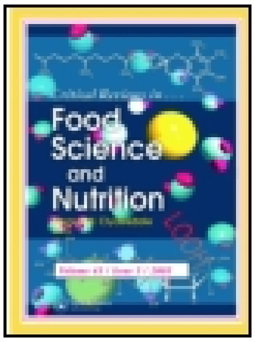

Critical Reviews in Food Science and Nutrition

ISSN: 1040-8398 (Print) 1549-7852 (Online) Journal homepage: https://www.tandfonline.com/loi/bfsn20

Recent nano-, micro- and macrotechnological applications of ultrasonication in food-based systems

Bababode Adesegun Kehinde, Poorva Sharma & Sawinder Kaur

To cite this article: Bababode Adesegun Kehinde, Poorva Sharma & Sawinder Kaur (2020): Recent nano-, micro- and macrotechnological applications of ultrasonication in food-based systems, Critical Reviews in Food Science and Nutrition, DOI: 10.1080/10408398.2020.1740646

To link to this article: https://doi.org/10.1080/10408398.2020.1740646

Published online: 25 Mar 2020.

CRITICAL REVIEWS IN FOOD SCIENCE AND NUTRITION
https://doi.org/10.1080/10408398.2020.1740646

Taylor & Francis
Taylor & Francis Group

REVIEW

Recent nano-, micro- and macrotechnological applications of ultrasonication in food-based systems

Bababode Adesegun Kehinde[a], Poorva Sharma[b], and Sawinder Kaur[b]

[a]Department of Biosystems and Agricultural Engineering, University of Kentucky, Lexington, Kentucky, USA; [b]Department of Food Technology and Nutrition, School of Agriculture, Lovely Professional University, Phagwara, Punjab, India

ABSTRACT
There is a neoteric and rising demand for nutritional and functional foods which behooves food processors to adopt processing techniques with optimal conservation of bioactive components in foods and with minimal pernicious impacts on the environment. Ultrasonication, a mechano-chemical technique has proven to be an efficacious panacea to these concerns. In this review, an analytic exploration of recent researches and designs regarding ultrasound methodology and equipment on diverse food systems, technological scales, procedural parameters and outcomes of such experimentations optimally scrutinized. The relative effects of ultrasonication on food formulations, components and attributes such as nanoemulsions, nanocapsules, proteins, micro-nutrients, sensory and mechanical characteristics are evaluatively delineated. In food systems where ultrasonication was employed, it was found to have a remarkable effect on one or more quality parameters. This review is a supplementation to the pedagogical awareness to scholars on the suitability of ultrasonication for research procedures, and a call to industrial food brands on the adoption of this technique for the development of foods with optimally sustained nutrient profiles.

KEYWORDS
Ultrasound; nanotechnology; microtechnology; food systems

Ultrasonication: history and contemporary industrial application

The historical timeline of the studies involving ultrasound technology dates back to 1794 when the Italian scientist Lazzaro Spallanzani discovered that bats applied unperceivable sound waves in their navigation. Other discoveries relating closely to ultrasound technology were made such as Jean Colladon in 1826 and the Curie brothers: Pierrie and Jacques who discovered that certain crystans, when under pressure have the potential to generate voltage. However, in 1942, Karl Dussik a medical doctor made a breakthrough achievement in the field of medical neurology and by using ultrasound technology in the diagnosis of brain tumors. The application of ultrasound thereafter was focused on medical diagnosis for physiological disorders in human body parts and imaging of internal organs including gall stones (1948), breast tumors (1951), and heart imaging (1966), 3-Dimensional fetus imaging (1986) and others (Waingankar, Goldenberg, and Gilbert 2015).

With regards to food processing technology, the application of power ultrasound can be traced back to 1927 where Wood and Loomis in a study on the physicochemical effects of power ultrasound in an oil bath reported that it was beneficial in the mixing of oil-in-water emulsion.

With the passage of time, ultrasound, being an emerging technology, and a fitting alternative to thermal processing has found its application in the commercial scale food processing in versatile areas such as energy-efficient cutting of food materials, homogenization of food products such as milk, mayonnaise, extraction of flavonols from plant parts, degassing, cleaning, microbial deactivation, and enzyme inactivation (Chemat, Huma, and Khan 2011; Majid, Nayik, and Nanda 2015). Based on the nature of usage, heterogenous food systems where ultrasound is used can be categorized into three groups viz: (1) solid-gas systems (such as solid-gas filtration and agglomeration); (2) gas-liquid systems comprising of nebulization (atomization, spraying or aerolization) and foaming-defoaming operations; and (3) solid-liquid systems such as crystallization, aggregation, sonophoresis, filtration and slurry formation (Castro and Capote 2007).

Ultrasonic cutting works on the proficient acoustic energy in synergy with the movement of a cutting blade to effect quality cutting with relatively minimized energy usage, smooth cut surface and without cracking or any sticky food left on the blades (McHugh 2016). Based on its ability to reconfigure meat proteins, ultrasonication has been adopted in the commercial meat industry, for improving meat processing operations such as microbial inactivation, meat tenderization, margination and mass transfer and it has been appraised as a potential replacement for the traditional meat aging process (Rojo et al. 2018). Ultrasonic vertical

CONTACT Bababode Adesegun Kehinde bababode.kehinde@uky.edu; mrkenny05@gmail.com Department of Biosystems and Agricultural Engineering, University of Kentucky, Lexington, KY-40503 KY.

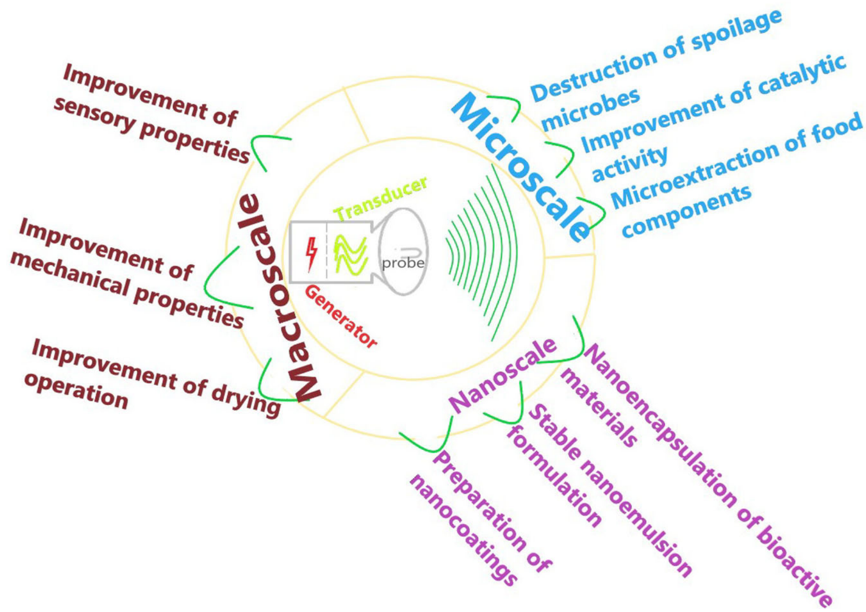

Figure 1. Ultrasound and its food-based applications at different scales.

and horizontal sealing equipment are currently used for sealing of food packages, and in the carbonic beverage industry where the constraint of excess foam production during bottle filling exists, airborne sonication emitters are being applied for the rapid breakage of such foams (McHugh 2016).

Ultrasound working principle and equipment

Sound, being a mechanical wave requires a material medium for its propagation and as such, cannot travel through a vacuum. Ultrasound is a form of sound wave traveling at a frequency greater than 20 kHz. Human audibility is known to be within the range of 20–20 kHz (Dong et al. 2019) which implies that ultrasound cannot be perceived by the human ear. However, primates and other related animals whose upper audibility limits exceed 20 kHz can detect ultrasound. Common examples of such animals include cats (79 kHz), dogs (67 kHz) and bats (200 kHz) (Zhang et al. 2016; Strain et al. 2016; Jiang et al. 2019).

Ultrasound can be categorized into two classes based on its energy-frequency combination. One class consists of the low energy-high frequency ultrasound having intensities less than 1 W cm^2 and frequencies greater than 100 kHz. The second class termed as high energy-low frequency ultrasound with intensities higher than 1 W cm^2 and finite frequency ranging from 20 to 500 kHz (Rana, Meena, and Shweta 2017).

