Harnessing Sound: Emerging Applications of High-Intensity Ultrasound in Dairy and Meat Processing

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Abstract

High-intensity ultrasound is being investigated as a versatile technology for improving dairy and meat processing. Its effects arise mainly from acoustic cavitation, which generates shear forces, microstreaming and localised heating. Under controlled conditions, ultrasonication can reduce fat-droplet size, modify protein functionality, accelerate mass transfer and assist microbial inactivation. However, treatment responses vary with frequency, acoustic power, duration, temperature, reactor design and food composition. Excessive processing may promote oxidation, protein damage or undesirable sensory changes. Ultrasound should therefore be considered a condition-dependent processing aid rather than a universally non-thermal replacement for conventional processing.

Keywords: High-intensity ultrasound; Acoustic cavitation; Dairy processing; Meat processing.

Introduction

Sound is associated with hearing, communication and medical imaging. At sufficient intensity, however, sound waves can change the structure and processing behaviour of foods. This possibility has attracted interest from dairy and meat processors seeking methods to improve product stability, texture and safety while limiting severe heat treatment.

Ultrasound refers to sound waves above the upper limit of human hearing, conventionally 20 kHz. Food processing uses high-power, low-frequency ultrasound, often within approximately 20–100 kHz. Its applications include homogenisation, emulsification, fermentation, protein modification, marination, tenderisation, freezing, thawing and microbial control. These benefits are not automatic: the outcome depends on how ultrasonic energy is delivered and how the food matrix responds.

How ultrasound acts on food

During ultrasonication, alternating compression and rarefaction cycles travel through a liquid or coupling medium. The pressure fluctuations cause pre-existing gas nuclei in the liquid to grow and undergo rapid collapse. This phenomenon, known as acoustic cavitation, produces turbulence, mechanical shear, microjets and localised increases in temperature and pressure. These effects can break droplets, modify proteins, disrupt microbial cells and accelerate heat and mass transfer. Treatment severity cannot be described by equipment wattage alone. Frequency, amplitude, pulse cycle, probe diameter, sample volume, treatment time, vessel geometry and temperature control all influence the delivered acoustic effect. Nominal power is not necessarily equal to the acoustic power received by the food.

Ultrasound should also not be described automatically as a non-thermal technology. Monteiro et al. (2020) applied the same nominal energy density of 5,000 J/mL to a chocolate whey beverage using either 160 W for 937 seconds or 720 W for 208 seconds. Final temperatures were approximately 34°C and 71°C, respectively, and the products differed in droplet size and microstructure. Equal energy density therefore did not produce equivalent processing.

