16%; better rehydration, lower water activity
Fikry <i>et al.</i> , (2023) ^[10]	Asian seabass fish skin	32 kHz, 150 W, treated for 30 minutes	Drying time down up to 28%; more porous structure, better energy efficiency

Fikry *et al.*, (2023)^[10] found similar results in Asian seabass skin, pre-treated at 32 kHz and effective power of 150 W for 30 minutes at 30 °C before drying at 45 to 65 °C. The modified Page model fit best; drying time dropped by up to 28%, and specific energy consumption fell by about 22%. Microscopy showed the treated skin developed a more open, porous structure i.e. microchannels created by cavitation gave moisture an easier path out during drying.

Together, these studies show a consistent pattern: ultrasonic cavitation loosens tissue structure and opens up pathways for moisture, which is what drives the improvements in drying speed, energy use, and product quality seen across different seafood types.

3.4.3 Extraction of bioactive compounds

Shrimp processing waste which includes, shells and heads, is rich in valuable compounds like astaxanthin, chitin, proteins, and antioxidants, but conventional extraction relies on high solvent volumes, long extraction times, and heat that can degrade thermolabile compounds like astaxanthin. Ultrasound-Assisted Extraction (UAE) sidesteps this: cavitation disrupts cell walls, improves solvent penetration, and speeds up mass transfer, cutting both extraction time and solvent use. Putra *et al.*, (2024)^[19], reviewing green extraction technologies for shrimp shell valorisation, such as ultrasonic assisted extraction alongside microwave-assisted, supercritical carbon dioxide, and enzyme-assisted extraction as methods capable of recovering chitin, astaxanthin, proteins, and calcium carbonate with far less environmental impact than conventional solvent extraction.

Astaxanthin recovery has been the most studied application. Several optimization studies converge on a consistent picture: modest ultrasound amplitude combined with moderate extraction time reliably outperforms harsher or more prolonged treatment. Sharayei *et al.*, (2021)^[25] found that just 23.6% amplitude, 13.9 minutes, and 26.3 °C gave the best astaxanthin yield (51.5%) from green tiger shrimp shells, alongside strong antioxidant activity. A study was carried out with an objective to enhance the extraction of astaxanthin from black tiger shrimp shells using a combination treatment of deep eutectic solvent and ultrasonic-assisted extraction, where 330 W, 35% ethanol, and 33 minutes produced the highest astaxanthin content (47.42 µg/g), outperforming Soxhlet extraction and maceration (Hai *et al.*, 2024)^[11]. For astaxanthin extraction, the choice of solvent is also important. In a study of testing six solvents on deep-water pink shrimp shell waste, methanol gave the highest astaxanthin concentration (310

µg/g) after just 2 hours, while polar solvents like petroleum ether gave the lowest value, reinforcing the general finding that higher-polarity solvents extract astaxanthin more effectively (Dikel & Yanar, 2025)^[7].

Beyond conventional solvents, researchers have also explored greener environmentally friendly alternatives. Panagiotakopoulos *et al.*, (2023)^[17] replaced organic solvents entirely and carried out Ultrasound-assisted extraction (UAE) in vegetable oils such as olive, sunflower, and flaxseed and found olive oil at a 1:60 (by-product and vegetable oil ratio), 60% amplitude, and 210 minutes gave a strong astaxanthin yield (235 µg/g) with good antioxidant activity, plus successful encapsulation using gum Arabic and soy lecithin. This suggests UAE's benefits are not only tied to any one solvent but the cavitation mechanism works regardless of whether the extracting medium is a conventional organic solvent, a deep eutectic solvent, or a food-grade oil.

UAE's usefulness extends beyond astaxanthin extraction. Duppeti *et al.*, (2023)^[8] applied it to flavor compound extraction from shrimp heads, optimizing amplitude, sonication time, and solvent-to-solid ratio to reach a 40.87% extraction yield. Similarly, result showed increased equivalent umami concentration from 8.32 to 55.44 g MSG/100 g, showing that ultrasonic protein denaturation can meaningfully improve flavor extraction, not just recovery of structural compounds.

