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Exploring Impact of the Ultrasound and Combined Treatments on Food Quality: A Comprehensive Review

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ABSTRACT

As a response to the evolving consumer demand for healthier food choices, ultrasound application in food processing emerges as a sustainable and green solution with no residual effects. This method, known for its cost-efficiency and sustainability, holds significant promise in meeting the increasing need for high-quality, chemical-free, and natural-tasting convenience foods in the ever-changing landscape of the food industry. Ultrasound, leveraging mechanical sound waves, spans across various frequencies: power ultrasound (20–100 kHz), high-frequency ultrasound (100 kHz-1 MHz), and diagnostic ultrasound (1–500 MHz). This study focuses on investigating the impact of ultrasound and combined treatments on food quality, summarizing their diverse applications across different unit operations such as texture and rheology, emulsification and homogenization, crystal formation and modification, dehydration and drying, fermentation, filtration, preservation and shelf-life extension, flavor enhancement, color and appearance, antioxidant activity, enzyme activity and food digestibility, bioavailability and bio-accessibility, and specific food divisions including unprocessed, minimally processed, processed, and ultra-processed foods, as well as culinary ingredients. It delves into their effects on technological and functional aspects of food products, explores emerging trends, offers possible recommendations in ultrasound technology for the food industry, while also recognizing existing challenges and limitations associated with ultrasound and related technologies.

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Introduction

The demand for premium, chemical-free convenience foods has propelled the adoption of non-thermal processing technologies within the food industry. Among these innovations, ultrasound technology stands out as a promising solution, offering favorable effects on food quality and efficiency, both independently and in combination with other treatments (Singla & Sit, 2021). With a growing interest from the food processing sector, ultrasound has gained recognition for its ability to enhance the functional, chemical, and physical characteristics of various food products (Téllez- Morales et al., 2020). Notably, it is esteemed for its minimal impact on the intrinsic qualities of processed foods (Balakrishna et al., 2020).

Ultrasound, operating beyond the human hearing threshold, harnesses vibrational energy generated by transducers converting electrical energy into acoustic energy. Categorized into power ultrasound (20–100 kHz), high-frequency ultrasound (100 kHz-1 MHz), and diagnostic ultrasound (1–500 MHz) based on frequency, it finds application across a spectrum of food processing tasks (Chen et al., 2020). The systems facilitating ultrasonic wave generation typically comprise a generator, transducer, and application system, with the generator producing either mechanical or electrical energy, subsequently transformed by the transducer into ultrasonic frequencies for various food processing applications (Chavan et al., 2022).

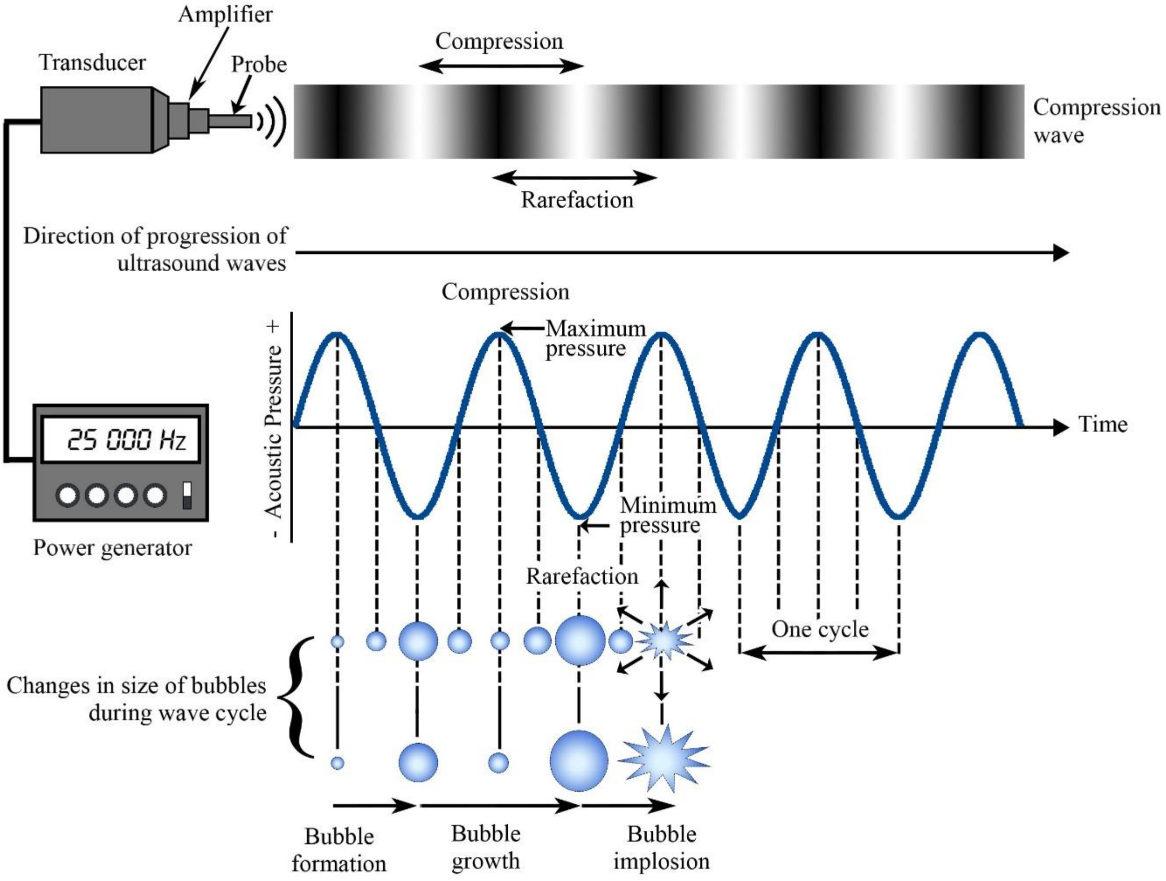

Figure 1. Graphical summary depicting the sequence of events in acoustic cavitation bubble formation, growth, and eventual collapse across multiple acoustic cycles.

Figure 1 illustrates a graphical summary detailing the progression of acoustic cavitation, from the inception of bubbles to their expansion and eventual collapse over successive acoustic cycles. This dynamic sequence provides insight into the complex phenomenon of cavitation and its significance in various applications.

Embracing an environmentally friendly approach, ultrasound processing eliminates the need for toxic solvents, reduces energy and water consumption, and promotes waste recycling, thus aligning with priorities of environmental preservation and consumer health (Muthukrishnan et al., 2022). Its versatility in the food industry spans cutting-edge applications like cutting, freezing, drying, and emulsification, among others (Chavan et al., 2022; Gallo et al., 2018).

Moreover, ultrasound treatments exert diverse effects on food components' physicochemical and functional properties, influenced by processing parameters and the food matrix, thereby facilitating controlled interaction among food components and preserving primary compound structures (Li et al., 2021; Téllez-Morales et al., 2020). The ability of high-intensity ultrasound to penetrate biological materials and induce particle compression and decompression is increasingly acknowledged, leading to enhancements in material functioning (T.J. Mason et al., 2011; Téllez- Morales et al., 2020).

Customizing ultrasound parameters to specific food items is crucial for optimal outcomes, and its low environmental impact further underscores its favorability in the food industry (Téllez- Morales et al., 2020). Our review aims to comprehensively explore specific applications of ultrasound and integrated treatments within the food industry, assessing their impacts on technological and functional properties of food products. Additionally, we discuss future prospects and research directions in emerging trends of ultrasound technology for food applications, while addressing the challenges and constraints associated with its implementation.

The Influence of Ultrasound on the Techno-Functional Properties of Foods

Texture and Rheology

The impact of ultrasound on foods. and structure varies based on food type, process variables, and operating conditions. Low-intensity and high-power sound waves induce cavitation, disrupting tissue structure and reducing turgor pressure for a softer processed product (Aslam et al., 2022). Ultrasound finds versatile applications in the food industry, enhancing texture in fruits and vegetables, optimizing meat tenderization, and improving dairy product characteristics. In fruits and vegetables, it improves firmness, especially in thermal processes, and shows potential for surface modification. Optimization is crucial for effective tenderization in meat, as ultrasound accelerates glycolysis and modulates physiological mechanisms, potentially reducing dark, firm, dry (DFD) meat (Terefe et al., 2016; Sikes et al., 2014). In the dairy industry, ultrasound plays a crucial role in structuring milk and enhancing the properties of cheese and yogurt (Terefe et al., 2016). Low-frequency ultrasound is known to modify casein micelle size, leading to protein aggregation, thereby improving the renneting process of cheese. This results in firmer gels and accelerated cheese curd formation, providing the opportunity for distinctive rheological characteristics in yogurts (Chandrapala et al., 2012). The technology also holds promise for energy savings in milk concentrate processing and cream separation, underscoring its potential impact across various food processing domains (Terefe et al., 2016).When considering industrial applications, investigating the impact of ultrasonic processing on quality parameters of functional yogurts fortified with banana-resistant starch and green papaya powder, (Sarker & Siddiqui, 2023) found that non-thermal processing significantly improved physical and textural properties, including firmness, stiffness, stickiness, thickness, and viscosity ($p < 0.05$). Examining ultrasonic treatment in whole freezing and maximum ice crystal formation, Li et al. (2021) discovered that ultrasound-assisted freezing enhanced dough quality by reducing damage to gluten structure caused by freezing. Moreover, Sheng et al. (2022) investigated the effects of ultrasonic-assisted glycosylation on the gel properties of ovalbumin (OVA), revealing strengthened water-protein interactions and increased water holding capacity. High-intensity ultrasound promoted the Maillard reaction rate, evidenced by successful xylose connection to the OVA molecule. The resulting ultrasonic-assisted glycosylated OVA exhibited improved hardness attributed to changes in protein structure, intermolecular interactions, and microstructure. Zhang et al. (2020) explored the positive impact of multi-frequency ultrasound on wheat-less gluten protein noodles, revealing improved quality characteristics and altered protein structure. This study offers a promising method for enhancing noodle quality and potentially reducing gluten content in food formulations. Studies employing low-intensity ultrasound (40-400 kHz) demonstrate improved firmness in potatoes, carrots, and pears (Önal et al., 2021), which is not only useful in assessing quality but also influences various stages of the supply chain, consumer preferences, and the overall culinary experience. Ultrasound technology has proven effective in hindering enzymes such as pectin methylesterase (PME) and polygalacturonase (PG), crucial for texture maintenance in fruits and vegetables (Terefe et al., 2015). To mitigate adverse effects, it is advisable to apply ultrasound during the early climacteric phase when polygalacturonase activity is minimal, preserving texture and flavor (Terefe et al., 2011).

Emulsification and Homogenization

The growing awareness of healthy and natural food consumption has sparked widespread interest in natural emulsifier-stabilized emulsions within the food industry. Ultrasound-assisted emulsification (UE) has demonstrated a multifaceted impact on emulsion properties, affecting viscosity, emulsifying properties, droplet size, zeta potential, emulsifier characteristics, and oil phase properties. This showcases its potential to enhance rheological and emulsifying properties, reduce droplet size, and increase absolute zeta potential, particularly in protein, polysaccharide, and protein-polysaccharide-surfactant stabilized emulsions (Zhou et al., 2021a).

Emulsifiers play a crucial role in enhancing product stability and ensuring a satisfactory shelf-life by preventing the formation of peroxides and maintaining the fatty acid composition of food. High-pressure homogenization, a conventional method known for its efficiency in preparing emulsions, has been challenged by recent experiments conducted by Li and Xiang (2019). These experiments highlight the superior benefits of ultrasound treatment. Both high-pressure homogenization and ultrasound effectively reduce apparent viscosity and average droplet size, narrowing the distribution range of emulsions. Interestingly, while high-pressure homogenization led to emulsion aggregation, ultrasound-treated emulsions remained stable during a 30-day storage period. This study underscores the valuable role of ultrasound in optimizing and extending food shelf-life, presenting a promising method for the food and beverage industries.

Emulsion systems are widely used in the food industry, with high-intensity ultrasound (HIU) emerging as an eco-friendly and cost-effective method for emulsion preparation. HIU induces acoustic cavitation, enhancing oil droplet disruption and promoting stable emulsion formation. HIU improves emulsifying properties of food emulsifiers like proteins and polysaccharides, increasing emulsion stability. Protein-polysaccharide complex-stabilized emulsions via HIU exhibit superior stability against environmental stresses compared to those stabilized by individual components. Additionally, studies suggest that HIU homogenizers are more energy-efficient than high-pressure homogenizers and microfluidizers (Delmas et al., 2023; Taha et al., 2020a).

Zhou et al. (2022b) found that ultrasound-assisted emulsification (UAE) is a superior method for fabricating myofibrillar protein (MP)-stabilized soybean oil emulsions compared to high-speed homogenization (HSH) and high-pressure homogenization (HPH). UAE resulted in smaller particle size, better storage stability, and improved emulsion properties under the same power consumption conditions. Utilizing ultrasound for milk emulsification and homogenization requires careful consideration of potential drawbacks such as fat oxidation, enzyme deactivation, and protein denaturation (Režek Jambrak et al., 2009). This technology enables milk fractionation, reducing fat content and improving renneting capabilities (Leong et al., 2014a; Zhao et al., 2014). Sonication disrupts casein micelles, resulting in smaller particle sizes and more efficient production (Leong et al., 2014b).