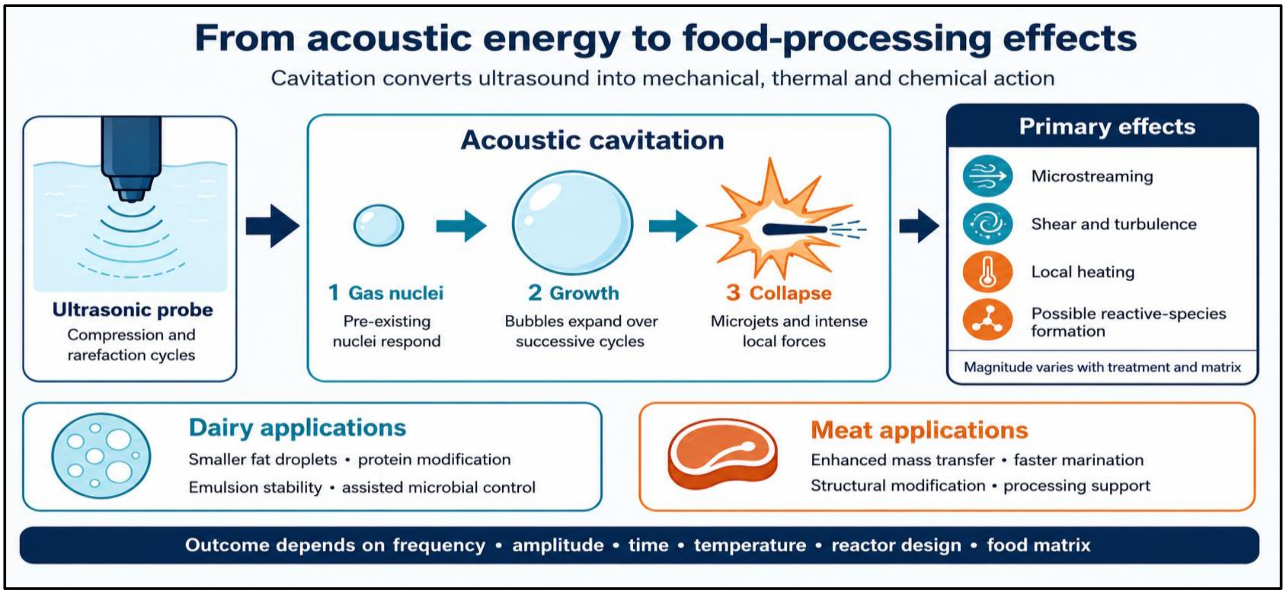

Figure 1. Acoustic cavitation and its principal effects in dairy and meat processing

Applications in dairy processing

Milk is well suited to ultrasound treatment because its continuous liquid phase permits cavitation and acoustic transmission. One prominent application is homogenisation. Cavitation can fragment large fat globules and disperse smaller droplets throughout the aqueous phase. Proteins may adsorb at newly formed interfaces, influencing emulsion stability. Ultrasound can therefore improve dispersion, but the final outcome depends on milk composition and treatment severity.

Protein functionality may also change. Mechanical shear and local physicochemical effects can alter protein aggregation, solubility, emulsifying ability, foaming and gel formation. Moderate structural modification may be technologically useful, whereas excessive treatment can promote aggregation or oxidation and reduce functionality. In raw milk, Scudino et al. (2020) evaluated high-intensity ultrasound at energy densities of 1–7 kJ/mL. The more intensive treatment reduced aerobic mesophilic bacteria by up to approximately 3.9 log cycles and produced fat globules smaller than 1 µm. Nevertheless, the final temperature exceeded 70°C under some high-energy conditions. The microbial reduction could consequently not be attributed solely to non-thermal cavitation. This distinction between ultrasonication and thermosonication is essential when comparing ultrasound with pasteurisation.

Ultrasound is being examined in fermented dairy products. Pretreatment may increase substrate availability, influence enzyme activity and accelerate acid development. Mild, sublethal sonication can stimulate the metabolic activity of certain starter or probiotic strains, while greater intensity can damage their membranes and reduce viability. These responses are strain-, dose- and matrix-dependent. Moreover, sonicating milk before inoculation is fundamentally different from directly exposing probiotic cells to ultrasound (Guimarães et al., 2019).

Table 1. Evidence-based applications of ultrasound in dairy processing

Application	Main action	Potential outcome	Scientific limitation
Homogenisation	Fat-globule disruption	Smaller droplets and improved dispersion	Stability depends on composition and treatment conditions
Protein modification	Structural unfolding or aggregation	Modified emulsification and gelation	Excessive treatment may cause oxidation or aggregation
Fermentation	Increased mass transfer and altered microbial activity	Faster acidification under selected conditions	Response varies among strains
Microbial control	Cavitation combined with possible heating	Reduction in microbial load	Ultrasound alone may not meet pasteurisation requirements

Source: Synthesised from Monteiro et al. (2020), Guimarães et al. (2019) and Scudino et al. (2020).

Table 2. Potential applications and limitations in meat processing

Application	Principal mechanism	Potential benefit	Major caution
Tenderisation	Structural and protein modification	Improved tenderness in responsive muscles	Effects vary among species, muscles and conditions
Marination and curing	Enhanced mass transfer	Faster ingredient penetration	Distribution may remain uneven
Meat emulsions	Improved protein extraction and fat dispersion	Better stability and texture	Oxidation may increase at excessive intensity
Freezing and thawing	Modified heat transfer and ice formation	Faster processing and possibly lower drip loss	Risk of local heating
Microbial control	Membrane disruption, often combined with another hurdle	Reduced surface contamination	Incomplete inactivation when used alone

Source: Synthesised from Cichoski et al. (2019) and Li et al. (2024).