Across all five studies, it can be stated that, cavitation-driven cell disruption improves extraction yield and quality regardless of target compound (carotenoid, flavor, or protein) or solvent system (organic, deep eutectic, or vegetable oil), while cutting extraction time and reducing reliance on hazardous solvents, positioning UAE as a genuinely scalable green technology for shrimp by-product valorization across food, nutraceutical, and cosmetic applications.

3.4.4 Microbial inactivation and preservation

Seafood spoils quickly because of its high moisture, active enzymes, and rapid microbial growth make conventional thermal methods like smoking, salting, and pasteurization effective at killing microbes but damaging to nutritional and sensory quality. Ultrasound offers a non-thermal alternative: cavitation generates localized heat, pressure, shear forces, and reactive oxygen species that rupture microbial cell membranes and cause leakage of intracellular content, leading to cell death all without the heat-driven quality

losses of conventional preservation (Sireesha *et al.*, 2022) [27].

Individually, ultrasound produces meaningful antimicrobial effects, but the more consistent finding across recent studies is that it performs best paired with a second intervention. Against *Vibrio parahaemolyticus* in salmon, blue light irradiation alone already caused near-complete bacterial death, but adding 15 minutes of ultrasound pushed the bactericidal rate to 98.81% without harming salmon color or freshness (Zhu *et al.*, 2023) [33]. A similar synergetic effect was observed with slightly acidic electrolyzed water when combined it with ultrasound, reducing total viable counts of *Aeromonas*, and lactic acid bacteria by 0.73, 0.74 and 0.79 log CFU/g in mirror carp fillets compared to the control, while also slowing protein degradation and lipid oxidation, extending shelf life by four days under refrigeration (Zhong *et al.*, 2025) [32].

Ultrasound also performs well as a standalone treatment when the objective is simply slowing microbial growth during storage rather than achieving rapid kill rates. In blue shrimp held on ice for 20 days, high-intensity ultrasound

(70% amplitude, 60 minutes) kept total bacterial counts at 5.01 log CFU/g by the end of storage, well below the 6.09 log CFU/g reached by the untreated control sample without significantly affecting pH, texture, water-holding capacity, or TVB-N (Torres-Arreola *et al.*, 2025) [28]. This distinction matters, where blue light and electrolyzed water combinations with ultrasound aim for maximum bacterial kill, ultrasound alone in cold storage settings works more as a growth suppressant that buys extra shelf-life days while leaving quality attributes largely untouched.

Ekonomou and Bozaris (2021) and Arumugam *et al.*, (2026) [9, 1] both identify ultrasound, whether alone or combined with electrolyzed water, plasma-activated water, ozone, or pulsed electric fields as an energy-efficient, environmentally sustainable route to microbial safety that avoids the sensory trade-offs of heat treatment. Taken together, these studies suggest ultrasound's real strength in preservation lies not in replacing other non-thermal methods but in amplifying them, making combined treatments the more promising direction for extending seafood shelf life without compromising quality.

Table 2: Ultrasound-assisted extraction of bioactive compounds from shrimp by-products

Author (Year)	Species/Material	Conditions	Key Findings
Sharayei <i>et al.</i> , (2021) [25]	Green tiger shrimp shell	Ultrasound at 23.6% amplitude, 26.3 °C, for 13.9 minutes	Astaxanthin yield 51.5%; free radical scavenging capacity 73.9%
Hai <i>et al.</i> , (2024) [11]	Black tiger shrimp shell	Ultrasound-assisted deep eutectic solvent extraction, 330 W, 35% ethanol, 33 minutes	Astaxanthin yield 47.42 µg/g; outperformed Soxhlet/maceration
Panagiotakopoulos <i>et al.</i> , (2023) [17]	Shrimp by-products	Olive oil, 60% amplitude, 210 min	Astaxanthin 235±4.07 µg/g; encapsulation efficiency 66.6%
Duppeti <i>et al.</i> , (2023) [8]	White shrimp head	Ultrasound at 63.2% amplitude, 20.5 minutes, 20.8 mL/g solvent-to-solid ratio	Extraction yield 40.87%; EUC up from 8.32 to 55.44 g MSG/100g
Dikel & Yanar (2025) [7]	Deep water Pink shrimp shell waste	Six solvents tested, 2 and 4 hours; methanol gave best results	Highest astaxanthin: 310±2.00 µg/g after 2h