Ultrasonic processing significantly enhances emulsification, reducing fat globule size and producing a stable final product (Shanmugam and Ashokkumar, 2014). Cavitation bubbles created by ultrasound increase turbulence, breaking apart fat droplets and yielding a more consistent emulsion (Abbas et al., 2013; Leong et al., 2009). This approach proves efficient in achieving stable emulsions without additives, ensuring product stability and purity (Paniwnyk, 2017). In practical applications, ultrasound is valuable for creating water-in-oil emulsions, particularly in processes involving emulsion liquid membranes for cationic dye separation, influenced by various factors (Djenouhat et al., 2008).

Zhou et al. (2021a) investigated the impact of ultrasound-assisted emulsification on myofibrillar protein (MP) pork fat emulsions at various protein/fat ratios. Ultrasound significantly improved emulsifying activity, stability, and flow index, while reducing viscosity (except at a 1:15 protein/fat ratio). The study revealed that sonication decreased particle size, improved droplet distribution, enhanced protein-fat binding, and exposed more sulfhydryl groups. Overall, ultrasound-assisted emulsification directly enhanced emulsifying and rheological properties, particularly at a 1:10 protein/fat ratio. The study by Belgheisi et al. (2021) investigated O/W lycopene emulsions (30:70) processed with ultrasound (240 W and 360 W, 5-15 min). Results indicated improved emulsifying characteristics, reduced droplet size, increased ζ-potential, enhanced stability, and high lycopene retention. Ultrasound reduced viscosity by decreasing particle size, with the 360 W, 2160 J/cm³, 10-min treatment yielding emulsions suitable for food products.

Ultrasound homogenization, a cost-effective emerging technology, was employed by Sun et al. (2019) to produce stable rice bran protein-stabilized emulsions. The study demonstrated that varying ultrasound power and time influenced emulsion characteristics, and emulsions prepared at 20% power for 20 minutes exhibited notable stability against creaming, highlighting the efficacy of ultrasound homogenization in preparing high-quality emulsions with rice bran protein isolates possessing excellent stability, emulsifying properties, and tolerance to elevated NaCl concentrations and temperatures. Jiang et al., (2021) compared physicochemical properties of peanut protein-stabilized emulsions prepared by high-intensity ultrasound (HIU) and high-pressure homogenization (HPH). While HPH is commonly used but expensive, HIU was found to be a cost-effective method with superior physical stability for peanut protein-stabilized emulsions, suggesting its potential in the food industry.

Crystal Formation and Modification

Crystallization stands as a pivotal process within the food industry, orchestrating the formation of structured solid granules within a homogeneous phase, a phenomenon that significantly influences consumer preferences and product texture (Deora et al., 2013). One innovative approach in this realm is sonocrystallization, which harnesses ultrasound energy to exert control over the crystallization process (Pohlman et al., 2023), primarily leveraging the critical phenomenon of cavitation.

Cavitation manifests in two primary forms: stable, characterized by small bubbles within a liquid, and transient, involving rapidly fluctuating bubble sizes that collapse, generating localized high temperatures (up to 5,000 K) and pressures (up to 100 MPa) (Darsana and Sivakumar, 2023). Sonocrystallization offers a plethora of advantages over traditional methods, including enhanced product uniformity, elevated crystal purity, improved secondary physical properties such as flowability and packing density, expedited crystallization cycles, and diminished rework requirements (Luque de Castro and Priego-Capote, 2007). This technique is particularly adept at regulating the dimensions of sugar crystals, thereby exerting a significant influence on the texture of food products (Deora et al., 2013).

In 2007, Bund and Pandit conducted pioneering research demonstrating that subjecting a lactose solution to sonication with an ultrasonic bath at 22 kHz and 85% v/v ethanol as an anti-solvent facilitated rapid crystallization, resulting in an impressive 92% lactose recovery, a stark improvement over the 15% recovery achieved in mechanically stirred control samples. They also observed positive alterations in lactose crystal size and shape. Subsequent investigations into sonocrystallization have indicated a correlation between cavitation and the initiation of ice crystals. Cavitation bubbles generated during sonication enhance the freezing process by reducing the ice-liquid interface's resistance to heat and mass transmission, thereby expediting the freezing rate (Chow et al., 2003). Intense ultrasound with a low frequency has shown significant advancements in nucleation, a reduction in the crystal induction period, increased consistency in crystal growth, and enhanced reproducibility. Moreover, ultrasound exhibits potential for crystal elimination and retarding crystallization, presenting an economically viable technological solution (Deora et al., 2013).

When applied to substances like tripalmitoylglycerol and cocoa butter using 20 kHz ultrasound at 100–300 W for 3 seconds, sonocrystallization enables the direct crystallization of the stable form of the substance, bypassing the intermediate formation and subsequent melting of unstable forms, as demonstrated by Kabbani et al. in 2011. Research on the ultrasonication of fat globules suggests the potential to achieve a unique balance between crystallized and non-crystallized fat components in dairy systems, as reported by Martini et al. in 2008. Furthermore, an investigation into the effects of high-intensity ultrasound on fat crystallization revealed expedited crystallization processes leading to the formation of smaller crystals. Post-sonication, increased viscosity was observed in the samples, attributed to fat crystallization, as documented by Deora et al. in 2013.

Dehydration and Dying

Ultrasound technology has emerged as a significant advancement in the food industry, particularly in the realm of food drying, offering a modern solution to the challenges posed by conventional drying methods, such as prolonged dehydration periods, high energy consumption, and compromised product quality (Huang et al., 2020; Xu et al., 2022;). Ultrasound technology influences drying kinetics and food quality.

Ultrasound pre-treatment can cause water loss or gain in food products, with increased ultrasonic parameters intensifying these effects. Applying ultrasound before drying consistently accelerates drying kinetics, but outcomes vary. (Castañeda-López et al., 2021) explored ultrasound pretreatment as a means to enhance shrimp dehydration. Shrimps treated with ultrasound in a salt solution (10%) at 4°C for 15 and 30 min in an ultrasonic bath (130 W, 40 kHz) showed reduced dehydration time compared to controls, with improvements in ash content, water activity, and rehydration quality. Ultrasound pretreatment holds promise for enhancing shrimp dehydration, offering advantages in processing time and product quality. This method could contribute to producing consumer-demanded ready-to-eat shrimp products. Ultrasound-assisted drying benefits from increased ultrasound power, but the extent of improvement depends on variables like air velocity, temperature, microwave power and vacuum pressure. Ultrasound affects food quality by decreasing water activity, enhancing color, and minimizing nutrient loss (Huang et al., 2020). Ultrasound-assisted osmotic dehydration (UAOD) enhances fruit and vegetable dehydration by improving mass transfer rates and product quality. UAOD outcomes are influenced by various factors, including pre-treatment techniques, sonication intensity, treatment conditions, osmotic solution properties, and sample characteristics. UAOD increases weight reduction, moisture loss, and soluble solids gain, streamlining processing and reducing energy costs (Salehi, 2023). As reported by Fernandes et al. (2019) the efficacy of ultrasonic-assisted osmotic dehydration (UAOD) on drying kinetics of cube-shaped mangoes, finding that UAOD, coupled with a 500 kg sucrose/m3 osmotic solution, was effective in improving the process. (Bozkir et al., 2019) explored the impact of ultrasound and osmotic dehydration pretreatments on persimmon fruit drying, observing improved drying behavior and quality properties with ultrasound-assisted osmotic dehydration, resulting in shorter dehydration times and increased water diffusivity. (Li et al. (2020) used ultrasound-assisted vacuum drying (UAVD) to enhance efficiency and produce quality dried hawthorn fruit juice powders. They tested ultrasound intensity levels and found that higher intensity shortened drying time and improved drying rate.

Fermentation

The integration of ultrasound technology in fermented food production represents a transformative leap forward. It enhances fermentation efficiency, enables real-time process monitoring, and optimization (Pinto et al., 2021), and revolutionizes conventional methods that are typically time-consuming and demand extensive storage space for maturation. Thus, it offers substantial potential for generating premium-quality fermented foods (Yu et al., 2021). Several studies have highlighted ultrasound's capacity to improve the bioactive and functional properties of fermented dairy products, with an observed significant increase in peptide content with ultrasound amplitude up to 60%. This makes it a promising alternative for dairy heat processing and microorganism inactivation (Kaveh et al., 2023). Furthermore, Guimarães et al. (2019) showed that High-intensity ultrasound (HIUS) offers dairy industries potential benefits, including reduced processing time and resource usage in fermented dairy production, as well as the ability to modify prebiotic structures for improved probiotic access. However, precise control of HIUS parameters is necessary, and further research is needed to explore its potential applications in inactivating probiotic cultures and developing health-enhancing products. Moreover, Li et al. (2021) highlighted the benefits of low-frequency ultrasound and weak magnetic fields in enhancing rare edible mushroom fermentation, improving biosynthesis efficiency, product safety, and biological activity, with promising prospects for industrialization.

Extraction

Recent advancements in ultrasound-assisted extraction (UAE) of plant pigments, such as anthocyanins, betalains, carotenoids, and chlorophyll, have revealed improved extraction efficiency attributed to cavitation, cost-effectiveness, and energy reduction. This emphasizes the importance of optimizing conditions, stability, and bio-accessibility for enhanced performance (Kumar et al., 2023). UAE emerges as a promising method for efficiently extracting bioactive compounds from agri-food sources to produce bio-based colorants, catering to the increasing consumer demand for natural additives in food products. Studies optimizing parameters like power and duration have demonstrated maximum yields of anthocyanins and phenolics from grape pomace and jabuticaba peels while reducing extraction times and solvent usage compared to traditional methods (Singla & Sit, 2021). Previous studies have shown that ultrasonic (US) treatment enhances the extraction of phenolic compounds from diverse sources such as mango peel, avocado, apple, jussara (*Euterpe edulis* M.), and blueberry (Vaccinium myrtillus) by leveraging acoustic cavitation in the solvent (Qureshi et al., 2020). The optimized heat- and ultrasound-assisted extraction methods were utilized by Pinela et al. (2019) to yield high levels of anthocyanins from Hibiscus sabdariffa calyces, showcasing its potential as a sustainable source of natural colorants for various industrial applications. Furthermore,(Ordóñez-Santos et al. (2021) optimized ultrasound-assisted carotenoid extraction from mandarin epicarp, potentially offering a natural coloring alternative for bakery items, with peak extraction efficiency achieved at 60 °C for 60 minutes, yielding 140.70 ± 2.66 mg β-carotene/100 g dry sample, hold promise as natural coloring additives, potentially mitigating the need for synthetic dyes like tartrazine in bakery products such as cakes and bread.

Filtration

Ultrasound, a versatile tool in the food industry, revolutionizes filtration processes by mitigating fouling during whey ultrafiltration, reducing protein aggregate size, and pore blockage rates (Koh et al., 2014). The simultaneous application of ultrasound during membrane filtration processes, particularly in cow milk and whey, has shown promising results in increasing flux rates and improving efficiency, indicating a potential for enhanced food processing techniques (Córdova et al., 2020). Ultrasound effectively disrupts retentate layers during filtration, increasing flux and decreasing flow resistance, thus improving filtration efficiency and enhancing the quality of processed products, and prolonging filter life through continuous cavitation. Despite challenges such as membrane caking, polarization, and low-power transducers hindering widespread adoption, ultrasound ensures product quality and safety (Bhargava et al., 2021; Singla & Sit, 2021). Acoustic filtration not only enhances the quality of processed products by preventing membrane caking and clogging but also addresses safety concerns associated with industrial wastewater filtration, making it a pivotal technology in improving filtration efficiency and longevity (Bhargava et al., 2021).

Preservation and Shelf-life Extension

Food spoilage primarily occurs due to the actions of microbes and enzymes (Bhargava et al., 2021). Nutrient and moisture-rich environments promote microbial growth and enzyme activity. Ultrasound, a non-thermal preservation method, effectively inhibits the growth of unwanted microorganisms and enzymes. The success of ultrasound treatment depends on factors such as wave intensity, exposure duration, microbial variety, food composition, and treatment temperature (Chemat et al., 2017).

The deactivation of microorganisms by ultrasound is attributed to cavitation, induced by pressure variations (Piyasena et al., 2003). The rapid formation and collapse of bubbles generated by ultrasonic vibrations exert an antibacterial effect (Rathnakumar et al., 2023). Cavitation-induced localized changes in temperature and pressure lead to membrane rupture, cell wall breakdown, membrane thinning, and free radical production, causing DNA damage (Ercan and Soysal, 2013).

The effectiveness of ultrasonic treatment varies with different bacterial types due to variations in membrane composition (Beitia et al., 2023). Gram-positive bacteria, with thicker cell walls and no outer membrane, respond differently to ultrasonic waves compared to Gram-negative bacteria, which have thinner cell walls and an outer membrane (Piyasena et al., 2003). Generally, Gram-negative bacteria are more susceptible to ultrasound inactivation than Gram-positive bacteria (Drakopoulou et al., 2009).