When a sound source propagates sound into a solid or fluid medium, the sound waves travel in form of sinusoidal waves. The response of the medium to the wave causes to vibrate in an elastic manner. In liquid systems, sound waves of ultrasonic frequencies can result in pressures high enough to actuate a phenomenon called acoustic cavitation (Majid, Nayik, and Nanda 2015). The cavitation causes the formation of bubbles which expand progressively and eventually collapse. The cavitation zone experiences high pressure and temperature (Soria and Villamiel 2010) which favors certain mechanical, chemical and biological changes in the surrounding medium. Mechanical changes include; fluid turbulence, pressurized collapse and build of shear stresses (Yusaf and Al-Juboori 2014). Free radical and sonochemical generation (Sivagami et al. 2019) are known chemical effects and destruction of microbial cells and enzymes for the biological impacts.

The overall intensity (UI) of the employed ultrasound waves has been summarized in the equation: $UI = 4\,P/\pi D^2$, where D is the probe diameter (in cm) and P is the ultrasonic power (in Watts) (Tiwari et al. 2008; Kumari et al. 2017). The factors influencing the efficiency of ultrasonication especially with respect to extraction of inherent bioactives from foods have been categorized into three groups namely: (1) factors associated with the extraction medium such as solvent polarity, temperature, pressure and viscosity; (2) factors related with the food material such as its average particle size and moisture content and (3) sonication processing factors including the amplitude, frequency, treatment time and power (Patist and Bates 2008).

Irrespective of the application or industrial use of ultrasound technology, the generation and transmission of ultrasonic waves require similar fundamental system components (Figure 1). This includes a generator for electrical power supply, one or more transducers for conversion of the generated electrical energy into sound energy and an emitter for sound transmission and a probe rod for the transmission of the waves (Bellary and Rastogi 2015).

Recently, an appreciable amount of ingenuity has been incorporated to the design and fabrication of ultrasonic equipment which has led to its improved usage for clean cutting of baked and extruded food products, liquid food processing, nanocrystallization operations, and cleaning operations. Some recent studies have also involved the fabrication of novel ultrasonic equipment applicable in food processing. Song et al. (2019) welded an ultrasonic generator to a calandria evaporator and employed machine learning methodology to evaluate the impact of ultrasonication on

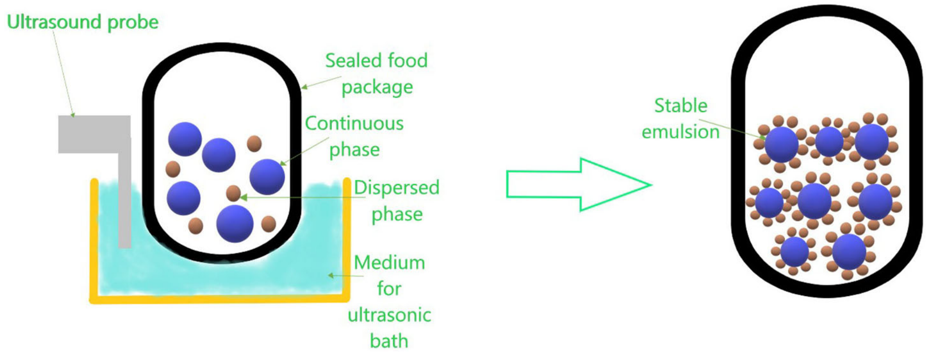

Figure 2. Schematic representation of ultrasound-aided in-pack emulsification (Gavahian et al. 2018).

the efficiency of the evaporator. Their study showed a 15–20% increase in the overall heat transfer coefficient of the evaporator resulting from the acoustic cavitation turbulence impacted on it from the generated ultrasonic waves. Amirante and Clodoveo (2017) also designed an innovative ultrasonic device applicable for continuous operation in the industrial-scale extraction of olive oil. The devices' functionality is to sufficiently replace the need for malaxation, efficiently treat the olive paste without imparting any undesirable changes in the sensorial attributes of the product. Çelik et al. (2018) productively designed and used an ultrasonic sensor device for the monitoring of the physicochemical changes in an industrial-scale malolactic wine fermentation process. The novel system measures the physicochemical alterations occurring during fermentation by the propagation, transmission and reechoing of ultrasonic waves through the fermenting medium. The differences in readings obtained regarding the ultrasonic velocity at initial and subsequent stages of fermentation is imputed into mathematical simulations and results are obtained. Several studies have shown that ultrasound is useful for conventional unit operations in food processing such as microbial inactivation (sea foods, meat, fruits and vegetables), extraction, freezing, drying and quality control processes (Papaioannou, Kyriakides, and Karabelas 2016; Arvanitoyannis, Kotsanopoulos, and Savva 2017) for continuous and batch processes.

Ultrasound is often combined with other conditions of temperature and/or pressure depending on the intended purpose. Thermosonication (TMS) (Ghosh 2017) is the application of ultrasonication at moderate temperatures, when combined with pressure, it is termed as manosonication (Ercan and Soysal 2013) and when pressure and temperature are used together – thermomanosonication (Chemat, Huma, and Khan 2011).

Emerging applications of ultrasound

In recent decades, the emerging adoptions of ultrasonication in the fields of health, manufacturing and processing has been facilitated by the principal factors of ease of scalability and the improving technical comprehension of the qualitative effects of acoustic energy where employed (Misra et al. 2017). In the health domain, it has found profound employment as a diagnostic tool for practices related to cardiology, obstetrics, and neurology especially where it is used for metabolic syndromes and disorders such as Parkinson's disease, tremors, tumors, neuropathic pain, psychiatric disorders and stroke (Leinenga et al. 2016). In food processing, ultrasound is currently used either as a single processing unit or in combination with other emerging technologies. The scope of usage of ultrasound has extended due to the improvement in the design schematics of ultrasound systems enabling them to reach power levels above 100 W and megasonic frequencies greater than 400 kHz (Misra et al. 2017). As a result, ultrasonication is used for casein micelle alteration and lactose crystallization in dairy products, airbone drying and defoaming operations, texture modification of foods, modification of thermodynamic and kinetic parameters of enzymes for their overall functionality, improvement of oil yield during extraction and in-pack processing of food products (Nadar and Rathod 2017; Leong, Juliano, and Knoerzer 2017).

Based on the penetrative attribute of acoustic waves, it has been used to process food products without changing or removing the food material from its package using the sonication bath mechanism (Figure 2). Gavahian et al. (2018) examined the feasibility of using ultrasound to induce the emulsification process for in-pack model oil-in-water salad dressing emulsions with lecithin as emulsifier and with a subsequent comparison with the mechanical homogenization (scaled-up) for such. An 80 W sonication energy was incorporated into a distilled water bath for 1 min where the already packaged 'unemulsified' mixture was filled. The study showed the applicability of such a design and with a resulting comparable emulsion stability output relative to the mechanical homogenization, and with similar readings for viscosity and lesser values for emulsion span. The study further proves the energy and cost-effectiveness of in-pack sonication in relation with mechanical homogenization.

Based on some constraints experienced by food processors during extraction operations such as energy costs and consumption, long duration of extraction and limitations associated with mass transfer especially with conventional extraction methodologies, emerging techniques such as ultrasound are integrated into the extraction systems (Gavahian, Sastry, and Farahnaky 2020). Kumari et al. (2017) investigated the extraction of polyphenols using different solvents (water, methanol and their mixture) and ultrasonication (33 kHz and 42 kHz) from the peels of different potato varieties (pink-skinned Lady Rosetta and cream-skinned Lady Claire). The study showed a significant difference in the extracted polyphenols with the ultrasound-aided treatment total polyphenolic content ranging from 3.80 ± 0.09 to 7.67 ± 0.79 mg GAE/gdb and the solvent extraction ranging from 3.28 ± 0.07 to 2.17 ± 0.02 mg GAE/gdb for both varieties. Contrastingly, Gavahian et al. (2017) in a study regarding the evaluation of ultrasound pretreatment and electrolyte concentration on the ohmic heating-aided hydrodistillation of essential oils from peppermint (*Mentha piperita* L). Ultrasonication pretreatment at a fixed frequency of 35 kHz, 50 W for 5, 10 and 15 minutes and sodium chloride at concentrations of 1, 3 and 6% w/v were examined. The results of the study showed that while the sodium chloride electrolyte significantly impacted the hydrodistillation process, the ultrasound pretreatment did not.