Table 3: Ultrasound-assisted microbial inactivation and preservation in seafood

Author (Year)	Species	Conditions	Key Findings
Zhu <i>et al.</i> , (2023) [33]	Salmon	Ultrasonic field combined with blue light; ultrasound for 15 minutes; blue light at 216 J/cm ²	98.81% bacterial inactivation; minimal quality impact (<i>V. parahaemolyticus</i>)
Torres-Arreola <i>et al.</i> , (2025) [28]	Blue shrimp	Ultrasound at 20 kHz, 70% amplitude, for 30, 60, or 90 minutes; best result at 60 minutes	Delayed microbial growth; quality preserved over 20 days
Zhong <i>et al.</i> , (2025) [32]	Mirror carp fillets	Ultrasound combined with slightly acidic electrolyzed water, 200 W, 30 kHz	Reduced microbial counts; shelf life extended 4 days

3.4.5 Freezing and thawing enhancement

Freezing preserves seafood well by slowing microbial and enzymatic activity, but the process itself can damage quality. Slow freezing produces large, irregular ice crystals that rupture muscle tissue, reducing water-holding capacity and causing drip loss and texture breakdown after thawing. Ultrasound-assisted freezing and thawing addresses this directly, using cavitation to speed up heat transfer and

control how ice crystals form thus promoting both primary and secondary ice nucleation while physically breaking large crystals into smaller and more uniform ones (Yu *et al.*, 2022) [30].

This effect has been demonstrated consistently across different seafood species and ultrasound configurations. In sea bass, ultrasonic-assisted immersion freezing (UIF) at and -40 °C produced smaller, rounder, more evenly distributed ice crystals than conventional quick freezing, along with lower thawing and cooking losses and more stable protein structure over 12 weeks of storage (Chen *et al.*, 2022). Similar results were reported in bay scallop adductor muscle, where UIF at 150 W treatment was a more effective treatment than immersion and air freezing over 90 days of frozen storage and effectively preserved protein stability, limited lipid oxidation, and produced the smallest, most regular ice crystals (Liu *et al.*, 2022). For shrimp, response surface optimisation identified 0 °C initial temperature, 180 W power, and an ultrasonic time (5 s on/2 s off cycle) as optimal freezing parameters, shortening the time spent in the critical ice-crystal formation zone and reducing tissue damage (Ying *et al.*, 2021) [29]. Across all three studies, the underlying mechanism is the same, which shows cavitation-driven ice nucleation controls crystal size, and smaller, more regular crystals translate directly into better protein and textural outcomes after freezing.

The same principle extends to thawing, where several studies have explored combining ultrasound with complementary technologies to push quality gains further. Dual-frequency ultrasound (28/40 kHz, 200 W) thawed

large yellow croaker faster than single-frequency or conventional water and refrigerated thawing, while also giving better color, texture, water-holding capacity, and lower pH and TVB-N (Cheng *et al.*, 2022) ^[5]. Pairing ultrasound with a low-concentration salt solution similarly improved outcomes for mirror carp. Ultrasound-assisted saline thawing has shown improved result than both air and ultrasound-only thawing across thawing, centrifugal, and cooking losses, alongside better-preserved texture and microstructure (Li *et al.*, 2022). Combining ultrasound with slightly basic electrolyzed water took this further for shrimp, cutting thawing time by 48.9% compared to conventional methods while significantly reducing lipid oxidation and protein carbonyl formation. The electrolysed water's antioxidant activity worked alongside cavitation to limit

oxidative damage (Li *et al.*, 2024) ^[16]. A comparable combined approach of ultrasound and microwave thawing gave oysters the shortest thawing time and the quality profile closest to fresh among five methods tested, including better-preserved aroma and lower oxidative damage (Li *et al.*, 2025). Taken together, these studies point to two consistent findings. First, ultrasound alone reliably improves both freezing and thawing outcomes by controlling ice crystal size and speeding heat transfer. Second, and more strikingly, ultrasound's benefits compound when combined with a second intervention salt, electrolyzed water, or microwave energy suggesting that hybrid, multi-mechanism approaches may be the more promising direction for seafood freeze-thaw processing going forward.