The efficacy of ultrasound in deactivating bacteria is influenced by frequency, intensity, size, shape, and growth phase of microorganisms (Palanisamy et al., 2019). Higher-frequency ultrasound, typically in the range of 200 to 600 kHz, enhances efficacy (Wordon et al., 2011). Larger cells with increased surface area tend to be more sensitive to ultrasound, with cocci showing greater resistance compared to bacilli (Cho and Chung, 2020).

Saccharomyces cerevisiae and Escherichia coli are among the microorganisms studied with ultrasound (Iorio et al., 2019; Pinon et al., 2019). While ultrasound alone may not eliminate certain microorganisms completely, its combination with heat or pressure effectively deactivates bacterial and fungal spores, thus preventing food spoilage (Palanisamy et al., 2019; Silva and Evelyn, 2020).

Ultrasound not only deactivates microorganisms but also enhances food quality (Feng et al., 2011). It disrupts enzyme activity by altering protein structures through cavitation-induced pressure spikes and temperature increases (Tian et al., 2004). High-energy intermediates generated during cavitation, such as hydroxyl and hydrogen radicals, interact with amino acid residues, affecting enzyme stability and activity (Feng et al., 2011).

The extent of tissue disruption during ultrasound affects enzyme inactivation (Bermúdez-Aguirre et al., 2011). Oxidases are commonly deactivated by sonication, while catalases are affected at lower concentrations (Ercan and Soysal, 2013). Free radical scavengers like mannitol can protect enzymes from ultrasound-induced inactivation (Barteri et al., 2004). Enzyme susceptibility to ultrasound varies based on amino acid composition and structural conformation (Tiwari et al., 2012).

Ultrasound is highlighted for disinfection and enzyme inactivation in ready-to-eat salads and fresh-cut produce (Chen et al., 2020). It effectively removes microbes and biofilms, reducing the need for chemical disinfectants. Ultrasound preserves food by inactivating microorganisms, including spores, while maintaining sensory and nutritional qualities (Onyeaka et al., 2023). Its cost-effectiveness makes it a promising option for food preservation without compromising quality.

Flavor Enhancement

The growing demand for natural, premium, and additive-free fast food has fueled a shift towards non-thermal processing methods, with ultrasound emerging as a prominent option in recent research (Chavan et al., 2022; Jalizadeh et al., 2018). Various studies highlight the significant impact of ultrasound interventions on the flavor of different food products, showcasing its potential in enhancing both flavor and taste attributes. Cheese samples, when subjected to ultrasound treatment, exhibited a favorable impact on flavor, with increased lipolysis and proteolysis compared to untreated samples (Chavan et al., 2022; Jalizadeh et al., 2018). The improvement in flavor was attributed to the breakdown of molecules, leading to enhanced sensory properties.

Soy sauce samples treated with ultrasound demonstrated improvements in attributes such as umami, sweetness, sourness, and kokumi (Gao et al., 2019). This enhancement was linked to increased levels of 1–5 kDa peptides, sugars, amino acids, and organic acids in the treated samples. In the case of chicken soup, Alshehhi et al. (2023) found that ultrasound treatment, particularly at 120 W power, significantly heightened the umami taste by increasing flavor-enhancing nucleotides, with IMP being the primary contributor. Different ultrasound powers influenced nucleotide content and flavor, with 240 W power intensifying the meaty flavor, showcasing the versatility of ultrasound in flavor modulation.

Ultrasonication was compared with ultra-high-pressure processing (UHP) in the treatment of melon juice by Liu et al. (2023). While both methods impacted volatile components, ultrasonication exhibited a higher correlation coefficient with the control group, indicating a closer preservation of the original flavor composition. This highlights the potential of ultrasound in retaining the characteristic taste of melon juice. The meat industry's quest to reduce salt content and explore alternatives has led to the application of ultrasound technology in various meat processing stages (Gomez et al., 2021; Jianzhang et al., 2020). Customization of ultrasound parameters for each meat product is crucial due to their diverse structures and compositions, leading to unique ultrasound effects.

Research on unsmoked bacon by J. Zhang et al. (2021) demonstrated that ultrasound, especially at 500W, increased sensory scores by enhancing metabolite levels, showcasing its potential in improving bacon flavor. Ultrasound treatments were also found to enhance the flavor of freeze-dried carrots, extending their shelf life and gaining positive reception from consumer taste panels (Lyu et al., 2022).

Combining mild heat and ultrasound pretreatment showed promise in enhancing the flavor profile of seafood proteins (Li et al., 2021). Additionally, Zou et al. (2018) reported notable increases in sodium chloride, sugar, and 5'-ribonucleotide content, along with enhanced volatile flavor compounds in spiced beef treated with ultrasound. Ultrasound treatment positively influenced the flavor of various foods, including sonicated melon, which received higher acceptance scores for aroma and taste (Da Silva et al., 2018). Acoustic pretreatment with grape and mulberry syrups was found to enhance kiwifruit flavor compared to other methods (Roueita et al., 2020).

Using an electronic nose (E-Nose), Zhang et al. (2018) assessed the flavor of dried carrots and found that ultrasound positively affected carrot flavor by increasing aromatic compounds and reducing undesirable flavor chemicals. For Chinese ginger, An et al. (2019) showed that pulsed vacuum Osmo dehydration closely resembled fresh ginger, while ultrasound treatment introduced new aromatic compounds, altering the ginger's flavor. Despite variations in treatment methods applied to carrots, dried samples received moderate approval from sensory panels, with diminished appreciation attributed to carbohydrate loss and alterations in volatile profiles (Gamboa-Santos et al., 2013). The flavor enhancement observed with ultrasound treatment is contingent on the type of food and the specific parameters of the treatment (Xu et al., 2022).

Finally, coupling ultrasound treatment with a 0.5% salt mixture significantly improved the flavor of restructured bacon, as observed by Zhou et al. (2020). This improvement was associated with heightened lipid and protein oxidation, the generation of free amino acids, and the release of distinctive volatile compounds, ultimately elevating the taste and overall appeal of the bacon product.

Color and Appearance

The effects of ultrasound on color are significant as color serves as a visual cue for food quality, influencing consumer satisfaction.Ultrasonic waves enhance food color intensity and appearance(Wang et al., 2019). As explained by (Pandiselvam et al. (2023) pre-treatment with ultrasound reduces browning and total color change during drying, with shiitake mushrooms showing higher L* values and reduced yellowness. Ultrasonic pre-treatment increases whiteness and reduces yellowness, with no significant effect on redness. Carrot pre-treatment samples maintain consistent redness with fresh samples before drying. Furthermore, Nowak et al. (2019) aimed to assess the impact of ultrasound pre-treatment on the color of blueberries, revealing that such treatment preserved the desirable reddish-blue hue, particularly when applied before freezing, while cautioning against high-power ultrasound post-freezing due to adverse color alterations without affecting texture. The experiments conducted by Strieder et al. (2020) showcased the successful production of a novel natural blue colorant through the cross-linking of milk proteins and genipin, facilitated by low-frequency and high-power ultrasound technology, with genipin extracted from unripe Genipa americana L. using milk as a solvent, indicating the promising potential of ultrasound-assisted techniques in enhancing food colorant production.

Enzyme Activity and Food Digestibility

Ultrasound technology stands as a crucial element in the realm of food processing, particularly due to its capacity to disrupt cell walls in fruits. This disruption yields notable advantages such as reduced oxygen content, shorter processing durations, and enzyme inactivation. Guerra-Almonacid et al. (2019) and Qian et al.(2023)observed significant enhancements in enzymatic protein hydrolysis through ultrasound pretreatment, and Wang et al. (2021) along with Zhang et al. (2017) reported diverse chemical and physical changes in proteins induced by ultrasound. These changes included covalent bond disruption, alterations in protein structures, and improved enzymatic breakdown.

The influence of ultrasound is intricately linked to the disruption of essential intermolecular interactions such as Van der Waals forces and hydrogen bonds(Kozell, Solomonov, & Shimanovich, 2023).Guerra-Almonacid et al. (2019) illustrated that ultrasound pretreatment amplifies the Alcalase enzyme's activity, attributed to ultrasound-generated forces capable of breaking protein molecule chains. Previous studies have explored ultrasound's potential to deactivate enzymes like polyphenol oxidase and peroxidase, mitigating the risk of browning in juices (Qureshi et al., 2020).

Furthermore, Vanga et al.'s (2020) research revealed a substantial increase in protein digestibility in soymilk due to ultrasound treatment, marked by a 52% rise and reduced trypsin inhibitor activity. These benefits were echoed in microwave processing, suggesting potential for improved protein digestion. Across various animal-derived foods, ultrasonication has demonstrated effectiveness in enhancing protein digestibility through favorable structural and microstructural alterations that facilitate enzymatic interactions. However, factors like glycation, freezing, culinary preparation, and the existence of compounds like plant phytochemicals can influence the overall impact of ultrasonication on protein digestibility (Bhat et al., 2022).

Zhu et al. (2019) discovered that subjecting egg white proteins to 16 minutes of ultrasound processing significantly improved their digestibility in simulated gastrointestinal conditions, resulting in an 8% rise compared to the control group. Additionally, a 12-minute treatment demonstrated a 5% improvement in digestibility, showcasing ultrasound's potential in enzyme deactivation (Ekezie et al., 2018). Ultrasound has also demonstrated potential in improving the breakdown of muscle proteins by causing alterations in their structure, resulting in increased accessibility to gastrointestinal enzymes (Bhat et al., 2022).

Ultrasonic-assisted enzymolysis utilizes mechanisms like radical sonochemistry, enabling precise modification of polyphenols and carotenoids. Additionally, ultrasound's ability to alter cell molecules enhances nutrient availability while maintaining quality. Expert ultrasonication utilizes cavitation effects and mechanical action to improve enzymolysis, as demonstrated by Umego et al. (2021). Zhang et al. (2020) explained that ultrasound treatment increases thiol content and reduces disulfide content, disrupting protein molecule disulfide bonds and enhancing protein digestibility.

In fresh fruits and vegetables prone to enzymatic browning, enzymes significantly affect quality. Ultrasound provides a non-thermal approach to deactivate enzymes, potentially preserving product quality and increasing shelf life. However, the effect of ultrasonography may differ based on the specific food product and the circumstances of the trial (Chen et al., 2020). According to Gao et al. (2019), moromis enzyme activity is significantly impacted by ultrasound treatment, with acid protease consistently exhibiting increased activity during fermentation, attributed to low-intensity ultrasound application from Day 1 to Day 15. Similar effects on enzyme activities have been noted in earlier studies, with low-intensity ultrasound potentially increasing the activity of specific enzymes (Khan et al., 2021). Conversely, Huang et al. (2017) found that ultrasound treatment led to the highest alcalase activity, attributed to changes in the enzyme's surface structure. Furthermore, Su et al. (2021) and Huang et al. (2017) demonstrated that ultrasound could enhance the performance of other enzymes by modifying their structure and facilitating interactions with substrates.

Antioxidant Activity

Utilizing ultrasound in fruit and vegetable processing holds promise for preserving crucial antioxidant compounds, such as vitamin C and polyphenols, vital for both food stability and human health (Xu et al., 2022). Sonication has been shown to enhance antioxidant activity in various food matrices. For instance, (Gholamhosseinpour & Hashemi, 2019) demonstrated improved antioxidant activity in sonicated milk fermented with Lactobacillus plantarum AF1, with increased cell membrane permeability and population of the probiotic strain. Similarly, Saikia et al. (2016) found that sonication and microwave treatments improved phenolic content and antioxidant activity in fruit juices, suggesting alternatives to conventional pasteurization methods.

Moreover, ultrasound can enhance the antioxidant activity of specific compounds, such as anthocyanins from red radish (Li et al., 2022) and protein concentrate hydrolysates from Erythrina edulis (Guerra-Almonacid et al., 2019). Ultrasound treatment has also been linked to increased antioxidant capacity in pectin, attributed to changes in its physicochemical properties (Chen et al., 2019). Additionally, ultrasound's antimicrobial properties make it a potential alternative to high-temperature pasteurization, preserving bioactive compounds in processed fruit juices (Roobab et al., 2023).

Studies suggest that ultrasound treatment can have varying effects on antioxidant activity compared to thermal methods, with some juices showing initial increases followed by decreases upon storage (Paniwnyk et al., 2017). Nonetheless, ultrasound has consistently shown potential in preserving bioactive components in fruit juices, such as ascorbic acid and anthocyanins (Qureshi et al., 2020). While prolonged ultrasound treatment may lead to a decline in antioxidant properties, the response varies among different fruit varieties (Qureshi et al., 2020). Furthermore, Cao et al. (2019) found that ultrasound treatment at lower intensity levels and shorter durations had minimal impact on antioxidant compounds and activity in bayberry juice, with progressive declines observed with increased intensity and treatment time.