Ultrasound: green attributes and safety considerations

Growing concerns over the emission of greenhouse gases, discharge effluents, chemical and thermal wastes from industries on a global scale, which have resulted into climate change of deleterious consequences on earth's natural environment have increased the need for the adoption of technological procedures with remarkably lesser adverse effects on the environment (Jones, Pfeifer, and Castillo 2019). Such techniques and processing methodologies are termed as clean or green technologies (Zhang et al. 2018) and they possess the distinctive characteristic of conserving the resources and environment of nature.

Agricultural industries have been acknowledged as the largest producers of greenhouse gases with meat, vegetables and dairy-producing industries contributing massive fractions (The Washington Post 2019). The processing procedures conventionally used by these industries are doubtlessly responsible for such outcomes. Their high demand and resulting consumption of energy (mostly generated from fossil fuel combustion), prerequisite need for water and other solvents with a consequential discharge of large quantities of effluents, and the mushrooming of toxic chemical and/or thermal wastes (lubricants, cleaning agents and infrared radiations amongst others) have placed them on global watch (Sinha et al. 2018; Gavahian, Chu, and Farahnaky 2019). These and several other constraints have necessitated the need for the introduction of green food processing on the premise of green engineering and chemistry and has been defined as food-based operations with attributes of remarkably decreasing water and energy expenditure, enabling the bio-refined by-product recycling and assurance of quality and safe products (Wu et al. 2017; Chemat et al. 2017). On another note, with a progressively expanding functional food market and the after-effect of conventional procedures on the nutritional and other physicochemical attributes of processed foods, it behooves food manufacturers the responsibility of adopting other techniques (Lafarga et al. 2019). Techniques such as such as high-pressure processing, pulsed electric field (PEF), cold plasma, ultrasonication, supercritical fluid processing and pulsed light have been appraised as green technologies (Zhang, Zhu, and Sun 2018) especially because they are water and energy efficient. Interestingly, some of these technologies are based on fields: PEF, electrohydrodynamic (EHD) processing, and cold plasma are linked with electromagnetic fields while ultrasound is related to the acoustic force field (Misra et al. 2018).

Ultrasonication involves no large magnitude of electrical or mechanical energies for its operation, making it relatively less energy demanding than other food processing techniques especially the thermal ones. Even when congruously utilized in the field of medical radiography, it is regarded as safe (Ter 2011; Appis, Tracy, and Feinstein 2015). This benign attribute and the associated characteristic of minimal pollution which are subsets of the standards of green chemistry resultantly defines ultrasonication as one of such (Tao and Sun 2015; EPA 2017).

Ultrasonication possesses the superlative advantages of low investment costs, low processing time, higher efficiency in extraction and mixing applications, rapid transfer of energy, low working temperature and other qualities of similar kind (Chemat et al. 2017; Pojić, Mišan, and Tiwari 2018). Unlike other food processing techniques which might require large floor space and higher energy inputs for usage which contribute to their high investment and running costs, ultrasound is preferably recommended. In addition, the safety factor to humans and/or other equipment employed in food processing facilities which attract meticulous heedfulness to all stakeholders in such establishments would encourage the adoption of ultrasonication.

Nanotechnological applications of ultrasound in food-based systems

Nanotechnology entails the scientific study, manipulation and the practicable application of materials in proportional dimensions ranging from 1 to 100 nanometer, thus relating to particles on the nanoscale. The concept was originally birthed by the renown quantum physicist Richard Phillips Feynman (1918–1988), who in 1959 gave a talk describing the likelihood of scientific control and manipulation of molecules and atoms for the synthesis of novel materials (Ray and Gupta 2018). In 1974, the vocabulary coinage of the terms nano and technology was done by Prof. Norio Taniguchi (1912–1999) with reference to technical attributes of semi-conductors. In subsequent decades, studies related to nanotechnology were conducted (Maher 2018).

In neoteric times however, the integration of this finesse technique in food-related subjects have been actuated for diverse purposes (Table 1), but the paramount ones have been; novel product formulation and the retainment and/or improvement of inherent, desirable properties of food materials (Dasgupta and Ranjan 2018). A comprehensive method of classifying nano-based food systems or particles would be by the nature of the base material from which they are synthesized, which would include; metal, polymer, lipids, phytosomes and combination-based nanosystems (Jhala, Rather, and Vasita 2018). Metallic nanoparticles have been utilized for the improvement of delivery of food-based medications. Metals such as gold, iron, copper and aluminum are used and are synthesized from the extracts of plant and animal food such as tea leaves, olives, citrus fruits, honey and eggs

Table 1. Nanoscale applications of ultrasonication in food-based systems.

Food	US parameters	US functionality	Results	Other techniques and/or materials employed	References
Plant protein - polysaccharide complex (Soy and Pea starch)	Manothermosonication (MTS): 20 kHz, 750 W, 5mins, 200 kPa, 60 s, 50 °C, pH 12	Formation of a stable emulsion with polysachharides (modified starch, gum arabic and pectin)	MTS disruption of soy and pea protein nanoaggregates for emulsions with droplet sizes <400nm	(Environmental Scanning Electron Microscopy) ESEM	Yildiz, Ding, Andrade, et al. 2018
Multilayer refined clove oil and water emulsion	20 kHz, 40%, 750 W, pH 4.7, 30 ± 2 °C	Nanoemulsion stabilized by Whey Protein Isolate (WPI) and sodium alginate	Reduction in droplet size from 473nm to 312nm and further to 308nm	(Dynamic Light Scattering) DLS and electrophoresis	Carpenter, George, and Saharan 2018
Citral oil and chitosan nanoemulsion	50 kHz, 10 mins, 5 cycles/sec	Nanoemulsion preparation at citral:chitosan ratios of 0.1:1, 0.2:2, 0.4:1, 0.8:1	Uniform nanoemulsion droplets of droplet sizes ranging from 27.0-1283nm, PDI from 0.614-0.571 and dynamic viscosity from 5.1 ± 0.05 to 3.1 ± 0.04 mPa.s	Scanning Electron Microscopy (SEM), DLS	Marei, Rabea, and Badawy 2018
Lemon oil in water	120 W, 20% amplitude, 5 mins	Nanoemulsion (NE) preparation with probe and bath sonicators	Probe / Bath Final NE droplet size: 31.68 ± 1.78 nm / 44.95 ± 2.16 nm	Use of the surfactant decyl-β-D-glucopyranoside. Transmission Electron Microscopy (TEM)	Kumar et al. 2018
Egg yolk and egg yolk lecithin	20 kHz, 58.5 W	Preparation of nanoliposomes for vitamin nanoencapsulation	Small Unilamellar Vesicles of 40–51 nm diameter Multilamellar Large Vesicles ranging from 2.9 to 5.7 µm Vitamin / Encapsulation efficiency (%) B12: 56.2 ± 8.51 α-tocopherol: 76.3 ± 14.2 Ergocalciferol: 57.5 ± 13.9	Optical microscopy. Thin-field hydration	Bochicchio et al. 2016
Eugenol	0–750 W, 0–15 mins	Preparation of Eugenol-chitosan nanoemulsion	US Power (W) / US time(min) / Droplet size (µm) 0 / 0 / 722.8 450 / 15 / 344.2 750 / 6 / 433.2	SEM, X-Ray Diffraction (XRD), UV-VIS Spectrophotometry at 278 nm	Shao et al. 2018
Baltic cod fillet packed with nanoparticles	20%, 10 mins, cycle:0.5	Preparation of nanocoatings and examination of preservation activity	US-nano coating / Alternative coating Mesophilic bateria log increase after 72 h: 1 / 2	Methyl Hydroxypropyl Celluloses (MHPC) with 2% polylysine	Mizielińska et al. 2018
Potato starch	15 mins, Pulse: 3 sec off, 1 sec on.	Acid hydrolysis, modification and antioxidant loading of starch	Treatment / Size(nm) Conventional modification: 1596 US only: 80 US + Acid treatment: 40 US(30 mins) + L-ascorbic acid: 230 US(30 mins) + Oxalic acid: 270 US(60 mins) + L-ascorbic acid: 158 US(60 mins) + Oxalic acid: 183	TEM, XRD, HPLC, Particle Size Analysis	Shabana et al. 2019
Nata de Coco	20 kHz, 3 W/ mL, 30–90 min	Preparation of functional nanosized bacterial cellulose particles	Control / US-treated SEM micrograph: Sediments present / Sediments absent TEM micrograph: Black / Transparent Particle size (nm): >60 / 10 Crystallinity index: Normal / 15% reduced Decomposition temperature: 373 °C / 357 °C Functional groups: Normal / Normal	SEM, TEM, XRD, FTIR, Thermogravimetry Analysis (TGA), Differential Thermal Analysis (DTA)	Abral et al. 2018
Hazenut meal proteinand clove essential oil	50–100%, 9.42–70.13 W/cm^2	Preparation of edible forming nano-emulsions (FFNs)	Control / 50%, 2 min / 75%, 6 min / 100%, 6 min Particle size (nm): 306.65 ± 1.34 / 247.65 ± 2.05 / 170.05 ± 2.78 / 160.45 ± 2.35 PDI: 0.544 ± 0.001 / 0.478 ± 0.015 / 0.288 ± 0.008 / 0.288 ± 0.008 Zeta Potential ζ (mV): −36.20 ± 0.57 / −35.65 ± 0.21 / −30.85 ± 0.36 / −9.975 ± 0.32 Solubility (%): 22.77 ± 1.76 / 22.87 ± 0.88 / 25.39 ± 2.34 / 23.14 ± 0.11 Tensile Strength (MPa): 2.64 ± 0.04 / 3.08 ± 0.21 / 4.04 ± 0.03 / 4.20 ± 0.06 Elongation at break (%): 222.98 ± 24.08 / 314.16 ± 15.58 / 344.01 ± 7.91 / 338.84 ± 6.17a	SEM	Gul et al. 2018
Pork meat	25 kHz, 30 or 60 mins, 4.0 ± 1.0 °C	Incorporation of nanoencapsulated docosahexanoic and eicosapentanoic acids (16 and 42%)	Enhancement of mass transfer of the nanoencapsulated fatty acids into the porcine meat sample	Gas chromatography-flame ionization detector (GC-FID)	Ojha, Mason, et al. 2017