Applications in meat processing

The behaviour of ultrasound in meat is more complex because intact muscle is a heterogeneous solid. Cavitation occurs mainly in the surrounding water, brine or marinade, which acts as the acoustic coupling medium. Treatment effectiveness is influenced by muscle thickness, fibre orientation, fat content, connective tissue and distance from the ultrasound source. Ultrasound may improve tenderisation through mechanical disruption of muscle structure, modification of myofibrillar proteins and possible enhancement of endogenous proteolytic processes. However, reported responses are inconsistent, and treatment cannot be assumed to improve every muscle or meat cut. Another important application is the enhancement of mass transfer. Microstreaming and tissue disruption can accelerate the movement of water, salt and curing ingredients during marination or brining. This may shorten processing time or improve ingredient distribution, although penetration can remain uneven in thick cuts.

Ultrasound can also modify salt-soluble myofibrillar proteins used to stabilise processed-meat emulsions. Cichoski et al. (2019) reported improvements in selected technological properties of meat emulsions following ultrasound treatment. Such findings remain formulation-specific because protein concentration, salt content, fat level and treatment temperature influence emulsion behaviour. Other applications include ultrasound-assisted freezing and thawing. Acoustic energy may influence ice nucleation, crystal formation and heat transfer, potentially reducing thawing time and drip loss. Poor control, however, can cause local heating or uneven processing. Reviews of muscle foods conclude that ultrasound has potential in tenderisation, marination, freezing–thawing and microbial control, but excessive intensity may impair quality (Li et al., 2024).

Microorganisms: stimulation or inactivation?

Ultrasound can produce opposite microbial responses. Severe cavitation may damage cell walls and membranes, causing leakage of intracellular material and loss of viability. Mild exposure may temporarily increase membrane permeability, enzyme activity or nutrient transport and thereby stimulate selected starter cultures. The response depends on species, strain, growth phase, physiological condition, food matrix, temperature and treatment dose (Guimarães et al., 2019).

These objectives must remain separate. Conditions designed to stimulate a probiotic should not be assumed to inactivate pathogens, while conditions that substantially reduce pathogens may also destroy beneficial cultures. Microbial reduction in a laboratory study also does not establish regulatory equivalence to pasteurisation. Product-specific challenge studies, validated processing targets and storage testing remain necessary.

Advantages, limitations and safety

When appropriately controlled, ultrasound can accelerate mass and heat transfer, reduce processing time, improve emulsification and modify protein functionality. It may be particularly useful in combination with mild heating, pressure, vacuum or approved antimicrobials. Such hurdle approaches may achieve a desired effect at lower severity than either treatment alone.

Important limitations remain. Cavitation can be non-uniform in large vessels, complicating scale-up from laboratory probes to continuous industrial systems. Ultrasound-induced heating must be measured rather than assumed absent. Reactive species generated during cavitation may promote lipid and protein oxidation, with possible changes in colour, flavour and nutritional or functional quality. Probe erosion, hygienic equipment design, cleaning, noise control, energy consumption and processing cost also require evaluation.

Ultrasound should not be labelled inherently green or energy-efficient without comparative energy and life-cycle evidence. Similarly, microbial reduction should not be translated automatically into claims of safety or longer shelf life.

Future prospects and conclusion

Future progress will depend on continuous-flow processors, real-time monitoring of acoustic power and temperature, standardised dosimetry and product-specific optimisation. Mathematical modelling and sensor-based control may help maintain uniform treatment during scale-up.

High-intensity ultrasound has credible potential in selected dairy and meat operations, particularly emulsification, protein modification and mass transfer. Commercial adoption will require evidence that these benefits outweigh potential oxidative and sensory deterioration, safety risks and economic costs.

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