Bioavailability and Bio-accessibility

The application of ultrasound to cell walls induces cavitation effects, resulting in localized heating and disruption of the cell wall and membrane, which facilitates solvent penetration into the food matrix, promotes compound extraction, and ultimately leads to effective leaching of intracellular active compounds, increased bioavailability, and enhanced accessibility for the absorption of active compounds and minerals(Meena et al., 2024). Ultrasound treatment of fruit juices, as demonstrated by Aadil et al. (2013), significantly increases vitamin C content, with a 14% rise after 30 minutes and a further increase to 28% after 90 minutes, showcasing its potential to enhance bioavailability through improved extraction efficiency and stability, offering a viable alternative to high-temperature preservation methods like pasteurization. Additionally, Mieszczakowska-Frąc et al. (2021) found that ultrasound treatment of mango juice at 40 kHz and 30 W for varying durations (15, 30, and 60 minutes) at 25°C results in enhanced retention of L-ascorbic acid compared to traditional high-temperature pasteurization at 90°C, further highlighting its potential to improve nutrient bioavailability.

Similarly, when strawberry juice was exposed to varying levels of acoustic energy densities, it led to substantial preservation of ascorbic acid. However, with an increase in sonication duration and intensity, there was a decrease in the retention of ascorbic acid. Notably, the longest sonication duration resulted in a loss of less than 15% of ascorbic acid (Aadil et al., 2013; Tiwari et al., 2009). Paniwnyk (2017) found that simultaneous application of ultrasonic and UV treatment to fruit and vegetable juices maintained their nutritional characteristics, including total phenol content, antioxidant activity, vitamin C levels, and carbohydrate content.

Furthermore, a study compared the effects of high-temperature treatment (90°C) with varying durations of ultrasonic treatment (15, 30, and 60 minutes) at 25°C (40 kHz, 30 W) on freshly squeezed mango juice. The thermally treated juice exhibited the highest degradation of ascorbic acid, with a 65% loss. In contrast, ultrasound treatment notably improved the retention of L-ascorbic acid compared to heat pasteurization. After 15 and 30 minutes of sonication, the reduction was approximately 13% and 16%, respectively. However, the loss of vitamin C increased to 28% with an extended ultrasound exposure of 60 minutes. Additionally, ultrasound had a positive impact on the carotene content in mango juice, consistent with prior research on sonicated purple cactus pear juice. In the case of cactus juice, various ultrasonic amplitude levels and treatment durations were evaluated. It was found that, except for the juice treated at 80% amplitude level for 8 and 15 minutes, the vitamin C content was approximately 25% lower than the control sample (Aadil et al., 2013).

Despite ultrasonication being widely employed in drying processes, there is limited research on the stability of L-ascorbic acid during ultrasound-assisted drying. This is likely due to the fact that this antioxidant degrades more rapidly when exposed to ultrasound. In a recent study, Tao et al. (2019) investigated the impact of water blanching (for 30 seconds) and surface-contacting ultrasound-assisted air drying (at power levels of 429.3 and 1131.1 W/m2) on white cabbage. Surprisingly, they found that among the blanched cabbage samples, those dried using only air exhibited significantly higher vitamin C content compared to those dried using sonication. Similarly, when papaya underwent drying through four different methods, a notable reduction in ascorbic acid content was observed. The study revealed that samples dried using ultrasound experienced the lowest losses of this chemical, with a reduction of only 41.3% compared to samples dried using vacuum, ultrasound-assisted drying, and control methods (Tao et al., 2019; Da Silva Júnior et al., 2018).

Exploring the Impact of Diverse Ultrasound Techniques on Food Product Quality

Ultrasound has emerged as a versatile tool in food processing, exerting diverse effects on the properties of various food products across different stages of production. This technology, when applied under specific ultrasonic treatment conditions, induces changes in food composition and structure, leading to alterations in texture, flavor, and nutritional content. Furthermore, the combination of ultrasound with other processing techniques amplifies its impact, often enhancing food quality parameters such as shelf life and sensory attributes. Table 1 enumerates the ultrasonic treatment conditions, elucidating the causative factors underlying the observed changes in food properties, and delineates how these modifications influence the overall quality of food products.

Difficulties and Constraints of Ultrasound and Integrated Treatments

The utilization of ultrasound and integrated treatments in the food industry brings about various advantages, including enhanced processing efficiency, enhanced product quality, and reduced energy consumption. However, they also face certain challenges and limitations.

Cost and Scalability Considerations

The implementation of ultrasound and combined technologies can be expensive, requiring specialized equipment and trained personnel, making it challenging for small-scale food processors to adopt this technology (Aslam et al., 2022; Khouryieh, 2021). Additionally, the scalability of ultrasound processing for large-scale production may be limited, as it requires specialized equipment and expertise. Limited expertise, awareness, and resistance to tradition impede ultrasound tech adoption. Combining ultrasound with existing/novel tech can promote awareness and eco-friendly solutions in food industries (Singla and Sit, 2021).

Equipment Requirements and Operational Parameters

Despite its many benefits, ultrasound technology's use in the food industry is limited by challenges such as scalability issues, technical knowledge gaps, lack of standardized reporting, restricted activation zones, and potential impacts on product texture and nature, highlighting the need for affordable instrumentation with proven advantages over alternative technologies for continued high-intensity ultrasound applications (Onyeaka et al., 2023). Inconsistencies in ultrasound processing methods and control parameters in the food industry hinder widespread adoption due to variable outcomes. Standardizing energy consumption, test types, and sample volumes is essential for technoeconomic evaluation before industrial implementation (Singla and sit, 2021). Ultrasound faces limitations in dense, protein-rich food matrices, posing challenges for deep penetration and target region access (Chen et al., 2022). Ultrasound effects vary with food type and protein state (Wang et al., 2021). Challenges include attenuation, reduced resolution at lower frequencies, and obtaining clear results amidst concurrent variable changes in complex food matrices (Rastogi, 2011).

Ultrasound-induced food quality degradation may result from suboptimal process variables, encompassing frequency, intensity, exposure duration, temperature, food volume, and material characteristics (Salazar et al., 2010). Thorough research and development endeavors are crucial for improving the understanding and fine-tuning of ultrasound treatments to achieve the highest level of effectiveness. Fully investigating the safety of ultrasound devices, addressing potential metal contamination risks, and funding large-scale research and development projects are crucial steps in enhancing the effectiveness and durability of ultrasound devices for widespread use in the food industry (Taha et al., 2022). As ultrasound technology continues to advance, it is expected to emerge as a superior replacement for traditional methods in food science processing and instrumentation.

Safety and Regulatory Aspects

Ultrasound, when combined with temperature and pressure, can generate free radicals capable of oxidizing bioactive compounds in solid foods, leading to modifications in food matrix properties and potentially rendering it unfit for consumption (Alshehhi et al., 2023). Reactive species possess the capacity to interact with food components, leading to reactions that detrimentally impact nutritional quality. However, it has been demonstrated by Aslam et al. (2022) that employing ultrasound at low intensities effectively reduces the production of free radicals. These free radicals, generated during cavitation, can lead to unfavorable outcomes such as lipid oxidation, resulting in undesirable tastes and odors, as well as protein denaturation and a decrease in overall phenolic content due to the breakdown of ascorbic acid, as evidenced in the study conducted by Bhargava et al. (2021). Therefore, precise adjustment and optimization of ultrasound intensity, along with its integration with other techniques, are imperative when applying this method in food processing. Moreover, it's important to note that utilizing ultrasound and integrated technologies in the food industry may entail compliance with regulatory standards and approval processes, which can introduce additional complexity and time when adopting these innovative approaches.

Table 1a. Effects of Various Ultrasound Treatments on Various Food Products

Ultrasonic treatment condition	Food product	Cause	How it influences the nature of food quality	References
Properties in food: Color and Appearance				
Ultrasound-assisted thawing	Common Carp *(Cyprinus carpio)* Slow/fast freezing bighead carp (*Aristichthys nobilis) fillet*)	Preservation of Color By using low-temperature processing and shorter treatment times, ultrasound helps to preserve the original color of the food.	Preservation of Color	Sun et al., 2021; Li et al., 2020
Ultrasound-Ethanol (US-E) Pretreatment	Apple slices	Enhancement of Pigments Extraction and solubility within food matrix	Enhancement of Pigments Extraction and solubility within food matrix	Amanor et al., 2020
Ultrasound-assisted irradiation	Red wine Goat milk	Mechanical forces associated with cavitation break down the cell walls and membranes, releasing the pigments trapped like anthocyanins, chlorophylls, carotenoids, and betalains, from plant cells.	Uniform Color distribution	Ragab et al., 2019
Ultrasound and microwave-assisted vacuum frying	Mushroom (*Agaricus bisporus*) chips. Fried, purple-fleshed sweet potato chips		Induce color changes	Devi et al. 2018; Su et al., 2018
Ultrasound drying	Garlic (*Allium sativum* L.)	Uniform Color distribution Cavitation-induced forces on food particles lead to a reduction in particle size which enhances the dispersion of pigments.		Tao et al., 2018
Ultrasonic pretreatment	Beetroot	Induce color changes. High-intensity ultrasound degrades and makes changes in pigments.		Janiszewska-Turak et al., 2021
Properties in food: Enzyme activity and food digestibility				
Ultrasound processing	Coconut water Dairy products	Enhance the activity of certain enzymes. Induces mechanical forces, cavitation, which leads to the breakdown of cell structures and increased release of enzymes and it improve enzyme accessibility to substrates, enhancing enzymatic activity.	Enhance the activity of certain enzymes	Munir et al., 2019
Ultrasonication	Pumpkin juice Tomato	Improve food digestibility Release intracellular enzymes due to cell disruption. Mechanical disintegration of food particles in to smaller particles which increase the surface area available for enzymatic action, potentially improving food digestibility.	Improve food digestibility	Suo et al., 2022
Properties in food: Antioxidant activity				
US assisted irradiation	Plum (*Prunus salicina* L.) juice	Enhance the extraction of antioxidants from plant materials	Enhance the extraction of antioxidants from plant materials	Olawuyi et al., 2021
Ultrasound-assisted extraction	Mango by-product extracts (Seed and peel) Orange flesh sweet potato Red Radish	Induce Acoustic Cavitation, associated mechanical forces and cause Cell wall destruction which leads to the release of bound polyphenols. Improves mass transfer, aiding in the release of antioxidants from solid matrices into the liquid phase	Enhance richness in antioxidant compounds like polyphenols	Castañeda-Valbuena et al., 2021 Rios-Romero et al., 2018 Li et al., 2022
Flat sweep frequency and pulsed ultrasound pretreatment	Fresh, dark green okra pods	Enhance richness in antioxidant compounds like polyphenols Induce disruption cell structures, releasing antioxidants trapped within cell walls.	Modification of antioxidant molecules	Xu et al., 2020
Ultrasound pre-treatment	Red pepper, green pepper, tomato, lettuce, and zucchini.			Lafarga et al., 2019
Ultrasound-assisted low-temperature drying	kiwifruit	Modification of antioxidant molecules Induces structural changes due to mechanical forces and cavitation in food matrixes, potentially modifying antioxidant molecules.		Vallespir et al., 2019
High-intensity ultrasound treatment	Tomato fruits			Lu et al., 2020
Properties in food: Nutrient retention and bioavailability				
Ultrasound in vacuum frying	Button mushroom chips fried purple-fleshed sweet potato	Decrease in nutrient loss and vitamin C degradation This leads to more efficient heat transfer and shorter processing times which minimize nutrient losses. The turbulence and micro-convection created by cavitation enhance the diffusion of nutrients through the food matrix	Decrease in nutrient loss and vitamin C degradation	Devi et al., 2019 Su et al., 2018
Ultrasound drying	Pear slices Fruit, vegetables, meat, and fish Carrot slices			Liu et al., 2019; Bhargava et al., 2021;
Ultrasound-Ethanol (US-E) Pretreatment	Apple slices			Sarheed et al., 2020; Amanor-Atiemoh et al., 2020
Ultrasound assisted osmotic dehydration	Sweet Potato (*Ipomea Batatas*)			Su et al., 2018; Oladejo et al., 2017