(*continued*)

Table 1. Continued.

Food	US parameters	US functionality	Results				Other techniques and/or materials employed	References
Soy protein isolate	20 kHz, 200 W, 25 ± 2 °C, pH 7.0, 0–30 mins, pulse: 2 sec on, 2 sec off.	Protein isolate dissociation	US Treatments (min)	Particle size of suspensions (nm)	Particle size of emulsions (nm)		Circular dichroism (CD) spectroscopy, Ultraviolet–visible (UV–vis) spectroscopy, Optical microscopy	Huang et al. 2019
			0	1281.7 ± 22.8	1002.8 ± 19.6			
			5	186.7 ± 4.9	961.9 ± 15.6			
			10	133.6 ± 7.9	833.1 ± 12.2			
			20	135.7 ± 10.3	961.7 ± 11.6			
			30	161.7 ± 9.2	1001.2 ± 24.6			
Rice husk powder	30 mins	Preparation of silver-assisted biobased silica-carbon nanoparticle composite films for food packaging	Nanoparticle dispersion into viscous biopolymer solution				XRD, Raman spectroscopy, X-ray photoelectron spectroscopy (XPS), BET surface area analysis, Field emission scanning electron microscope (FE-SEM), TEM, DSC, TGA, Atomic adsorption spectroscopy (AAS).	Biswas et al. 2019
	10 mins	Material pretreatment for SEM analysis						
Cassava, corn and yam starch	20 kHz, 30 mins	Preparation of nano-sized starch particles		Corn starch: native, US-treated	Cass. Starch: native, US-treated	Yam starch: native, US-treated	XRD, SEM, FTIR, TGA, UV-VIS spectrophotometry	Minakawa, Faria-Tischer, and Mali 2019
			Particle size	5–20µm, 36 − 68 nm	7–14µm, 35 − 65 nm	12–37µm, 8 − 32 nm		
			Relative Crystallinity Index (%)	31, 8	29, 0	32, 9		
			Degradation Temperature (°C)	321.26, 306.41	327.30, 299.71	324.19, 290.27		
Apple juice concentrate and full cream whole milk	20 kz, 20 sec, below 1 °C	Generation of nano-bubbles from dissolved CO_2 for improvement of freezing parameters	At 2000 ppm CO_2 after 20 seconds, nucleation time and freeze time decreased from 11.1 ± 1.9 to 5.2 ± 0.5 mins and 39.2 ± 1.7 to 35.5 ± 0.5 mins respectively.				DSC	Adhikari et al. 2019

or directly from their salts by the reduction process (Hoseinnejad, Jafari, and Katouzian 2017; Shankar, Oun, and Rhim 2018). Starch, cellulose, gelatin and chitosan are common examples of polymeric raw materials used for the manufacture of nanomaterials used in food systems (Noorbakhsh-Soltani, Zerafat, and Sabbaghi 2018). Carbohydrates and proteins fall in the category of polymers but lipids cannot be fully classified as such because polymers have the defining characteristic of monomeric build-up, a feature lacking in lipids which are made basically of esters, though they all are biological macromolecules. Lipid nanoparticles are further subdivided into solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs) (Naseri, Valizadeh, and Zakeri-Milani 2015). The solids being crystalline with entrapment slots in their structures and the oil-in-water emulsions which could be nearly crystalline, amorphous or complex in structure. Whey protein, palmitic acids, hard fats and lecithin are popular examples of food materials used for the fabrication of solid nanolipid materials and for the NLCs (70% solid lipids and 30% liquid lipids), oleic acid, cocoa butter and parrafin oil are common unsaturated and saturated oils used for their development (Aditya and Ko 2015; Babazadeh, Ghanbarzadeh, and Hamishehkar 2016). Phytosome is a technical name coined from two words phyto (implying a plant source) and some (implying cell-like). Nano-phytosomes are nano-sized complexes comprising of herbal extracts and phospholipids conjugated by hydrogen bonds, employed in food systems especially for the biodelivery of functional components (Ghanbarzadeh, Babazadeh, and Hamishehkar 2016). Such complexes involve specific mixture ratios of herbal extracts and phospholipids such as phosphatidylserine, phosphatidylethanolamine or phosphatidylcholine in solvents such as methlylene chloride, acetone and dioxane; methanol being highly recommended based on its food-grade nature (Rafiee and Jafari 2018).

Techniques adopted for the preparation of nanomaterials employed in food processing have been categorized on the basis of their mode of preparative occurrence as separate, (or *ex situ*) or the top-down synthesis whereby the nanomaterials are separately prepared before incorporation into the system of interest; usually involves thorough size reduction and includes techniques such as mechanical milling, extrusion, spray drying, supercritical fluid process and microfluidization (Vasile 2018). The alternative category termed as joined or bottom up involves the joint synthesis of the nanomaterials and the systems where they are applied and includes; sol-gel processing, chemical syntheses and precipitation amongst others (Oliveira and Machado 2013). Categorizing ultrasonication could be cumbersome due to its versatility of use: it can function both in joint or separate applications. However, ultrasonication is proficiently employed in the fabrication of nanomaterials in virtually all fields of technology. More so, ultrasonication has proven to be more efficient in several researches involving its comparative application with other techniques mentioned. In nanosized food systems, it is commonly utilized as a processing technique or for the improvement of desired outcomes. Nanoemulsions, particulate nanomaterials for food packaging (Jokar and Abdul Rahman 2014), nanopolymers (Zhang et al. 2015) and nanolipids are typical products of ultrasound integration in food nanotechnology. For quality improvement; enhanced nutrient delivery and bioavailability (through nanoencapsulation) and nanofortification (Öztürk 2017) are some outcomes of implementing ultrasonication at the processing phases of food systems. In the preparation of nanoemulsions for instance, ultrasonication is understood in several researches to improve the storage stability of the end products from parameters such as low polydispersity index (PDI) values and high modulus magnitudes for Zeta potential readings. Furthermore, the inexhaustible list of already developed and future developments of novel nanoformulations with the application of ultrasound is remarkable in food technology.