Table 4: Ultrasound-assisted freezing and thawing in seafood processing

Author (Year)	Species	Conditions	Key Findings
Chen <i>et al.</i> , (2022)	Sea bass	Ultrasonic-assisted immersion freezing vs. quick freezing at -20 °C and -40 °C	UIF at -40 °C: smaller ice crystals, better protein stability after 12-week storage
Liu <i>et al.</i> , (2022)	Bay scallop	Air freezing, immersion freezing, and ultrasonic-assisted immersion freezing at varying power; best result at 150 W	Best protein preservation, reduced oxidation, 90-day storage
Ying <i>et al.</i> , (2021) ^[29]	Chinese white shrimp	Response-surface-optimized conditions: 0 °C initial temperature, 180 W power, ultrasound pulsed 5 seconds on/2 seconds off	Reduced ice crystal formation time, preserved tissue integrity
Cheng <i>et al.</i> , (2022) ^[5]	Large yellow croaker	Single-frequency ultrasound-assisted thawing at 28 kHz or 40 kHz, and dual-frequency thawing at 28/40 kHz; 200 W; best result with dual-frequency treatment	Fastest thawing, best WHC, texture, freshness
Li <i>et al.</i> , (2022)	Mirror carp	Air thawing, ultrasound thawing, and ultrasound-assisted saline thawing (0.05%, 0.10%, or 0.20% salt); 200 W	UST reduced thawing/cooking loss, best texture and microstructure
Li <i>et al.</i> , (2024) ^[16]	Shrimp	Flowing-water thawing, air thawing, ultrasound thawing, and ultrasound-assisted slightly basic electrolyzed water thawing	UST cut thawing time 48.9%; minimized oxidation
Li <i>et al.</i> , (2025)	Oyster	Air thawing, refrigerated thawing, microwave thawing, ultrasound thawing, and combined ultrasound-microwave thawing	UWT: shortest thawing time, freshness closest to fresh

3.4.6 Emulsification and product development

Ultrasound-assisted emulsification has become a valuable tool for turning seafood processing waste like proteins, oils, and by-product extracts into stable, functional food ingredients. Cavitation helps this by unfolding proteins, increasing their surface hydrophobicity, and improving their adsorption at oil-water interfaces, which together reduce droplet size and improve emulsion stability. This effect has been demonstrated most clearly with fish myofibrillar protein (FMP) as the emulsifier. Rajasekaran *et al.*, (2023) ^[20] found that ultrasonication Asian seabass FMP at 40% amplitude for 15 minutes (20 kHz and 750 W) significantly improved protein solubility, surface hydrophobicity, along with both emulsifying activity and stability. Similarly, when ultrasonication used to stabilize shrimp oil emulsions, produced smaller, more uniform droplets that showed no phase separation even after 30 days of storage. In the same study, ultrasonication was compared against micro fluidization for preparing shrimp oil nano emulsions using the same FMP stabiliser (Rajasekaran *et al.*, 2024) ^[21]. Ultrasonication at 50% amplitude for 10 minutes consistently performed better than micro fluidization at high pressure producing smaller droplets (426 to 494 nm vs. 536 to 638 nm), lower polydispersity, and higher zeta potential.