Table 1b. Effects of Various Ultrasound Treatments on Various Food Products

Ultrasonic treatment condition	Food product	Cause	How it influences the nature of food quality	References
Properties in food: Texture and rheology modification				
Ultrasonication	Cheese	Modification of chemical composition and changes in its microstructural components	Reduce the melting time and improve the thread-forming capacity	Carrillo-López et al., 2023
		Presence of permanent intermolecular cross-links (disulphide bonds and ε-(γ-glutamyl) lysine residues)	Consistent, chewy, and rubbery texture	
	Whey Protein		More elastic and stronger gel, smaller, regular and more homogenous and ordered structures	Khatkar et al., 2018
	Wheat dough	Increase of specific due to promoted yeast activity and decrease of firmness due to destroying hydrogen bonds between large protein polymers and composing them into small soluble protein aggregates	Increase of specific volume and decrease firmness	Luo et al., 2018; Yaver & Bilgiçli 2022
	Set yoghurt	Homogenization of milk fat globule and denaturation of serum proteins	Increases the viscosity and firmness	Abeysinghe et al., 2020
Mano-Thermo-Sonication	Set yoghurt	Enhances interactions within milkfat globules and/or casein micelles, leading to modifications in the milkfat globule membrane	Increase the viscosity and firmness	Bui et al., 2021; Gamlath et al., 2020
Ultrasound-assisted enzyme treatment	Meat	The degree of rupture of myofibrils gradually increased	Increase meat tenderization	Cao et al., 2021 Kang et al., 2020
Properties in food: Emulsification and homogenization				
Ultrasonication	Chicken myofibrillar protein	Disruption of myofibrillar integrity and protein dissociation by the cavitation and shear force accompanied by microstreaming and turbulence under the operation of the ultrasonic probe	A decrease in the particle size of myofibrillar protein resulted in decreasing droplet size. Improved emulsifying properties and formation of better oil/water emulsion gel	Li et al., 2020; Zou et al., 2018
	Yoghurt	Very high temperature and pressure regions generate through cavitation and this extreme pressure caused by the violent collapse of bubbles disintegrates the milk fat globule membrane (mainly of triacylglycerols micro-droplets) and alters its composition and structure.	Improve homogenization and emulsification by reducing milk fat globule size	Akdeniz and Akalın, (2019)
Properties in food: Crystal formation and modification				
Ultrasonication	Milk fat	The cavitation effect generates cavitation bubbles in the transmission medium, and the motion of the cavitation bubbles can result in a microstreaming effect, thereby enhancing the heat and mass transfer efficiency. Besides, cavitation bubbles can act as crystal nuclei, increasing the number of nucleation sites. In addition, large ice crystals can be broken by microstreaming effect, leading to further reduction in the size of ice crystals	Shortened the freezing time	Bhargava et al., 2021
	Ice Cream		Accelerate freezing Reducing crystal size	Kumar et al., 2020; Dadan et al., 2021
	Potatoes		Uniform distribution and preventing incrustation of freezing surface	Kumar et al., 2020; Zhu et al., 2020
Properties in food: Fermentation				
Ultrasonication	Sweet whey	Improve membrane permeability of starter bacteria and allow the better release and higher activity of intracellular enzymes such as β-galactosidase	Reduced fermentation time	Bella et al., 2022
	Set Yoghurt	A slight increase in temperature due to the heat derived from ultrasonic absorption may activate the lactic bacteria and shorten the fermentation time		Li et al., 2023
Properties in food: Extraction				
Ultrasound-Assisted Extraction	Food and plant material (Papaya peel, Apple pomace, Rambutan peel, etc.) e.g. bioactive compounds, pectin	Enhancing the diffusion and leveraging acoustic cavitation effect in the solvent.	Increasing the extraction ability of compounds by allowing the rupture of cell walls besides releasing the compounds in their medium	Kumar et al., 2021; Singla & Sit, 2021
Liquid-liquid dispersion micro-extraction assisted by ultrasound				Singla & Sit, 2021; Leong et al., 2018
Ultrasonic enzyme-assisted extraction				Zadeike & Degutyteb2023
Properties in food: Filtration				
Ultrasonic Membrane Filtration	Liquid food products e.g. Juices	The inherent membrane permeability remains unaltered despite the distortion caused by the formation of retentive layers.	Prevention of membrane caking and clogging, enabling continuing cavity around filter surface. This results in a decrease in resistive flow and an increase in flux.	Singla & Sit, 2021
Properties in food: Flavor Enhancement				
Ultrasonication Ultrasound during the low-temperature frying	Bacon, mushroom (*Agaricus bisporus*)	Cavitation phenomenon, thermal and mechanical effects caused by ultrasonic waves	Altering of the microstructures and physicochemical characteristics of food	Zhang et al., 2021 Devi et al., 2018

Consumer Acceptance and Perception

While high levels of ultrasound application can lead to heat generation, potentially affecting the sensory and nutritional aspects of food products, Bhargava and colleagues demonstrated in 2021 that it can also induce unwanted physical and chemical changes. Despite progress in using ultrasound to enhance the nutritional value of fruit and vegetable juices, it faces challenges, notably limited shelf life as highlighted by Bevilacqua et al. in 2015 and Khandpur and Gogate in 2015. It's important to note that ultrasonic treatment can negatively impact the flavor and texture of lettuce (Neto et al., 2019), lead to decreased cherry firmness (Muzaffar et al., 2016), and result in a 3% reduction in firmness and a 5% decline in vitamin C content in Docynia indica fruits (Vivek et al., 2017). The use of low-frequency ultrasound may lead to the formation of larger cavitation bubbles, resulting in higher pressure and energy levels. This can cause a significant temperature increase, which may not be suitable for preserving fruits and vegetables (Leong et al., 2017). Most enzymes exhibit substantial resistance to ultrasound, necessitating prolonged exposure to high-intensity treatment, potentially affecting processed food and compromising sensory characteristics (Jiang et al., 2020). However, the combination of ultrasound with complementary techniques shows promise in enhancing the overall quality of the final food product. Therefore, further research in this direction holds potential. To enable the widespread adoption of ultrasound on an industrial scale, it is essential to optimize parameters and conduct foundational studies to assess the effects of acoustic treatment on large-scale food production. It finds diverse applications in fruit, juice, and dairy industries for analysis, control, and processing. However, the complex structures and unique physicochemical properties of agricultural products pose challenges for industrial-scale ultrasound use. Factors such as growth conditions, harvest, and postharvest processes contribute to each product's distinct behavior, making uniform application difficult.

Emerging Trends and Possible Recommendations in Ultrasound Technology on Food Industry

Future research in the application of ultrasound in the food industry should strategically prioritize key areas to advance the field comprehensively. Critical avenues for further investigation include the optimization of ultrasound parameters, exploration of synergistic combinations with other techniques, analysis of safety implications, and overcoming energy consumption hurdles for industrial-scale implementation. A significant trend involves the real-time monitoring of protein structural changes, emphasizing the integration of advanced techniques such as foodomics and molecular dynamics simulation to gain deeper insights into the effects of ultrasound on protein structures. Moreover, there is a noticeable shift towards exploring proteins from underutilized sources like oil cake and insects, indicating a broader scope for ultrasound applications in novel food ingredient research. To facilitate industrial scale-up, there is a growing need for multi-mode ultrasound equipment with noise reduction features to ensure worker safety and efficiency (Chen et al., 2022). Zhou et al. (2022) observed that high-intensity ultrasound exhibited no significant impact on oil oxidation and profiles, enhancing the anti-oxidative ability of certain emulsions. However, this underscores the necessity for developing large-scale ultrasonic devices and further investigation into the effects of ultrasound energy on emulsifiers and oil phases. In the realm of ultrasound-assisted enzymatic food processing, establishing international standards for measuring ultrasonic intensity and related parameters is imperative (Córdova et al., 2022). Additionally, a comprehensive multidisciplinary approach is required to understand the effects of different ultrasound processing conditions on enzyme kinetics, especially in synthesis reactions, integrating knowledge from food science, enzyme catalysis, computational chemistry, and multiphysics simulations. This approach should also consider energy consumption and environmental metrics to assess sustainability. Future trends in ultrasonic technology for food processing necessitate addressing current limitations, such as the lack of real-time monitoring of protein structure and enzymatic hydrolysis products during ultrasonic pretreatment. In-situ intelligent monitoring systems are needed to optimize enzymatic hydrolysis processes, and exploration of functional properties and bioavailability of peptides from various substrate materials is crucial. Optimization of ultrasonic parameters for leafy vegetables, addressing noise hazards in industrial manufacturing, and overcoming economic and technical challenges in implementing new technology are essential for advancing ultrasonic washing methods in the future (Xu et al., 2021). Eco-friendly pre-treatment methods, particularly alkali extraction, are gaining attention for their potential environmental, economic, and technological benefits (Ampofo & Ngadi, 2022). The integration of ultrasound as a pretreatment in reverse osmosis processes holds promise in deagglomerating bacterial clusters and improving the quality attributes of concentrated fruit juices, potentially paving the way for a novel technology termed RO assisted by ultrasound (RO-US) (Córdova et al., 2020). However, caution is warranted in applying ultrasound to sensitive products, as undesirable effects may occur, especially when transitioning from controlled laboratory conditions to industrial settings. Ongoing research is essential to comprehensively understand the technology's impact, with companies actively commercializing ultrasound equipment for the food industry and exploring continuous systems with ultrasonic probes and larger radiating surfaces (Taha et al., 2022).

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Conflict of Interest

The authors declare no conflicts of interest.

References

Aadil, R. M., Zeng, X. A., Han, Z., & Sun, D. W. (2013). Effects of ultrasound treatments on quality of grapefruit juice. *Food chemistry*, *141*(3), 3201-3206. https://doi.org/10.1016/j.foodchem.2013.06.008

Abbas, S., Hayat, K., Karangwa, E., et al. (2013). An overview of ultrasound-assisted food-grade nano emulsions. Food Engineering Reviews, 5, 139–157. https://doi.org/10.1007/s12393-013-9066-3

Alshehhi, M., Wu, G., Kangsadan, T., Chew, K. W., & Show, P. L. (2023). Ultrasound-Assisted Food Processing: A Mini Review of Mechanisms, Applications, and Challenges. In *E3S Web of Conferences* (Vol. 428, p. 02011). EDP Sciences. https://doi.org/10.1051/e3sconf/202342802011

Ampofo, J., & Ngadi, M. (2022). Ultrasound-assisted processing: Science, technology and challenges for the plant-based protein industry. Ultrasonics Sonochemistry, 84, 105955. https://doi.org/10.1016/j.ultsonch.2022.105955

An, K., Tang, D., Wu, J., Fu, M., Wen, J., Xiao, G., & Xu, Y. (2019). Comparison of pulsed vacuum and ultrasound osmotic dehydration on drying of Chinese ginger (Zingiber officinale Roscoe): Drying characteristics, antioxidant capacity, and volatile profiles. Food Science & Nutrition, 7(8), 2537-2545. https://doi.org/10.1002/fsn3.1103

Aslam, R., Alam, M. S., Kaur, J., Panayampadan, A. S., Dar, O. I., Kothakota, A., & Pandiselvam, R. (2022). Understanding the effects of ultrasound processing on texture and rheological properties of food. Journal of Texture Studies, 53(6), 775-799. https://doi.org/10.1111/jtxs.12644

Balakrishna, A. K., Abdul Wazed, M., & Farid, M. (2020). A review on the effect of high pressure processing (HPP) on gelatinization and infusion of nutrients. Molecules, 25(10), 1–19. https://doi.org/10.3390/molecules25102369

Barteri, M., Diociaiuti, M., Pala, A., & Rotella, S. (2004). Low frequency ultrasound induces aggregation of porcine fumarase by free radicals production. *Biophysical Chemistry*, *111*(1), 35-42. https://doi.org/10.1016/j.bpc.2004.04.002

Beitia, E., Gkogka, E., Chanos, P., Hertel, C., Heinz, V., Valdramidis, V., & Aganovic, K. (2023). Microbial decontamination assisted by ultrasound-based processing technologies in food and model systems: A review. *Comprehensive Reviews in Food Science and Food Safety*, 22*(4)*, 2802-2849. https://doi.org/10.1111/1541-4337.13163

Belgheisi, S., Motamedzadegan, A., Milani, J. M., et al. (2021). Impact of ultrasound processing parameters on physical characteristics of lycopene emulsion. Journal of Food Science and Technology, 58, 484–493. https://doi.org/10.1007/s13197-020-04557-5

Bermúdez-Aguirre, D., Mobbs, T., & Barbosa-Cánovas, G. V. (2011). Ultrasound applications in food processing. *Ultrasound technologies for food and bioprocessing*, 65-105. https://doi.org/10.1007/978-1-4419-7472-3_3

Bevilacqua, A., Campaniello, D., Sinigaglia, M., & Corbo, M. R. (2015). Combination of ultrasound and antimicrobial compounds towards Pichia spp. and Wickerhamomyces anomalus in pineapple juice. *LWT-Food Science and Technology*, *64*(2), 616-622. https://doi.org/10.1016/j.lwt.2015.06.038

Bhargava, N., Mor, R. S., Kumar, K., & Sharanagat, V. S. (2021). Advances in application of ultrasound in food processing: A review. *Ultrasonics sonochemistry*, *70*, 105293. https://doi.org/10.1016/j.ultsonch.2020.105293

Bhat, Z. F., Morton, J. D., Kumar, S., Bhat, H. F., Aadil, R. M., & Bekhit, A. E. D. A. (2022). Ultrasonication as an emerging technology for processing of animal derived foods: A focus on in vitro protein digestibility. *Trends in Food Science & Technology*, *124*, 309-322. https://doi.org/10.1016/j.tifs.2022.04.012

Bozkir, H., Ergün, A. R., Serdar, E., Metin, G., & Baysal, T. (2019). Influence of ultrasound and osmotic dehydration pretreatments on drying and quality properties of persimmon fruit. Ultrasonics Sonochemistry, 54, 135-141. https://doi.org/10.1016/j.ultsonch.2019.02.006