Several studies conducted on the use of ultrasound technology in food nanosystems have explained its underlying mechanism of action with regards to such studies. Hadian et al. (2014) studied the comparative effects of bath and probe sonication (separate and combined) and extrusion technology in preparing a biocompatible nanoliposome encapsulation system functional in stabilizing omega-3 fatty acids against oxidative rancidity was the objective of their research. Their results showed that the combined use of probe and bath sonication (PBS) produced nanoliposomes of average smallest sizes (87.1 ± 4.1 nm) in comparison with extrusion (EXT) having 99.7 ± 3.5 nm. The electrokinetic potential (Zeta potential) also followed a similar trend with the (Bath sonication) BS having -43.8 ± 2.4 mV and EXT -42.4 ± 1.7 mV respectively. The size results showed that the sonication technique was more efficient in the size reduction in comparison with the mechanothermal extrusion technique. The zeta potential readings also signify that bath sonication influenced the electrostatic profile of the liposomes more effectively into having higher repulsions and lesser tendency to aggregate than the extrusion technique. Their results also showed that probe ultrasonication provided a more optimal encapsulation efficiency based on the quantity of the nano-delivered fatty acids in the end products. They inferred that the contact loading aspect of the fatty acids by sonication was the rationale behind its higher effectiveness than ultrasonication.

Bochicchio et al. (2016) conducted a similar study on the use of nanoliposomes prepared by ultrasonication as carriers for vitamin delivery. At ultrasonication conditions of 20 kHz, 45% power and 1 mL treatment volume, nanoparticles produce had encapsulation efficiencies of $56.2 \pm 8.51\%$ for Vitamin B12, $76.3 \pm 14.20\%$ for α-Tocophero and 57.5 ± 13.9 for Ergocalcifero, respectively. Their investigation showed that various parameters related to ultrasonication namely; amplitude, treatment time, sample volume and frequency all had remarkable effects on the size quality factor of the nanoliposomes produced.

Zhang et al. (2015) applied ultrasonication for the biocompatibility enhancement of curcumin nanoparticles (CUNP) in their study relating to the in vivo and in vitro effect of CUNP as anticancer drug carriers. A 5 min ultrasonication of CUNP favored its hydrophobic and non-covalent anchorage to the polymeric anticancer drug C18PMH-PEG poly (maleic anhydride-alt-1-octadecene)-polyethylene glycol and improved its biofunctionality.

Mizielińska et al. (2018) conducted an investigative study aimed at comparing polylysine (PLS) and sonication-produced nano-zinc oxide (SNZO) coatings on the microbial purity of cod fillets. SNZO were prepared by sonicating the mixture of water and zinc oxide nanoparticles for 10 mins at a cycle of 0.5 and an amplitude of 20%. Their results showed that subsequent to storage for 72 h at 5 °C, SNZO coated fillet preparations had a reduced population (1-log increase) of the characteristic mesophilic bacteria relative to the alternative coating which showed a 2-log increase. Ultrasonication was optimally employed for the production of the nanocoatings and may have also sterilized them; offering a more sterile environment for the fillets during storage as shown in the microbiological readings.

Shao et al. (2018) conducted a study designed at formulating and characterizing nanoemulsions comprising of eugenol and chitosan (1:1) with a nonionic surfactant (Tween 20) using a 450 W ultrasonication for 5mins. Nanoemulsions produced were found to have sizes ranging from 80 to 100 nm and of regular, spherical shapes. Their characterization with regards to antimicrobial and antioxidative functionalities relative to their separate preparations showed positive results. Against *E. coli,* the sonicated nanoemulsions showed a total population of 97.66 μg/mL in comparison with the eugenol and chitosan preparations which had 2762 and 726.25 μg/mL, respectively. For the antioxidative potential as determined by the DPPH scavenging activity, similar trends were found in the results. The chitosan and eugenol preparations showed 13.73 ± 0.71 and $82.11 \pm 0.18\%$ scavenging potentials while the ultrasonicated nanoemulsion proved superlative with $93.50 \pm 0.29\%$. The SEM images obtained showed uniformly distributed and spherically-shaped nanoparticles and low values of PDI Sand higher values of zeta potential confirmed a larger storage stability for the sonicated nanoemulsion.

Shabana et al. (2019) effectually adopted the use of ultrasound on potato starch for its acidified hydrolysis and its average size reduction to the nanoscale with a subsequent ultrasound-aided loading of antioxidants to the obtained nanosized starch particles. Prior to acid hydrolysis, the starch solution was US treated for 15 mins at 3 and 1 second on and off pulse mode. Their results showed a profound decrease in the average size of starch nanoparticles obtained from ultrasonication only (UO) and acid treatment aided with ultrasonication (ATU) relative to the nanoparticles prepared form the conventional technique (CT) with particle size analyzer readings for UO, ATU and CT found to be 80, 40 and 1596 nm respectively. These readings infer that the shear force of ultrasonication is beneficial and efficient for particle size reduction on the nanoscale. The antioxidants – oxalic and L-ascorbic acids were productively loaded to the starch nanoparticles. They reviewed that the mechanochemical impacts of ultrasound aided the constitution of sturdy interfacial bonds between the starch and the segment of the antioxidants bearing the oxygen groups.

Abral et al. (2018) conducted a study involving the concoction of nanoparticles from *nata de coco*, a fermented coconut water product. Their research was aimed at the preparation of bacterial cellulose nanosized particles with the employment of ultrasound for the nanoscale disintegration of the cellulose material. A pellicle solution made from the fermented product was subjected to ultrasonication at 20 kHz frequency, 600 W power, 100% amplitude and varying durations from 30 to 90 mins. Their experimentation showed that unlike the unsonicated control samples, the US-treated samples had no sediments and as such, a transparent TEM image was obtained from their micrograph. Unsonicated samples showed black coloring in their TEM imagery. SEM analysis showed a more proficient size reduction actuated by ultrasonication with average particle sizes of 10 nm and a larger 60 nm for control samples. Ultrasonication, from SEM micrographs, was also discovered to decrease the incidence of nanoporosity. The overall crystallinity index obtained from X-ray diffraction studies showed a 15% reduction instigated by ultrasound, an outcome affiliated to the remarkable kinetic energy resulting from acoustic cavitation.

Ojha, Mason, et al. (2017) used ultrasonication for the inclusion nanoencapsulated docosahexanoic and eicosapentanoic acids (16 and 42%) in pork meat for the enhancement of its fatty acid profile. *M. semitendinosus* porcine meat samples immersed into a nanovesicular suspension of the omega-3 fatty acids were subjected to an ultrasonic bath of working at a frequency of 25 kHz for a duration of 30 or 60 mins. Their tests showed that ultrasonication treatment time had a positive correlation with the quantity of the fatty acids in the final products obtained through the enhancement of mass transfer of the nanoencapsulated fatty acids into the porcine meat samples.

Yildiz et al. (2017) analyzed the denouement of differing manothermosonication (MTSN) parameters in the preparation of soy protein nanoaggregates and the outcome of process variability on the functional features of the end products. Soy protein isolate was subjected to varying MTSN parameters including absolute pressures of 100–400 kPa, temperatures of 40–50 °C and process times from 30 to 60 seconds and optimization studies (OPS) regarding the functional characteristics such as protein solubility, particle size and turbidity, disulfide bond (SS) and free sulfhydryl (SH) contents, surface hydrophobicity, emulsifying properties and total phenols of the nanoaggregates were conducted. OPS results showed that MTSN conditions at 200 kPa, 50 °C, pH of 12 and process time of 60 s was superlative for all functional characteristics. At OPS conditions, particle size and protein recovery of 27.1 ± 1 nm and $82.5 \pm 0.42\%$, respectively. Breakage of bonds (covalent and non-covalent), acoustic impact triggering electrostatic and polar tensions on globular proteins, configurational changes in the orientation of hydrophilic amino acid fragments and generation of soluble protein nanoagglomerates from the insoluble ones were possible mechanisms outlined for the solubility readings. The same OPS combination showed the least turbidity readings and highest emulsion activity and stability indices of $326.0 \pm 2\,m^2/g$ and 49.0 mins in comparison with the control (untreated protein isolate) preparations which had $128.0 \pm 2\,m^2/g$ and 22.0 mins. The ultrasound waves, being further energized by the pressure and temperature conditions showed their impacts in the readings obtained. The contents of the SS and SH bonds were found to be 21.97 ± 0.06 and $7.68 \pm 0.08\,\mu mol/g$ at OPS conditions and for the control, 14.82 ± 0.08 and $4.22 \pm 0.17\,\mu mol/g$ respectively. It was discussed that the MTSN treatment proficiently disintegrated the unfolded SPI proteins, thereby causing more exposure of the bonds. The same result framework was acquired for readings regarding surface hydrophobicity with the OPS found to be 241.0 ± 0.7 and control 124.0 ± 0.4. The MTSN-initiated collapse of macromolecular protein aggregates or the repositioning of the hydrophobic groups formerly lodged in the protein networks to their outer surfaces were the exegeses offered for the protein hydrophobicity.