That suggest that for protein-stabilized marine oil emulsions, moderate-intensity ultrasound is not just a cheaper alternative to micro fluidization but a genuinely more effective one. A similar line of work has focused on turning crustacean by-product proteins into functional emulsifiers. Briones-Labarca *et al.*, (2025) ^[3] extracted protein from yellow prawn by-products and used high-intensity ultrasound, optimized via response surface methodology, to stabilize oil-in-water emulsions. The resulting emulsions had very fine, uniform droplets (0.35 µm), gel-like rheological behaviour, and reasonable thermal stability at 80 °C. The result demonstrated that ultrasound-assisted emulsification isn't limited to muscle-derived proteins, but also extends to underutilized shell and viscera proteins as well. Together, these studies point to a broader principle: ultrasound consistently improves emulsion quality regardless of whether the protein source is fish muscle or crustacean by-product, or whether it's benchmarked against micro fluidization or evaluated on its own. This shows ultrasound-assisted emulsification as a practical route for incorporating marine bio actives like shrimp oil, astaxanthin, polyunsaturated fatty acids into functional food systems, while simultaneously offering a way to valorize seafood processing waste that would otherwise be discarded.

Table 5: Ultrasound-assisted emulsification and product development in seafood processing

Author (Year)	Species/Material	Conditions	Key Findings
Rajasekaran <i>et al.</i> , (2023) ^[20]	Asian seabass fish myofibrillar protein + shrimp oil	20 kHz, 750 W; 40% and 60% amplitude; 5 to 15 minutes; best result at 40% amplitude for 15 minutes	Improved protein solubility and emulsifying activity/stability; smaller oil droplets; no phase separation after 30 days of storage
Rajasekaran <i>et al.</i> , (2024) ^[21]	Shrimp oil nano emulsion with fish myofibrillar protein	20 kHz, 750 W; 40% and 50% amplitude; best result at 50% amplitude for 10 minutes	Smaller, more uniform oil droplets and better electrical stability than emulsions made by micro fluidization
Briones-Labarca <i>et al.</i> , (2025) ^[3]	Yellow prawn by-product protein (<i>Cervimunida johni</i>)	High-intensity ultrasound, 300 W, conditions optimized statistically	Very fine, uniform droplet size (0.35 μ m); gel-like texture; good stability when heated to 80 °C

3.5 Advantages and limitations of ultrasound technology in fish processing

3.5.1 Advantages

Ultrasound's biggest advantage is that it's non-thermal, so heat-sensitive nutrients like proteins, vitamins, and polyunsaturated fatty acids stay largely intact when compared to conventional thermal processing methods (Sireesha *et al.*, 2022) ^[27]. Because cavitation accelerates mass transfer, operations like marination, drying, and extraction which helps to reduce both processing time and energy use compared to thermal methods (Prempeh *et al.*, 2025) ^[18]. This also shows up in final quality of the product i.e. better texture, tenderness, water-holding capacity, color retention, and rehydration, all traceable to the way ultrasound modifies muscle microstructure (Bai *et al.*, 2023) ^[2]. Ultrasonication also helps to food-safety by improving microbial inactivation and processing efficiency on its own, ultrasound can reduce a product's reliance on chemical preservatives, which fits well with growing consumer demand for clean-label products (Ekonomou & Boziaris, 2021) ^[9]. Perhaps its most practical strength is versatility: the same core technology applies across extraction, freezing, drying, emulsification, and quality evaluation, and it combines readily with other preservation methods as part of a hurdle-technology approach (Prempeh *et al.*, 2025) ^[18].

3.5.2 Limitations

Despite these strengths, several barriers keep ultrasound from wider industrial use. The most immediate is cost ultrasonic equipment requires significant upfront investment that's often out of reach for smaller processors. Physically, ultrasound waves don't penetrate solid or dense materials well, which can mean uneven treatment in thick fillets or bulk processing. Pushed too far, ultrasound can also work against itself: excessive intensity or prolonged exposure risks lipid oxidation, protein denaturation, and off-flavors, meaning parameters have to be carefully optimized rather than simply maximized for effect (Sireesha *et al.*, 2022) ^[27]. Most published work so far is lab- or pilot-scale, and scaling up while keeping treatment uniform across a full production batch remains an open problem (Prempeh *et al.*, 2025) ^[18]. Compounding this, there's no standardized protocol for frequency, intensity, or treatment time across different fish species, which makes it hard for industry to adopt a one-size-fits-all approach. And ultrasound rarely works alone for safety purposes it typically needs to be paired with heat, pressure, or chemical treatment to achieve full microbial inactivation (Ekonomou & Boziaris, 2021) ^[9]. Taken together, ultrasound is a genuinely promising non-thermal technology for fish processing, but its future in industry depends on solving practical problems cost, scalability, and standardization rather than proving the underlying science works, which the literature already supports well.