Bund, R. K., & Pandit, A. B. (2007). Sonocrystallization: effect on lactose recovery and crystal habit. Ultrasonics sonochemistry, 14(2), 143–152. https://doi.org/10.1016/j.ultsonch.2006.06.003

Cao, X., Cai, C., Wang, Y., & Zheng, X. (2019). Effects of Ultrasound Processing on Physicochemical Parameters, Antioxidants, and Color Quality of Bayberry Juice. Journal of Food Quality, vol. 2019, Article ID 7917419, 12 pages. https://doi.org/10.1155/2019/7917419

Castañeda-López, G. G., Ulloa, J. A., Rosas-Ulloa, P., Ramírez-Ramírez, J. C., Gutiérrez-Leyva, R., Silva-Carrillo, Y., & Ulloa-Rangel, B. E. (2021). 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, 45(4). doi:10.1111/jfpp.15366

Chandrapala, J., Zisu, B., Kentish, S. E., & Ashokkumar, M. (2012). The effects of high-intensity ultrasound on the structural and functional properties of α-lactalbumin, β-lactoglobulin and their mixtures. Food Research International, 48, 940-943. https://doi.org/10.1016/J.FOODRES.2012.02.021

Chavan, P., Sharma, P., Sharma, S. R., Mittal, T. C., & Jaiswal, A. K. (2022). Application of high-intensity ultrasound to improve food processing efficiency: A review. *Foods*, *11*(1), 122. https://doi.org/10.3390/foods11010122

Chemat, F., Rombaut, N., Sicaire, A. G., Meullemiestre, A., Fabiano-Tixier, A. S., & Abert-Vian, M. (2017). Ultrasound assisted extraction of food and natural products. Mechanisms, techniques, combinations, protocols and applications. A review. *Ultrasonics sonochemistry*, *34*, 540-560. https://doi.org/10.1016/j.ultsonch.2016.06.035

Chen, F., Zhang, M., & Yang, C. H. (2020). Application of ultrasound technology in processing of ready-to-eat fresh food: A review. *Ultrasonics sonochemistry*, *63*, 104953. https://doi.org/10.1016/j.ultsonch.2019.104953

Chen, F., Zhang, M., Yang, C.-h. (2020). Application of ultrasound technology in processing of ready-to-eat fresh food: A review. Ultrasonics Sonochemistry, 63, 104953. https://doi.org/10.1016/j.ultsonch.2019.104953

Chen, W., Ma, H., & Wang, Y.-Y. (2022). Recent advances in modified food proteins by high intensity ultrasound for enhancing functionality: Potential mechanisms, combination with other methods, equipment innovations and future directions. Ultrasonics Sonochemistry, 85, 105993. https://doi.org/10.1016/j.ultsonch.2022.105993

Chen, X., Qi, Y., Zhu, C., & Wang, Q. (2019). Effect of ultrasound on the properties and antioxidant activity of hawthorn pectin. *International journal of biological macromolecules*, *131*, 273-281. https://doi.org/10.1016/j.ijbiomac.2019.03.077

Cho, W. I., & Chung, M. S. (2020). Bacillus spores: A review of their properties and inactivation processing technologies. *Food science and biotechnology*, *29*, 1447-1461. https://doi.org/10.1007/s10068-020-00809-4

Chow, R., Blindt, R., Chivers, R., & Povey, M. (2003). The sonocrystallisation of ice in sucrose solutions: Primary and secondary nucleation. Ultrasonics, 41(8), 595-604. https://doi.org/10.1016/j.ultras.2003.08.001

Córdova, A., Astudillo-Castro, C., Ruby-Figueroa, R., Valencia, P., & Soto, C. (2020). Recent advances and perspectives of ultrasound assisted membrane food processing. Food Research International, 133, 109163. https://doi.org/10.1016/j.foodres.2020.109163

Córdova, A., Henríquez, P., Nuñez, H., Rico-Rodriguez, F., Guerrero, C., Astudillo-Castro, C., & Illanes, A. (2022). Recent Advances in the Application of Enzyme Processing Assisted by Ultrasound in Agri-Foods: A Review. Catalysts, 12, 107. https://doi.org/10.3390/catal12010107

da Silva Júnior, E. V., de Melo, L. L., de Medeiros, R. A. B., Barros, Z. M. P., & Azoubel, P. M. (2018). Influence of ultrasound and vacuum assisted drying on papaya quality parameters. *Lwt*, *97*, 317-322. https://doi.org/10.1016/j.lwt.2018.07.017

Darsana, K., & Sivakumar, P. (2023). Potential of Ultrasound in Food Processing: An Overview. Current Journal of Applied Science and Technology, 42(32), 14-34. https://doi:10.9734/cjast/2023/v42i324217

Deora, N. S., Misra, N. N., Deswal, A., Mishra, H. N., Cullen, P. J., & Tiwari, B. K. (2013). Ultrasound for Improved Crystallisation in Food Processing. Food Engineering Reviews, 5, 36-44. https://doi.org/10.1007/s12393-012-9061-0

Djenouhat, M., Hamdaoui, O., Chiha, M., & Samar, M. H. (2008). Ultrasonication-assisted preparation of water-in-oil emulsions and application to the removal of cationic dyes from water by emulsion liquid membrane: Part 1: Membrane stability. Separation and Purification Technology, 62(3), 636-641. https://doi.org/10.1016/j.seppur.2008.03.018

Drakopoulou, S., Terzakis, S., Fountoulakis, MS., Mantzavinos, D. and Manios, T. 2009 Ultrasound-induced inactivation of gram-negative and gram-positive bacteria in secondary treated municipal wastewater. Ultrasonics Sonochemistry, 16 : 629-634. https://doi:10.1016/j.ultsonch.2008.11.011

Ekezie, F. G. C., Cheng, J. H., & Sun, D. W. (2018). Effects of mild oxidative and structural modifications induced by argon plasma on physicochemical properties of actomyosin from king prawn (Litopenaeus vannamei). Journal of Agricultural and Food Chemistry, 66(50), 13285-13294. https://doi.org/10.1021/acs.jafc.8b05178

Ercan, S. Ș., & Soysal, Ç. (2013). Use of ultrasound in food preservation. *Natural Science,* 5*(8)*, 5–13. https://doi.org/10.4236/ns.2013.58a2002

Feng, H., Barbosa-Cánovas, G. V., & Weiss, J. (Eds.). (2011). *Ultrasound technologies for food and bioprocessing* (Vol. 1, p. 599). New York: Springer. https://doi:10.1007/978-1-4419-7472-3

Fernandes, F.A.N., Braga, T.R., Silva, E.O. et al. Use of ultrasound for dehydration of mangoes (Mangifera indica L.): kinetic modeling of ultrasound-assisted osmotic dehydration and convective air-drying. J Food Sci Technol 56, 1793–1800 (2019). https://doi.org/10.1007/s13197-019-03622-y

Gallo, M., Ferrara, L., & Naviglio, D. (2018). Application of Ultrasound in Food Science and Technology: A Perspective. Foods, 7, 164. https://doi.org/10.3390/foods7100164

Gamboa-Santos, J., Soria, A. C., Pérez-Mateos, M., Carrasco, J. A., Montilla, A., & Villamiel, M. (2013). Vitamin C content and sensorial properties of dehydrated carrots blanched conventionally or by ultrasound. *Food Chemistry*, *136*(2), 782-788. https://doi.org/10.1016/j.foodchem.2012.07.122

Gao, X., Zhang, J., Liu, E., Yang, M., Chen, S., Hu, F., ... & Yu, X. (2019). Enhancing the taste of raw soy sauce using low intensity ultrasound treatment during moromi fermentation. *Food Chemistry*, *298*, 124928. https://doi.org/10.1016/j.foodchem.2019.05.202

Gholamhosseinpour, A., & Hashemi, S. M. B. (2019). Ultrasound pretreatment of fermented milk containing probiotic Lactobacillus plantarum AF1: Carbohydrate metabolism and antioxidant activity. Journal of Food Process Engineering, 42(1), e12930. https://doi.org/10.1111/jfpe.12930

Gómez-Salazar, J. A., Galván-Navarro, A., Lorenzo, J. M., & Sosa-Morales, M. E. (2021). Ultrasound effect on salt reduction in meat products: a review. *Current opinion in food science*, *38*, 71-78. https://doi.org/10.1016/j.cofs.2020.10.030

Guerra-Almonacid, C. M., Torruco-Uco, J. G., Méndez-Arteaga, J. J., & Rodríguez-Miranda, J. (2019). Effect of ultrasound pretreatment on the antioxidant capacity and antihypertensive activity of bioactive peptides obtained from the protein hydrolysates of Erythrina edulis. Emirates Journal of Food and Agriculture, 31(4), 288–296. https://doi.org/10.9755/ejfa.2019.v31.i4.1938

Guimarães, J. T., Balthazar, C. F., Scudino, H., Pimentel, T. C., Esmerino, E. A., Ashokkumar, M., Freitas, M. Q., & Cruz, A. G. (2019). High-intensity ultrasound: A novel technology for the development of probiotic and prebiotic dairy products. Ultrasonics Sonochemistry, 57, 12-21. https://doi.org/10.1016/j.ultsonch.2019.05.004

Huang, D., Men, K., Li, D., Wen, T., Gong, Z., Sunden, B., & Wu, Z. (2020). Application of ultrasound technology in the drying of food products. Ultrasonics Sonochemistry, 63, 104950. https://doi.org/10.1016/j.ultsonch.2019.104950

Huang, G., Chen, S., Dai, C., Sun, L., Sun, W., Tang, Y., Xiong, F., He, R., & Ma, H. (2017). Effects of ultrasound on microbial growth and enzyme activity. Ultrasonics Sonochemistry, 37, 144-149. https://doi.org/10.1016/j.ultsonch.2016.12.018

Iorio, M. C., Bevilacqua, A., Corbo, M. R., Campaniello, D., Sinigaglia, M., & Altieri, C. (2019). A case study on the use of ultrasound for the inhibition of Escherichia coli O157: H7 and Listeria monocytogenes in almond milk. *Ultrasonics Sonochemistry*, *52*, 477-483. https://doi.org/10.1016/j.ultsonch.2018.12.026

Jalilzadeh, A., Hesari, J., Peighambardoust, S. H., & Javidipour, I. (2018). The effect of ultrasound treatment on microbial and physicochemical properties of Iranian ultrafiltered feta-type cheese. *Journal of Dairy Science*, *101*(7), 5809-5820. https://doi.org/10.3168/jds.2017-14352

Jiang, Q., Zhang, M., & Xu, B. (2020). Application of ultrasonic technology in postharvested fruits and vegetables storage: A review. *Ultrasonics Sonochemistry*, *69*, 105261. https://doi.org/10.1016/j.ultsonch.2020.105261

Jiang, Y. S., Zhang, S. B., Zhang, S. Y., & Peng, Y. X. (2021). Comparative study of high-intensity ultrasound and high-pressure homogenization on physicochemical properties of peanut protein-stabilized emulsions and emulsion gels. Journal of Food Process Engineering, 44(6), e13710. https://doi.org/10.1111/jfpe.13710

Kabbani, D., Sepulcre, F., & Wedekind, J. (2011). Ultrasound-assisted liquefaction of rosemary honey: Influence on rheology and crystal content. Journal of Food Engineering, 107(2), 173-178. https://doi.org/10.1016/j.jfoodeng.2011.06.027

Kaveh, S., Gholamhosseinpour, A., Hashemi, S. M. B., Jafarpour, D., Castagnini, J. M., Phimolsiripol, Y., & Barba, F. J. (2023). Recent advances in ultrasound application in fermented and non-fermented dairy products: antibacterial and bioactive properties. International Journal of Food Science & Technology, 58(7), 3591-3607. https://doi.org/10.1111/ijfs.16457

Khan, A., Beg, M. R., & Waghmare, P. (2021). Intensification of biokinetics of enzymes using ultrasound-assisted methods: A critical review. Biophysical Reviews, 13, 417–423. https://doi.org/10.1007/s12551-021-00806-9

Khandpur, P., & Gogate, P. R. (2015). Effect of novel ultrasound based processing on the nutrition quality of different fruit and vegetable juices. *Ultrasonics Sonochemistry*, *27*, 125-136. https://doi.org/10.1016/j.ultsonch.2015.05.008

Khouryieh, H. A. (2021). Novel and emerging technologies used by the US food processing industry. *Innovative Food Science & Emerging Technologies*, *67*, 102559. https://doi.org/10.1016/j.ifset.2020.102559

Kozell, A., Solomonov, A., & Shimanovich, U. (2023). Effects of sound energy on proteins and their complexes. Volume 597, Issue 24, 3013-3037. https://doi.org/10.1002/1873-3468.14755

Kumar, G., Upadhyay, S., Yadav, D. K., Malakar, S., Dhurve, P., & Suri, S. (2023). Application of ultrasound technology for extraction of color pigments from plant sources and their potential bio-functional properties: A review. Journal of Food Process Engineering, 46(6), e14238. https://doi.org/10.1111/jfpe.14238