Gul et al. (2018) critically exploited ultrasonication for the homogenized preparation of a nanoemulsion films comprising of clove essential oil and hazelnut meal protein (3% v/v and 4%w/v respectively). The film forming nanoemulsions were prepared at a fixed power of 750 W and temperature of $25 \pm 2\,°C$ but with varying amplitudes of 0–100%, energy values of $0–70.13\,W/cm^2$ and sonication periods of 0–6 mins after which their characterization on zeta potential, polydispersity index (PDI) and droplet size of the nanoemulsions and the optical, physicochemical, mechanical, antioxidant and the antimicrobial properties of the nanofilms were evaluated in relation to the US parameters adopted in their preparations. US treatment conditions of 100% amplitude, $70.13\,W/cm^2$ and 6 mins were found to be optimal for most attributes analyzed. PDI, a measurement without dimension and droplet size were found to be remarkably decreased by US treatment relative to control samples prepared merely by shear homogenization; thus, signifying that US homogenization Is sufficient for preparing the nanoemulsion. The readings obtained for zeta potential however followed a different course. Though all samples showed negative zeta potentials, the control samples had larger magnitudes, thus suggesting that for a better emulsion stability, it might be considered. Albeit, ultrasonication was found to have a slight change impact on surface charge. This was attributed to the distribution of protein and oil droplet induced by the US waves, having the likelihood of promoting the adsorption of protein particles at oil/water interfaces and subsequently effecting a negative charge to circumambient the oil droplets which consequently deters additional aggregation or flocculation occurrences. Regarding the physicochemical attributes, the reduced droplet size was linked to the thickness and the increased hydrophobicity was related to the US-induced decrease in solubility; a desirable feature for its application as a packaging material. Ultrasonication was discussed to have denatured the proteins into a more stable network which could be the cause of the low solubility. With respect to optical properties, only lightness (L*) values were found to increase with US treatment. The redness (a*) values showed no correlation with US treatment irrespective of the processing amplitudes and duration while for the yellowness values (b*), US imparted only a slight decrease. Ultrasonication was found to progressive increase the transparency with the 50% amplitude and 2 mins (US-502) treatment found to be 0.119 ± 0.001 and 100% for 6 mins (US-1006), 0.226 ± 0.001. Nano-emulsification by ultrasound was found to remarkably increase the tested mechanical properties viz; elongation at break and tensile strength with US-502 and US-1006 found to possess $314.16 \pm 15.58\%$, $3.08 \pm 0.21\,MPa$ and $338.84 \pm 6.17\%$, $4.20 \pm 0.06\,MPa$ respectively. In terms of antioxidative and antimicrobial biofunctionalities, the acoustic energy released during sonication was considered to have increased the surface area of oil molecules, thereby enlarging the exposure of each microbe to them. Gram-positive bacteria were described to have their mitochondria and cell membranes adhered to the hydrophobic lipid molecules thus creating a destructive cytoplasmic leakage and escalated permeability of the cell membranes. In reference to US-improved antioxidative properties, the increased surface area of nano-films and decreased lipid particle sizes actuated by ultrasonication were inferred as the possible basis for such.

Ultrasonication in food microtechnology

Food microtechnology comprises of microscale components and methodologies incorporated to the food chain in its entirety, for the purpose of augmenting remarkable improvements in salient subjects such as; safety, health, analysis and traceability (Nazzaro, Fratianni, and Coppola 2012).

On the microscale, microencapsulation, proteomics, microextraction, microbiology and micronutrient profile improvement are typical aspects of application of ultrasound technology to food- based systems (Table 2). The non-thermal attribute in synergy with its reproducibility, energy optimization and simplicity of usage are inherent factors, making ultrasound superlative and choicer, relative to other food processing techniques (Shekar, Rajamma, and Shivallyboregowda 2018; Zhang, Zhu, and Sun 2018).

Microencapsulation is the enclosure of bioactive, minutely sized core materials (solids, liquids or gases) in micro-sized coatings primarily to protect the functionality of such materials (Gutiérrez and Álvarez 2017). There are two fundamental constituents of every food microcapsule: the core material and the wall material (or coating). The wall material, which must be biocompatible with the core material is added for purposes such as improved bioavailability and specific delivery, minimization of undesirable organoleptic attributes such as odors and flavors, and less cumbersome handling and storage (Bharathi, Moses, and Anandharamakrishnan 2018). Ultrasonication has been employed in numerous studies for the accomplishment of one or more of these objectives. Wang, Xia, and Li (2018) applied ultrasonication for the homogenization of the micro-encapsulated blend of duck oil diacylglycerol (core material) and sodium caseinate (wall material). Their study showed

Table 2. Microtechnological applications of ultrasound in food systems.

Food	US parameters	US functionality	Results	Other techniques and/or materials employed	References
Gum-arabic oil-in-water emulsion	20 kHz, 40%, 5 mins	Preparation of emulsion and antimicrobial effects of US treatment	Stable emulsion with zeta potential of -19.37 ± 0.06mV. Reduction of Minimum Inhibitory Concentration (MIC) against *B. cereus* and *E. coli*	Geranol and carvacrol. Confocal Laser Scanning Microscopy (CLSM). Transmission Electron Microscopy (TEM).	Syed and Sarkar 2018
Honey bee pollen	80 kHz, 1000 W, 20 °C, 1–16 h	Improved nutrient release	Fatty acids: Before treatment 12 present; After treatment 19 present Amino acids, crude fat, beta-carotene, Ca, Fe, Zn, Se all increased after treatment	High shear force, Transmission Electron Microscopy (TEM), Ion Mass Spectrometry.	Wu et al. 2018
Bacterial isolate from chicken	Thermosonication TSN: 40 kHz, 120 W, 4, 15 and 54 °C, 1–3 mins	Anti-bacterial effects	Destruction of *Camphylobacter jejuni*	Lactic acid, trisodum phosphate, sodium decanoate	Kassem et al. 2018
Squid ovary powder	20 ± 0.05 kHz, 750 W, 21.72–72.28%, 5.86–34.14 min, 25–30 °C	Effects on physico-chemical properties	(Untreated / Treated) Mean particle size (µm): 17.14 ± 1.4 / 6.1 ± 0.3 Solubility (%): 72.12 ± 0.4 / 66.12 ± 0.1 Surface hydrophobicity: 421.4 ± 9.7 / 585.36 ± 7.2 Total sulfhydryl groups: 428.8 ± 8.1 / 369.3 ± 1.1 Protein profile: No change in molecular weight Particle size dispersion: Significantly reduced Transition temperature: + Foam whipping time: + Foam rheology: Increase in viscoelastic properties		Singh, Benjakul, and Kijroongrojana 2018
Fermented mulberry juice	28 kHz, 60 W, 15 min	Improvement of antioxidant profile	Antioxidants (mg/100mL): Before / After Total phenolics: 934 / 1201 Total anthocyanin: 143 / 193 Total flavonoid: 441 / 534	Pulse light 1.213 J/cm^2 per pulse for 360 µs at 3 Hz	Kwaw et al. 2018
Pea starch	20 kHz, 600 W, 100%, pulse mode: 1 min on, 9 min off	Starch digestivity *in vitro*	Pullulanase enzyme activity: Unaffected by ultrasonication Linear gluten content: Increase Starch digestibility: Rapidly digested starch (RDS) –; Slowly DS +; Resistant starch +	Pullulanase enzyme 40 (npun/g). High Performance Size Exclusion Chromatography (HPSEC)	Lu et al. 2018
Skim milk	Double stage emulsification. 1st stage: 20 kHz, 10 W, 30%, 90 seconds. 2nd stage: 6 W, 20%	Preparation of a monodisperse emulsion	Emulsification with sunflower oil/PGPR/lecithin(30%*w/w*), 4% w/w NaCl as entrapment marker for an emulsion more stable to coalescence than HPH-prepared emulsion	High Pressure Homogenization (HPH). SEM.	Leong et al. 2018
Goose breast muscle meat	20 kHz, 215.6 W/cm^2, 20 mins, 4 °C, 2 s:on time, 3 s:off time	Meat tenderization	pH: + Myofibrillar Fragmentation Index (MFI): + Thermal properties Centre temperature: + Denaturation temp. of actin and myosin: – Microstructural gaps and cavities created between myofibrils and sarcomeres	SEM, Differential Scanning Calorimetry, SDS-PAGE, Atomic Force Microscopy	Zou et al. 2018
Water and food samples; Mushroom powder and lake superior fish tissue	1–5 mins in an ultrasonication bath	Disperse liquid-phase microextraction of cadmium	Improved analyte recovery at optimized US time of >3mins	Tetrahydrofuran (THF)-aided extraction	Zounr et al. 2018
Fresh apple juice	TMS: 20–25 kHz, 950 W, 20-80%, on: 3 s, off:3s, TMS: 37–52 °C	Retention of microbial, nutritional, and physicochemical quality attributes after a 15-day storage	Inactivation of microbial cells at 52 °C and 40 mins; Aerobic bacteria: reduced by2.38, 2.79 and 3.55 log cycles, Yeasts and Mold: 3.12 log cycle reduction	Electron Spin Resonance Spectroscopy. Use of the antimicrobial- Nisin	Liao et al. 2018
Golden carp skin *Probabus jullieni*	20 kHz, 20–80 kHz, 750 W, pulse: 5 s on, 5 s off, 10–30 min	Extraction of pepsin (PSC) and acid (ASC)soluble collagens	Increase in extract yield by 81.53% for ASC and 94.88% for PSC	Dialysis, Differential Scanning Calorimetry (DSC)	Ali, Kishimura, and Benjakul 2018
α-amylase preparation	20 kHz. 1st series: 0–35 W/mL, 60 sec, 30 ± 2 °C. 2nd series: 20–60 °C, 25 W/mL, 60 sec. 3rd series: 25 W/mL, 0–150 sec, 30 °C	Effects on the catalytic activity (CA) of α-amylase	1st series: 36% CA increase. 2nd series: Decrease from 124 ± 0.5 to 87 ± 0.3kU/mL. 3rd series: at 25W/mL, 30 °C and 75sec, highest activity of 47%.	SDS-PAGE	Tran, Nguyen, and Le 2018