4. Conclusion

Ultrasound has emerged as one of the more promising non-thermal technologies for fish and seafood processing, largely because of what acoustic cavitation makes possible: faster mass transfer, modified muscle microstructure, and effective microbial inactivation, all without the heat damage that comes with conventional processing. Across the studies reviewed here, this translates into real gains marination and curing that penetrate faster, drying that uses less energy, cleaner extraction of bioactive compounds like astaxanthin, better-controlled freezing and thawing, and more stable emulsions generally while preserving nutritional and sensory quality better than thermal alternatives. Ultrasound-assisted extraction in particular stands out for its relevance to sustainability, offering a genuinely green route to recovering value from seafood processing waste that would otherwise be discarded. That said, ultrasound is not yet a finished, industry-ready technology. Equipment costs remain high, penetration into thick or dense products is limited, treatment protocols vary widely between studies, and scaling from lab to plant floor is still largely unresolved. Closing these gaps through species and product-specific optimization, more energy-efficient industrial equipment, and combining ultrasound with complementary non-thermal methods like high hydrostatic pressure, cold plasma, or electrolyzed water is where the next phase of research needs to focus. Techno-economic evaluation and standardized protocols will matter just as much as further lab-scale studies in determining whether ultrasound moves from a well-documented research tool to a standard part of commercial seafood processing.

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6. Competing Interests

Authors have declared that no competing interests exist.

7. Consent

The authors declare that there is no consent is required for this work.