Leong, T. S. H., Wooster, T. J., Kentish, S. E., & Ashokkumar, M. (2009). Minimising oil droplet size using ultrasonic emulsification. Ultrasonics Sonochemistry, 16(6), 721-727. https://doi.org/10.1016/j.ultsonch.2009.02.008

Leong, T., Johansson, L., Juliano, P., Mawson, R., McArthur, S. and Manasseh, R., 2014a. Design parameters for the separation of fat from natural whole milk in an ultrasonic litre-scale vessel. Ultrasonics sonochemistry, 21(4), 1289-1298. https://doi.org/10.1016/j.ultsonch.2014.01.007

Leong, T., Juliano, P., & Knoerzer, K. (2017). Advances in ultrasonic and megasonic processing of foods. *Food Engineering Reviews*, *9*(3), 237-256. https://doi.org/10.1007/s12393-017-9167-5

Leong, T., Juliano, P., Johansson, L., Mawson, R., McArthur, S.L. and Manasseh, R., 2014b. Temperature effects on the ultrasonic separation of fat from natural whole milk. Ultrasonics sonochemistry, 21(6), 2092-2098. https://doi.org/10.1016/j.ultsonch.2014.02.003

Li, S., Zhang, R., Lei, D., Huang, Y., Cheng, S., Zhu, Z., ... & Cravotto, G. (2021). Impact of ultrasound, microwaves and high-pressure processing on food components and their interactions. Trends in Food Science & Technology, 109, 1-15. https://doi.org/10.1016/j.tifs.2021.01.017

Li, W., Gong, P., Ma, H., Xie, R., Wei, J., & Xu, M. (2022). Ultrasound treatment degrades, changes the color, and improves the antioxidant activity of the anthocyanins in red radish. LWT, 165, 113761. https://doi.org/10.1016/j.lwt.2022.113761

Li, W., Ma, H., He, R., Ren, X., & Zhou, C. (2021). Prospects and application of ultrasound and magnetic fields in the fermentation of rare edible fungi. Ultrasonics Sonochemistry, 76, 105613. https://doi.org/10.1016/j.ultsonch.2021.105613

Li, X., Zhang, Y., Yuan, J., & Sun, P. (2021). Effects of ultrasound on the structure and emulsifying properties of soy protein isolate and soy protein-sugar conjugate. Ultrasonics Sonochemistry, 70, Article 105326. https://doi.org/8.1016/j.ultsonch.2020.105326

Li, Y., & Xiang, D. (2019). Stability of oil-in-water emulsions performed by ultrasound power or high-pressure homogenization. PLOS ONE, 14(3), e02130189. https://doi.org/10.1371/journal.pone.0213189

Li, Y., Wang, X., Wu, Z., Wan, N., & Yang, M. (2020). Dehydration of hawthorn fruit juices using ultrasound-assisted vacuum drying. Ultrasonics Sonochemistry, 68, 105219. https://doi.org/10.1016/j.ultsonch.2020.105219

Li, Y., Wang, X., Wu, Z., Wan, N., & Yang, M. (2020). Dehydration of hawthorn fruit juices using ultrasound-assisted vacuum drying. Ultrasonics Sonochemistry, 68, 105219. https://doi.org/10.1016/j.ultsonch.2020.105219

Liu, X., Zhang, C., Wang, H., Wang, Y., Zhu, D., & Liu, H. (2023). Ultrasonic treatment maintains the flavor of the melon juice. *Ultrasonics Sonochemistry*, *92*, 106284. https://doi.org/10.1016/j.ultsonch.2022.106284

Luque de Castro, M. D., and Priego-Capote, F., 2007. Ultrasound-assisted crystallization (sonocrystallization). Ultrasonics sonochemistry, 14(6), 717–724. https://doi.org/10.1016/j.ultsonch.2006.12.004

Lyu, Y., Bi, J., Chen, Q., Li, X., Wu, X., & Gou, M. (2022). Effects of ultrasound, heat, ascorbic acid and CaCl2 treatments on color enhancement and flavor changes of freeze-dried carrots during the storage period. *Food Chemistry*, *373*, 131526. https://doi.org/10.1016/j.foodchem.2021.131526

Martini, S., Suzuki, A.H., & Hartel, R.W. (2008). Effect of High Intensity Ultrasound on Crystallization Behavior of Anhydrous Milk Fat. Journal of the American Oil Chemists' Society, 85, 621-628.https:// doi:10.1007/S11746-008-1247-5

Meena, L., Nanje Gowda, N. A., Sunil, C. K., Rawson, A., & Janghu, S. (2024). Effect of ultrasonication on food bioactive compounds and their bio-accessibility: A review. Journal of Food Composition and Analysis, 126, 105899. https://doi.org/10.1016/j.jfca.2023.105899.

Mieszczakowska-Frąc, M., Celejewska, K., & Płocharski, W. (2021). Impact of Innovative Technologies on the Content of Vitamin C and Its Bioavailability from Processed Fruit and Vegetable Products. Antioxidants, 10, 54. https://doi.org/10.3390/antiox10010054

Muthukrishnan, Y., Sunial, C. K., & Rawson, A. (2022). Power Ultrasound: A Green Technology for Processing of Food. In Food Processing and Preservation Technology (1st ed., pp. 31). Apple Academic Press. eBook ISBN: 9781003153184

Muzaffar, S., Ahmad, M., Wani, S. M., Gani, A., Baba, W. N., Shah, U., ... & Wani, T. A. (2016). Ultrasound treatment: effect on physicochemical, microbial and antioxidant properties of cherry (Prunus avium). *Journal of food science and technology*, *53*, 2752-2759. https://doi.org/10.1007/s13197-016-2247-3

Neto, L., Millan-Sango, D., Brincat, J. P., Cunha, L. M., & Valdramidis, V. P. (2019). Impact of ultrasound decontamination on the microbial and sensory quality of fresh produce. *Food Control*, *104*, 262-268. https://doi.org/10.1016/j.foodcont.2019.04.047

Nowak, K. W., Zielinska, M., & Waszkielis, K. M. (2019). The effect of ultrasound and freezing/thawing treatment on the physical properties of blueberries. Food Science and Biotechnology, 28, 741–749. https://doi.org/10.1007/s10068-018-0528-5

Önal, B., Adiletta, G., Di Matteo, M., Russo, P., Ramos, I. N., & Silva, C. L. M. (2021). Microwave and ultrasound pre-treatments for drying of the “Rocha” pear: Impact on phytochemical parameters, color changes and drying kinetics. Foods, 10, 853. https://doi.org/10.3390/foods10040853

Onyeaka, H., Miri, T., Hart, A., Anumudu, C., & Nwabor, O. F. (2023). Application of Ultrasound Technology in Food Processing with emphasis on bacterial spores. Food Reviews International, 39(7), 3663-3675. https://doi.org/10.1080/87559129.2021.2013255

Ordóñez-Santos, L. E., Esparza-Estrada, J., & Vanegas-Mahecha, P. (2021). Ultrasound-assisted extraction of total carotenoids from mandarin epicarp and application as natural colorant in bakery products. LWT, 139, 110598. https://doi.org/10.1016/j.lwt.2020.110598

Palanisamy, N., Seale, B., Turner, A., & Hemar, Y. (2019). Low frequency ultrasound inactivation of thermophilic bacilli (Geobacillus spp. and Anoxybacillus flavithermus) in the presence of sodium hydroxide and hydrogen peroxide. *Ultrasonics sonochemistry*, *51*, 325-331. https://doi.org/10.1016/j.ultsonch.2018.09.025

Pandiselvam, R., Aydar, A. Y., Kutlu, N., Aslam, R., Sahni, P., Mitharwal, S., ... Kothakota, A. (2023). Individual and interactive effect of ultrasound pre-treatment on drying kinetics and biochemical qualities of food: A critical review. Ultrasonics Sonochemistry, 92, 106261. https://doi.org/10.1016/j.ultsonch.2022.106261

Paniwnyk, L. (2017). Applications of ultrasound in processing of liquid foods: A review. *Ultrasonics Sonochemistry*, *38*, 794-806. https://doi.org/10.1016/j.ultsonch.2016.12.025

Paniwnyk, L., Alarcon-Rojo, A., Rodriguez-Figueroa, J. C., & Toma, M. (2017). Chapter 10 - The Use of Ultrasound as an Enhancement Aid to Food Extraction. In A. M. Grumezescu & A. M. Holban (Eds.), Handbook of Food Bioengineering: Ingredients Extraction by Physicochemical Methods in Food (pp. 399-440). Academic Press. ISBN 9780128115213. https://doi.org/10.1016/B978-0-12-811521-3.00010-7

Pinela, J., Prieto, M. A., Pereira, E., Jabeur, I., Barreiro, M. F., Barros, L., & Ferreira, I. C. F. R. (2019). Optimization of heat- and ultrasound-assisted extraction of anthocyanins from Hibiscus sabdariffa calyces for natural food colorants. Food Chemistry, 275, 309-321. https://doi.org/10.1016/j.foodchem.2018.09.118

Pinon, M., Alarcon-Rojo, A., Paniwnyk, L., Mason, T., Luna, L., & Renteria, A. (2018). Ultrasound for improving the preservation of chicken meat. *Food Science and Technology*, *39*, 129-135. https://doi.org/10.1590/fst.39017

Pinto, C. A., Lima, V. J., Amaral, R. A., Pateiro, M., Lorenzo, J. M., & Saraiva, J. A. (2021). Development of fermented food products assisted by ultrasound. Design and Optimization of Innovative Food Processing Techniques Assisted by Ultrasound (pp. 275-298). Academic Press. https://doi.org/10.1016/B978-0-12-818275-8.00006-4.

Pinto, C. A., Lima, V. J., Amaral, R. A., Pateiro, M., Lorenzo, J. M., & Saraiva, J. A. (2021). Development of fermented food products assisted by ultrasound. Design and Optimization of Innovative Food Processing Techniques Assisted by Ultrasound (pp. 275-298). Academic Press. ISBN 9780128182758. https://doi.org/10.1016/B978-0-12-818275-8.00006-4

Piyasena, P., Mohareb, E. and Mckellar, R.C., 2003. Inactivation of microbes using ultrasound: A review. *International Journal of Food Microbiology*, 87, 207-216. https://doi:10.1016/S0168-1605(03)00075-8

Pohlman, D. A., Boukerche, M., Chen, J., Shariff, H., & Nere, N. K. (2023). Experimental and Computational Evaluation of Sonofragmentation: Toward Enhanced Understanding of Sonocrystallization for Pharmaceuticals. Industrial & Engineering Chemistry Research. https://doi.org/10.1021/acs.iecr.3c00811

Qian, J., Chen, D., Zhang, Y., et al. (2023). Ultrasound-Assisted Enzymatic Protein Hydrolysis in Food Processing: Mechanism and Parameters. Foods (Basel, Switzerland), 12(21), 4027. https://doi.org/10.3390/foods12214027

Qureshi, T. M., Nadeem, M., Maken, F., Tayyaba, A., Majeed, H., & Munir, M. (2020). Influence of ultrasound on the functional characteristics of indigenous varieties of mango (Mangifera indica L.). Ultrasonics Sonochemistry, 64, 104987. https://doi.org/10.1016/j.ultsonch.2020.104987

Rastogi, N. K. (2011). Opportunities and challenges in application of ultrasound in food processing. *Critical reviews in food science and nutrition*, *51*(8), 705-722. https://doi.org/10.1080/10408391003770583

Rathnakumar, K., Kalaivendan, R. G. T., Eazhumalai, G., Charles, A. P. R., Verma, P., Rustagi, S., ... & Pandiselvam, R. (2023). Applications of ultrasonication on food enzyme inactivation-Recent review report (2017-2022). *Ultrasonics Sonochemistry*, 106407. https://doi.org/10.1016/j.ultsonch.2023.106407

Režek Jambrak, A., Lelas, V., Herceg, Z., Badanjak, M., Batur, V., & Muža, M. (2009). Advantages and disadvantages of high power ultrasound application in the dairy industry. Mljekarstvo: Časopis za unaprjeđenje proizvodnje i prerade mlijeka, 59(4), 267-281.

Roobab, U., Abida, A., Madni, G. M., Ranjha, M. M. A. N., Zeng, X.-A., Khaneghah, A. M., & Aadil, R. M. (2023). An updated overview of ultrasound-based interventions on bioactive compounds and quality of fruit juices. Journal of Agriculture and Food Research, 14, 100864. https://doi.org/10.1016/j.jafr.2023.100864

Roueita, G., Hojjati, M., & Noshad, M. (2020). Study of physicochemical properties of dried kiwifruits using the natural hypertonic solution in ultrasound-assisted osmotic dehydration as pretreatment. International Journal of Fruit Science, 20(sup2), S491-S507. https://doi.org/10.1080/15538362.2020.1741057

Saikia, S., Mahnot, N. K., & Mahanta, C. L. (2016). A comparative study on the effect of conventional thermal pasteurisation, microwave and ultrasound treatments on the antioxidant activity of five fruit juices. *Food Science and Technology International*, *22*(4), 288-301. https://doi.org/10.1177/1082013215596466

Salazar, J., Chávez, J. A., Turó, A., & García-Hernández, M. J. (2010). Effect of ultrasound on food processing. *Novel food processing: Effects on rheological and functional properties*, 65-84.