Bacillus subtilis	TMS: 20 kHz, pH7.0, 6.67 W/mL and 60 °C, 13.3 W/mL and 70 °C, 20 W/mL and 80 °C, 10–40 mins	Destruction of bacterial spores	60 and 70 °C after 40 mins achieved 0.61 ± 0.06 log reduction					SEM, Flow cytometry	Fan et al. 2019
			Acoustic energy (W/mL)	Log reduction at 80 °C and 40 mins					
			6.67	1.84 ± 0.14					
			13.30	2.09 ± 0.1					
			20.00	2.43 ± 0.08					
			No significant change in the microstructure of spores						
Porcine myocardium	20 kHz, 750 W, 60 and 80%, 20 s/20 s pulse, 4 °C	Protein extraction	Novel procedure for protein extraction using salts such as sodium chloride, sodium phosphate (SP), sodium pyrophosphate (SPY)					SDS-PAGE	Kim et al. 2018
			Highest extraction yield of 91.5% *w/w* with 80 mins US and SPY						
Indian clove essential oil with gum arabic (GA) and/or maltodextrin	20 kHz, 240 W, 5 min	Emulsification and microencapsulation efficiency	Property	US; GA:MD at 50:50		Agitation 50:50		Spray drying. SEM	Teodoro et al. 2018
			Viscosity (mPa.s)	71.18 ± 0.49		60.34 ± 1.32			
			Spray-dried microparticle diameter(µm)	18.62 ± 0.15		17.39 ± 0.22			
			Microparticle hygroscopicity (g/100g)	17.18 ± 0.89		16.51 ± 1.22			
			Microparticle treatment efficiency (%)	83.82 ± 2.41		82.46 ± 3.18			
Esterified Krill oil	on: 30 s, off: 30s, total process time: 270s	Preparation of emulsion for microencapsulation		Microcapsule size				Stereomicroscopy	Kermasha et al. 2018
			pH	Homogenization-prep. emul. (µm)		US-prepared emul. (µm)			
			6.5	708 ± 16		457 ± 22			
			7.5	594 ± 10		417 ± 3			
			8.0	677 ± 12		408 ± 6			
Sweet orange essential oil	240 W, 1 min	Microencapsulation with a blend of gum arabic, maltodextrin and cellulose nanofibre	Droplet size of 3.8 ± 0.9µm					Microencapsulation by spray drying. SEM. Optical microscopy	De Souza et al. 2018
Geobacillus sp (G) and *A. flavithermus* (A)from milk processing plant	20 kHz, 8 W, 90%, 5 mins, pulse: 0.5–20 min, 85 °C	Microbial inactivation		Veg. cells (Log red.)		Spores (Log red.)		Sodium hydroxide and hydrogen peroxide. TEM	Palanisamy et al. 2019
				G	A	G	A		
			20 min	5.2	nil	1.5	nil		
			30 min	nil	1.6	nil	nil		
Bovine colostrum	37 kHz, 160 W, 20 min, 40 °C	Decontaminative reduction in microbial load and nutritional quality improvement		Initial	US + ferm.	US + vac.dry.		Fermentation (ferm.) and vacuum drying (vac. dry.)	Bartkiene et al. 2018
			Unsaturated F.A (%F.A)						
			Palmitoleic	1.3 ± 0.01	1.9 ± 0.01	1.9 ± 0.01			
			Oleic	25.1 ± 0.02	28.0 ± 0.2	28.3 ± 0.06			
			Saturated F.A (%F.A)						
			Butyric	2.4 ± 0.03	2.0 ± 0.04	1.9 ± 0.02			
			Caproic	1.5 ± 0.02	1.3 ± 0.04	1.2 ± 0.05			
			Caprylic	0.9 ± 0.01	0.7 ± 0.04	0.7 ± 0.04			
			Microbes (Log CFU/g)						
			LAB	8.32 ± 0.1	6.92 ± 0.13	6.30 ± 0.09			
			Spore formers	8.26 ± 0.07	7.01 ± 0.17	6.45 ± 0.04			
			Micronutrients (mg/kg of dry weight)						
			Chromium	0.05 ± 0.01	0.249 ± 0.02	0.121 ± 0.01			
			Manganese	0.124 ± 0.04	0.491 ± 0.03	0.491 ± 0.03			
			Iron	1.41 ± 0.4	9.838 ± 0.09	9.838 ± 0.09			
Listeria inocua suspension in water	10%, 100 W, pulse mode: on:1 s and off:10 s, <35 °C, 4 min	Microbial inactivation			N/N_O			High Pressure Processing (HPP) and Pulse Electric Field (PEF)	Pyatkovskyy et al. 2018
			US + 2 mins		>10\bar^1				
			US + HPP at 20 MPa		<10\bar^1				
			HPP at 400 MPa + US at 200 W		<10\bar^3				
Fresh and frozen semi-skimmed Sheep milk	20 kHz, 78 and 104 W, 4–6 mins, pulse: 4 sec	Microbial inactivation		Mesophilic bacteria	Total Coliform	*Lactobacilli*	*Streptococcus spp.*	High Temperature Short Time (HTST) pasteurization	Balthazar et al. 2018
			Raw	4.85 ± 0.06	4.60 ± 0.05	3.74 ± 0.01	3.25 ± 0.02		
			78 W, 8 min	n.d	n.d	2.00 ± 0.04	1.48 ± 0.15		
			104 W, 4 min	0.70 ± 0.09	n.d	1.49 ± 0.15	1.00 ± 0.04		
			104 W, 6 min	1.00 ± 0.04	n.d	n.d	n.d		
Heamatocarpus validus (Blood fruit)	20 kHz, 1500 W, 80%, 44 and 55 °C, 5 and 10 mins	Isolation of bioactive components, microbial quality and improvement of sensory attributes		Control	1.2 W/mL, 5 min, 44 °C	1.4 W/mL,5 min, 44 °C	1.4 W/mL,10 min, 55 °C	Juice extraction	Raju and Deka, 2018
			Total polyphenols (mg GAE/100 g)	478.21 ± 1.78	517.21 ± 1.11	484.21 ± 1.08	428.21 ± 1.06		
			Total flavonoids (mg QE/100 g)	398.80 ± 1.11	407.8 ± 1.68	381.80 ± 1.24	339.80 ± 1.05		
			Total anthocyanins (mg C3GE/100 g)	321.21 ± 1.1	397.21 ± 1.11	342.21 ± 1.90	292.21 ± 1.06		
			Lightness (L*),	29.14 ± 1.54	31.35 ± 1.58	34.87 ± 1.92	40.12 ± 1.32		
			Redness (a*)	69.67 ± 1.44	69.12 ± 1.38	66.98 ± 1.17	50.63 ± 1.62		
			Blueness (b*)	16.22 ± 1.08	16.12 ± 1.14	15.02 ± 1.13	12.43 ± 1.09		
			Yeast and Mold(log CFU/ml)	3.56 ± 0.51	3.48 ± 0.42	3.04 ± 0.22	n.d		
			Total bacteria count (log CFU/ml)	3.96 ± 0.36	3.76 ± 0.21	3.14 ± 0.20	n.d		
Coffee silverskin	20 kHz, 10 min, 20 or 100 % amplitude, 5 and 38 W/cm^2 intensity	Extraction of bioactive components	TPC yields obtained ranging from 95.80 ± 0.06 to 8.94 ± 0.01 mg GAE/g sample					UHPLC-MS/MS and SEM	Wen et al. 2019