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9. Conflicts of interest

The authors declare no conflicts of interest

References

- Arumugam D, Li S, Rao M, Peng R, Liu H, Huo B, *et al.* Nonthermal technologies for seafood preservation and shelf-life extension: a detailed review. *Food Quality and Safety*. 2026;10.
- Bai H, Li L, Wu Y, Chen S, Zhao Y, Cai Q, *et al.* Ultrasound improves the low-sodium salt curing of sea bass: insights into the effects of ultrasound on texture, microstructure, and flavor characteristics. *Ultrasonics Sonochemistry*. 2023;100:106597. <https://doi.org/10.1016/j.ultsonch.2023.106597>
- Briones-Labarca V, Giovagnoli-Vicuña C, Bugueño MJ, Pérez-Won M. Optimization and characterization of prawn by-product protein-stabilized emulsions processed by high-intensity ultrasound. *LWT - Food Science and Technology*. 2025;225:117913. <https://doi.org/10.1016/j.lwt.2025.117913>
- Castañeda-López GG, Ulloa JA, Rosas-Ulloa P, Ramírez-Ramírez JC, Gutiérrez-Leyva R, Silva-Carrillo Y, *et al.* Ultrasound use as a pretreatment for shrimp (*Litopenaeus vannamei*) dehydration and its effect on physicochemical, microbiological, structural, and rehydration properties. *Journal of Food Processing and Preservation*. 2021;45(4). <https://doi.org/10.1111/jfpp.15366>
- Cheng H, Bian C, Chu Y, Mei J, Xie J. Effects of dual-frequency ultrasound-assisted thawing technology on thawing rate, quality properties, and microstructure of large yellow croaker (*Pseudosciaena crocea*). *Foods*. 2022;11(2):226. <https://doi.org/10.3390/foods11020226>
- Chen X, Liu H, Li X, Wei Y, Li J. Effect of ultrasonic-assisted immersion freezing and quick-freezing on quality of sea bass during frozen storage. *LWT*. 2022;154:112737. <https://doi.org/10.1016/j.lwt.2021.112737>
- Dikel Ç, Yanar Y. Ultrasound-assisted extraction (UAE) for the utilization of deep-water pink shrimp (*Parapenaeus longirostris*) processing waste: comprehensive characterization of carotenoid astaxanthin rich extract. *Veterinary Medicine and Science*. 2025;11. <https://doi.org/10.1002/vms3.70498>
- Duppeti H, Manjabhatta SN, Kempaiah BB. Optimization of ultrasonic-assisted extraction of flavor compounds from shrimp by-products and characterization of flavor profile of the extract. *Ultrasonics Sonochemistry*. 2023;101:106651. <https://doi.org/10.1016/j.ultsonch.2023.106651>
- Ekonomou SI, Bozaris IS. Non-thermal methods for ensuring the microbiological quality and safety of seafood. *Applied Sciences*. 2021;11(2):833. <https://doi.org/10.3390/app11020833>
- Fikry M, Benjakul S, Al-Ghamdi S, Tagrida M, Prodpran T. Evaluating kinetics of convection drying and microstructure characteristics of Asian seabass fish skin without and with ultrasound pretreatment. *Foods*. 2023;12(16):3024. <https://doi.org/10.3390/foods12163024>
- Hai TC, Man PV, Anh LTH. Optimization of ultrasound-assisted extraction of astaxanthin from black tiger shrimp (*Penaeus monodon*) shells using deep eutectic solvent and ethanol as a co-solvent. *LWT - Food Science and Technology*. 2024;212:116965. <https://doi.org/10.1016/j.lwt.2024.116965>
- Knorr D, Zenker M, Heinz V, Lee DU. Applications and potential of ultrasonics in food processing. *Trends in Food Science & Technology*. 2004;15(5):261–266. <https://doi.org/10.1016/j.tifs.2003.12.001>
- Li F, Wang B, Kong B, Xia X, Bao Y. Impact of ultrasound-assisted saline thawing on the technological properties of mirror carp (*Cyprinus carpio* L.). *Ultrasonics Sonochemistry*. 2022;86:106014. <https://doi.org/10.1016/j.ultsonch.2022.106014>
- Li J, Hu Y, Liu Z, Wang M, Ning X, He X, *et al.* Impact of thawing methods on the quality of frozen oysters: the superiority of combined ultrasound-microwave. *LWT*. 2025;235:118609. <https://doi.org/10.1016/j.lwt.2025.118609>
- Liu B, Liao YL, Jiang LL, Chen MM, Yang SB. Effects of ultrasound-assisted immersion freezing on the protein structure, physicochemical properties and muscle quality of the bay scallop (*Argopecten irradians*) during frozen storage. *Foods*. 2022;11(20):3247. <https://doi.org/10.3390/foods11203247>
- Li Y, Wang J, Zeng QH, Wang L, Wang JJ, Li S, *et al.* Novel thawing method of ultrasound-assisted slightly basic electrolyzed water improves the processing quality of frozen shrimp compared with traditional thawing approaches. *Ultrasonics Sonochemistry*. 2024;107:106931. <https://doi.org/10.1016/j.ultsonch.2024.106931>
- Panagiotakopoulos I, Karantonis HC, Kartelias IG, Nasopoulou C. Ultrasonic-assisted extraction of astaxanthin from shrimp by-products using vegetable oils. *Marine Drugs*. 2023;21(9):467. <https://doi.org/10.3390/md21090467>
- Prempeh NYA, Nunekpeku X, Murugesan A, Li H. Ultrasound in the food industry: mechanisms and applications for non-invasive texture and quality analysis. *Foods*. 2025;14(12):2057. <https://doi.org/10.3390/foods14122057>
- Putra NR, Rizkiyah DN, Che Yunus MA, Qomariyah L. Towards a greener future: bioactive compounds extraction from shrimp shells using eco-friendly techniques. *eFood*. 2024;5(3). <https://doi.org/10.1002/efd2.146>
- Rajasekaran B, Singh A, Ponnusamy A, Patil U, Zhang B, Hong H, *et al.* Ultrasound treated fish myofibrillar protein: physicochemical properties and its stabilizing effect on shrimp oil-in-water emulsion. *Ultrasonics Sonochemistry*. 2023;98:106513. <https://doi.org/10.1016/j.ultsonch.2023.106513>
- Rajasekaran B, Singh A, Nilsuwan K, Ma L, Nazeer RA, Benjakul S. Shrimp oil nanoemulsions prepared by microfluidization and ultrasonication: characteristics and stability. *RSC Advances*. 2024;14:6135–6145. <https://doi.org/10.1039/D3RA07342D>
- Ravikumar M, Suthar H, Desai C, Sachin G, Gowda AJ. Ultrasonication: an advanced technology for food preservation. *International Journal of Pure & Applied Bioscience*. 2017;5(6):363–371. <https://doi.org/10.18782/2320-7051.5481>
- Saklani P, Siddhnath, Dora KC, Singh SM, Lowansi A. Ultrasound technology for fish processing and preservation. *Indian Farmer*. 2021;8(3):231–237.
- Sandhya M, Ramasamy D, Sudhakar K, Kadirgama K, Harun WSW. Ultrasonication an intensifying tool for