Salehi, F. (2023). Recent advances in the ultrasound-assisted osmotic dehydration of agricultural products: A review. Food Bioscience, 51, 102307. https://doi.org/10.1016/j.fbio.2022.102307

Sarker, A., & Ali Siddiqui, R. (2023). Effects of ultrasonic processing on the quality properties of fortified yogurt. Ultrasonics Sonochemistry, 98, 106533. https://doi.org/10.1016/j.ultsonch.2023.106533

Shanmugam, A., & Ashokkumar, M. (2014). Ultrasonic preparation of stable flax seed oil emulsions in dairy systems – Physicochemical characterization. Food Hydrocolloids, 39, 151-162. https://doi.org/10.1016/j.foodhyd.2014.01.006

Sheng, L., Liu, Q., Dong, W., & Cai, Z. (2022). Effect of high intensity ultrasound assisted glycosylation on the gel properties of ovalbumin: Texture, rheology, water state and microstructure. Food Chemistry, 372, 131215. https://doi.org/10.1016/j.foodchem.2021.131215

Sikes, A. L., Mawson, R. F., Stark, J., & Warner, R. D. (2014). Quality properties of pre- and post-rigor beef muscle after interventions with high frequency ultrasound. Ultrasonics Sonochemistry, 21(6), 2138-2143. https://doi.org/10.1016/j.ultsonch.2014.03.008

Silva, F. V. (2020). Resistant moulds as pasteurization target for cold distributed high pressure and heat assisted high pressure processed fruit products. *Journal of food engineering*, *282*, 109998. https://doi.org/10.1016/j.jfoodeng.2020.109998

Singla, M., & Sit, N. (2021). Application of ultrasound in combination with other technologies in food processing: A review. Ultrasonics Sonochemistry, 73, 105506. https://doi.org/10.1016/j.ultsonch.2021.105506

Singla, M., Sit, N. (2021). Application of ultrasound in combination with other technologies in food processing: A review. Ultrasonics Sonochemistry, 73, 105506. https://doi.org/10.1016/j.ultsonch.2021.105506

Strieder, M. M., Neves, M. I. L., Silva, E. K., & Meireles, M. A. A. (2020). Low-frequency and high-power ultrasound-assisted production of natural blue colorant from the milk and unripe Genipa americana L. Ultrasonics Sonochemistry, 66, 105068. https://doi.org/10.1016/j.ultsonch.2020.105068

Su, J., & Cavaco-Paulo, A. (2021). Effect of ultrasound on protein functionality. Ultrasonics Sonochemistry, 76, 105653. https://doi.org/10.1016/j.ultsonch.2021.105653

Sun, J., Zhang, W., Hu, H., Tang, L., & Zhuang, X. (2019). Effects of ultrasound on the inactivation of Bacillus subtilis and the structural characteristics of their spores. Ultrasonics Sonochemistry, 50, 176–184. https://doi.org/10.1016/j.ultsonch.2018.08.022

Taha, A., Ahmed, E., Ismaiel, A., Ashokkumar, M., Xu, X., Pan, S., & Hu, H. (2020). Ultrasonic emulsification: An overview on the preparation of different emulsifiers-stabilized emulsions. Trends in Food Science & Technology, 105, 363-377. https://doi.org/10.1016/j.tifs.2020.09.024

Taha, A., Mehany, T., Pandiselvam, R., Siddiqui, S. A., Mir, N. A., Malik, M. A., Sujayasree, O. J., Alamuru, K. C., Khanashyam, A. C., Casanova, F., Xu, X., Pan, S., & Hu, H. (2022). Sonoprocessing: Mechanisms and recent applications of power ultrasound in food. Critical Reviews in Food Science and Nutrition. Advance online publication. https://doi.org/10.1080/10408398.2022.2161464

Tao, Y., Han, M., Gao, X., Han, Y., Show, P. L., Liu, C., ... & Xie, G. (2019). Applications of water blanching, surface contacting ultrasound-assisted air drying, and their combination for dehydration of white cabbage: Drying mechanism, bioactive profile, color and rehydration property. *Ultrasonics sonochemistry*, *53*, 192-201. https://doi.org/10.1016/j.ultsonch.2019.01.003

Téllez-Morales, J. A., Hernández-Santo, B., Rodríguez-Miranda, J. (2020). Effect of ultrasound on the techno-functional properties of food components/ingredients: A review. Ultrasonics Sonochemistry, 61, 104787. https://doi.org/10.1016/j.ultsonch.2019.104787

Terefe, N. S., Delon, A., Buckow, R., & Versteeg, C. (2015). Blueberry polyphenol oxidase: Characterization and the kinetics of thermal and high pressure activation and inactivation. Food Chemistry, 188, 193-200. https://doi.org/10.1016/j.foodchem.2015.04.040

Terefe, N. S., Pasero, C., Fernando, S., Rout, M., Woonton, B., & Mawson, R. (2011). Application of low intensity ultrasound to improve the textural quality of processed vegetables. In Institute of Food Technologists (IFT) Annual Meeting. IFT, New Orleans, LA. DOI: 10.13140/RG.2.2.16037.29927

Terefe, N. S., Sikes, A. L., & Juliano, P. (2016). Ultrasound for Structural Modification of Food Products. In K. Knoerzer, P. Juliano, & G. Smithers (Eds.), Innovative Food Processing Technologies (pp. 209-230). Woodhead Publishing. ISBN 9780081002940. https://doi.org/10.1016/B978-0-08-100294-0.00008-0

Tian, Z. M., Wan, M. X., Wang, S. P., & Kang, J. Q. (2004). Effects of ultrasound and additives on the function and structure of trypsin. *Ultrasonics Sonochemistry, 11*(6), 399-404. https://doi.org/10.1016/j.ultsonch.2003.09.004

Tiwari, B. K., & Mason, T. J. (2012). Ultrasound processing of fluid foods. In *Novel thermal and non-thermal technologies for fluid foods* (pp. 135-165). Academic press. https://doi.org/10.1016/B978-0-12-381470-8.00006-2

Tiwari, B. K., O'donnell, C. P., Patras, A., Brunton, N., & Cullen, P. J. (2009). Stability of anthocyanins and ascorbic acid in sonicated strawberry juice during storage. *European Food Research and Technology*, *228*, 717-724. https://doi.org/10.1007/s00217-008-0982-z

Umego, E. C., He, R., Ren, W., Xu, H., & Ma, H. (2021). Ultrasonic-assisted enzymolysis: Principle and applications. Process Biochemistry, 100, 59-68. https://doi.org/10.1016/j.procbio.2020.09.033

Vanga, S. K., Wang, J., & Raghavan, V. (2020). Effect of ultrasound and microwave processing on the structure, in-vitro digestibility and trypsin inhibitor activity of soymilk proteins. *Lwt*, *131*, 109708. https://doi.org/10.1016/j.lwt.2020.109708

Vivek, K., Mishra, S., & Sasikumar, R. (2017). Effect of ultra-sonication on postharvest quality parameters and microbial load on Docynia indica. *Scientia Horticulturae*, *225*, 163-170. https://doi.org/10.1016/j.scienta.2017.07.006

Wang, H., Zhao, Q.-S., Wang, X.-D., Hong, Z.-D., & Zhao, B. (2019). Pretreatment of ultrasound combined vacuum enhances the convective drying efficiency and physicochemical properties of okra (Abelmoschus esculentus). LWT, 112, 108201. https://doi.org/10.1016/j.lwt.2019.05.099

Wang, N., Zhou, X., Wang, W., Wang, L., Jiang, L., Liu, T., & Yu, D. (2021). Effect of high intensity ultrasound on the structure and solubility of soy protein isolate-pectin complex. Ultrasonics Sonochemistry, 80, 105808. https://doi.org/10.1016/j.ultsonch.2021.105808

Wordon, B. A., Mortimer, B., & McMaster, L. D. (2011). Comparative real-time analysis of Saccharomyces cerevisiae cell viability, injury and death induced by ultrasound (20 kHz) and heat for the application of hurdle technology. *Food Research International*, *47*(2), 134-139. https://doi.org/10.1016/j.foodres.2011.04.038

Xu, B., Azam, S. M. R., Feng, M., Wu, B., Yan, W., Zhou, C., & Ma, H. (2021). Application of multi-frequency power ultrasound in selected food processing using large-scale reactors: A review. Ultrasonics Sonochemistry, 81, 105855. https://doi.org/10.1016/j.ultsonch.2021.105855

Xu, B., Tiliwa, E. S., Yan, W., Azam, S. M. R., Wei, B., Zhou, C., Ma, H., & Bhandari, B. (2022). Recent development in high quality drying of fruits and vegetables assisted by ultrasound: A review. Food Research International, 152, 110744. https://doi.org/10.1016/j.foodres.2021.110744

Xu, B., Tiliwa, E. S., Yan, W., Azam, S. R., Wei, B., Zhou, C., ... & Bhandari, B. (2022). Recent development in high quality drying of fruits and vegetables assisted by ultrasound: A review. *Food Research International*, *152*, 110744. https://doi.org/10.1016/j.foodres.2021.110744

Yu, Z., Su, Y., Zhang, Y., Zhu, P., Mei, Z., Zhou, X., & Yu, H. (2021). Potential use of ultrasound to promote fermentation, maturation, and properties of fermented foods: A review. Food Chemistry, 357, 129805. https://doi.org/10.1016/j.foodchem.2021.129805

Zhang, H., Chen, G., Liu, M., Mei, X., Yu, Q., & Kan, J. (2020). Effects of multi-frequency ultrasound on physicochemical properties, structural characteristics of gluten protein and the quality of noodle. Ultrasonics Sonochemistry, 67, 105135. https://doi.org/10.1016/j.ultsonch.2020.105135

Zhang, J., Liu, Q., Chen, Q., Sun, F., Liu, H., & Kong, B. (2022). Synergistic modification of pea protein structure using high-intensity ultrasound and pH-shifting technology to improve solubility and emulsification. Ultrasonics Sonochemistry, 88, 106099. https://doi.org/10.1016/j.ultsonch.2022.106099

Zhang, J., Zhang, W., & Xing, L. (2021). Effects of ultrasound on the taste components from aqueous extract of unsmoked bacon. *Food Chemistry*, *365*, 130411. https://doi.org/10.1016/j.foodchem.2021.130411

Zhang, L., Jin, Y., Deng, L., Jin, H., & Hu, X. (2018). The effect of ultrasound on the properties of α-amylase. Journal of Food Engineering, 223, 125–132. https://doi.org/10.1016/j.jfoodeng.2017.11.029

Zhang, L., Wang, L.-J., Jiang, W., & Qian, J.-Y. (2017). Effect of pulsed electric field on functional and structural properties of canola protein by pretreating seeds to elevate oil yield. LWT, 84, 73-81. https://doi.org/10.1016/j.lwt.2017.05.048

Zhang, W., & Xiao, H. (2020). High-intensity ultrasound modification of rice protein: Functional and structural characterization. Ultrasonics Sonochemistry, 61, Article 104826. https://doi.org/10.1016/j.ultsonch.2019.104826

Zhao, L., Zhang, S., Uluko, H., Liu, L., Lu, J., Xue, H., Kong, F. and Lv, J., 2014. Effect of ultrasound pretreatment on rennet-induced coagulation properties of goat's milk. Food Chemistry, 165, 167-174. https://doi.org/10.1016/j.foodchem.2014.05.081

Zhou, L., Zhang, W., Wang, J., Zhang, R., & Zhang, J. (2022). Comparison of oil-in-water emulsions prepared by ultrasound, high-pressure homogenization and high-speed homogenization. Ultrasonics Sonochemistry, 82, 105885. https://doi.org/10.1016/j.ultsonch.2021.105885

Zhou, Y., Wang, Y., Pan, Q., Wang, X. X., Li, P. J., Cai, K. Z., & Chen, C. G. (2020). Effect of salt mixture on flavor of reduced-sodium restructured bacon with ultrasound treatment. *Food Science & Nutrition*, *8*(7), 3857-3871. https://doi.org/10.1002/fsn3.1679

Zhou, Z., Guo, Y., & Wang, Y. (2021). Ultrasound deep beamforming using a multiconstrained hybrid generative adversarial network. Medical Image Analysis, 71, 102086. https://doi.org/10.1016/j.media.2021.102086

Zhu, Z., Yang, R., Wang, Q., Xu, Y., & Tang, J. (2019). Effects of ultrasound-assisted acid treatment on the structure and physicochemical properties of soy protein isolate. Ultrasonics Sonochemistry, 58, Article 104594. https://doi.org/10.1016/j.ultsonch.2019.104594

Zou, Y., Kang, D., Liu, R., Qi, J., Zhou, G., & Zhang, W. (2018). Effects of ultrasonic assisted cooking on the chemical profiles of taste and flavor of spiced beef. *Ultrasonics sonochemistry*, *46*, 36-45. https://doi.org/10.1016/j.ultsonch.2018.04.005