- preparation of stable nanofluids and study the time influence on distinct properties of graphene nanofluids – a systematic overview. *Ultrasonics Sonochemistry*. 2021;73:105479.
<https://doi.org/10.1016/j.ultsonch.2021.105479>
25. Sharayei P, Azarpazhooh E, Zomorodi S, Einafshar S, Ramaswamy HS. Optimization of ultrasonic-assisted extraction of astaxanthin from green tiger (*Penaeus semisulcatus*) shrimp shell. *Ultrasonics Sonochemistry*. 2021;76:105666.
<https://doi.org/10.1016/j.ultsonch.2021.105666>
26. Singh NS, Vaishnav A, Pati B, Lalbiaknguri, Kulshrestha T, Mahanta P, *et al.* Ultrasonication: a developing technology for fish processing and preservation. *Journal of Inland Fisheries Society of India*. 2023;55(2):195–210.
<https://doi.org/10.47780/jifsi.55.2.2023.141476>
27. Sireesha T, Gowda NAN, Kambhampati V. Ultrasonication in seafood processing and preservation: a comprehensive review. *Applied Food Research*. 2022;2(2):100208.
<https://doi.org/10.1016/j.afres.2022.100208>
28. Torres-Arreola W, Partida-Rivera R, Ocaño-Higuera VM, Ruíz-Cruz S, Suárez-Jiménez GM, Montoya-Camacho N, *et al.* Impact of high intensity ultrasound on the quality and preservation period of blue shrimp (*Litopenaeus stylirostris*) muscle. *Journal of Fisheries*. 2025;13(2):132204. <https://doi.org/10.17017/j.fish.820>
29. Ying Y, Xiang Y, Liu J, Chen X, Hu L, Li Y, *et al.* Optimization of ultrasonic-assisted freezing of *Penaeus chinensis* by response surface methodology. *Food Quality and Safety*. 2021;5.
<https://doi.org/10.1093/fqsafe/fyaa034>
30. Yu H, Mei J, Xie J. New ultrasonic assisted technology of freezing, cooling and thawing in solid food processing: a review. *Ultrasonics Sonochemistry*. 2022;90:106185.
<https://doi.org/10.1016/j.ultsonch.2022.106185>
31. Zhao YM, De Alba M, Sun DW, Tiwari B. Principles and recent applications of novel non-thermal processing technologies for the fish industry-a review. *Critical Reviews in Food Science and Nutrition*. 2019;59(5):728–742.
<https://doi.org/10.1080/10408398.2018.1495613>
32. Zhong Q, Xia X, Li F. Study on the microbial inactivation and quality assurance of ultrasonic-assisted slightly acidic electrolyzed water for mirror carp (*Cyprinus carpio* L.) fillets during refrigerated storage. *Foods*. 2025;14(15):2652.
<https://doi.org/10.3390/foods14152652>
33. Zhu X, Yan H, Cui Z, Li H, Zhou W, Liu Z, *et al.* Ultrasound-assisted blue light killing *Vibrio parahaemolyticus* to improve salmon preservation. *Ultrasonics Sonochemistry*. 2023;95:106389.
<https://doi.org/10.1016/j.ultsonch.2023.106389>