+: increase; -:decrease; n.d: not determinded that an increase in the ultrasonication process time increased the overall microencapsulation efficiency with the optimal time and efficiency found to be 40 min and 92.4 ± 3.5% respectively. Yildiz, Ding, Andrade, et al. (2018) in a study involving the use of four different materials including sodium dodecyl sulfate (SDS), Tween 20, pea protein isolate and finally, a complex of pea protein isolate and modified starch (PPI-MS) for the microencapsulated emulsion of docosahexaenoic acid (DHA). A 60 seconds manothermosonication at 200 kPa and 50 °C was adopted for the production of soluble pea protein isolate (PPI) dispersions and a 5 mins, 20 kHz sonication was also used for complex formation between the protein isolate and modified starch. A core to wall ratio of 1:4 was achieved and subsequently ultrasonicated (5 mins, 20 kHz) to achieve a fine and homogenized mixture. Their results showed that of all preparations, the double-sonicated PPI-MS emulsion preparations had the highest encapsulation efficiency of 92.2 ± 4.0% in comparison with the unsonicated initial preparations for SDS: 84.1 ± 3.9% and tween20: 87.9 ± 2.2%.

Proteomics is the science involving the delineation of all proteinous elements in a biological entity in addition to their responses to environmental stimulus, spatial arrangement and the distinctions in their conditions between healthy and diseased entities (Lindon, Tranter, and Koppenaal 2016). In relation with food technology, proteomics is exploited as a tool for the establishment of comprehensible and rapid methodologies for procedural applications, the study of multiplex and immensely processed food systems and the measurement of analytes in trace amounts with profound selectivity (Gallardo, Ortea, and Carrera 2013; Kehinde and Sharma 2020). Considering the meticulousness and high degree of microbial immaculacy in this field, ultrasound is frequently utilized at different stages particularly for the preparation of sample(s). López-Pedrouso et al. (2019) conducted a study aimed at the overall evaluation of the upshot of mild ultrasound-aided thermal treatment on the proteomes of dry-cured ham slices. Their investigation involved examining the comparative effects of conventional heating in synergy with high power ultrasonication (25 kHz, 600 W) (CVUH) relative to the conventional heating (CVH) alone on the proteolytic breakdown of the concomitant meat proteins. Their results showed that actin, a myofibrillar protein was remarkably degraded by the CVUH treatment than that of the CVH. Their experimentation could be a rationale behind the employment of ultrasonication for meat tenderization purposes.

Wang, Xia, and Li (2018) in a quantitative proteomic analysis of proteins isolated from the food-borne intoxicant *Bacillus cereus* productively used a 20 kHz, 80 W ultrasonication procedure with on and off time of 10 and 15 seconds for extracting and quantifying proteins of germinated spores.

Mortierella alpine, the fungi commonly used for the production of arachidonic acid was examined on how nitrogen sources influence its aging process by Yu et al. (2018). In their proteomic analysis of Mycelia whole-cell, a 5-mins ultrasonication was carried out for the destruction of cells. Zhong et al. (2018) conducted a proteomic study on the growth-stimulating mechanism of stachyose on the probiotic: *Lactobacillus acidophilus*. Ultrasonication was used for the proficient extraction of crude enzymes in the course of their study.

The morphological and physiological changes initiated by ultrasonication on protein molecules has been of interest in recent years. β-Lactoglobulin (βLG) a substantial milk protein found in its whey portion has been a subject of several scientific investigations in relation to ultrasonication. Structural mutations such as its α-helix and β-sheet alterations, and its unfolding which affect the process of fibrillation (Stanic-Vucinic et al. 2012; Chandrapala et al. 2012). Protein fibrillation is the formation of linear protein clusters (technically referred to as amyloid fibrils) by incorrectly folded protein molecules; a process known to trigger health disorders like Creutzfeld-Jakob, Parkinson's and Alzheimer's diseases (Mahmoudi et al.; 2013). Food proteins are usually employed as models to understand the fibrillation process of proteins in general and ultrasonication is commonly employed in such studies (Jones et al. 2010). Zhao et al. (2018) applied ultrasonication at 20 kHz and 250 W power to regulate a thermally-induced fibrillation of β-Lactoglobulin (βLG). Their results showed that ultrasonication is effective in controlling fibril conformation and the predominant fibrillation kinetics of proteins, making it workable in the food and possibly biomedical fields. Stefanović et al. (2017) examined the structural and functional changes actuated by ultrasound treatment on egg white proteins (EWPs). Their approach involved the use of a high-intensity ultrasonication (HIU) of 40% amplitude and 20 ± 0.2 kHz frequency for a varying duration of 2–20 mins on EWPs and concurrently examine the change in their structures and functions along with their proteolytic vulnerability to the enzyme- alcalase. The prominent characteristics of EWPs responsible for their selection in food formulations; emulsification, foam formation and solubility were all found to increase following the ultrasonication treatment. The changes in conformation of proteins as such that hydrophilic portions of the amino acids were unfastened from within and directed at water molecules, thus initiating the rearrangement of those molecules and consequently improving the solubility of the EWPs. With respect to enzymatic susceptibility, their observation showed an initial increase and from 0 to 15 mins and a decrease from 20 mins. They attributed the increase to ultrasonication causing a complete or partial unfolding of the polypeptide chains of the EWP proteins. The latter decrease was attributed to a possible aggregation of protein molecules which created protective enclosures for internal bonds.

Microextraction is a separation technique entailing the inexhaustive extrication of relatively small quantities of a constituent from the parent analyte, with (liquid phase) or without (solid phase) the use of a solvent. This procedure is proficiently used in food analysis for the determination of the compositional framework and detection of poisonous contaminants and/or adulterants in food (Campone et al. 2019; Yilmez, 2018). Unlike conventional extraction techniques such as infusion, soxhlet and maceration which are known to be hazardous (fire outbreaks), time and energy consuming, less environmental-friendly, toxic, cost inefficient and poor yield in the long run due to minimal breakdown of food matrices, ultrasonication; by virtue of its cavitation mechanism defeats these short-comings and is thus an ideal option for microextraction operations involving food and pharmaceutical-based systems (Tiwari 2015). In several microextraction research studies, the conventional approach is to adopt ultrasonication in coaction with other analytical techniques such as spectrometry, chromatography and spectrophotometry amongst others for the qualitative evaluation of the extractants.

Altunay, Elik, and Gürkan (2018) conducted a study on the microextraction of the food toxicant, acrylamide from foods (white and brown bread) processed by thermal methods adopting an ultrasound-aided, ionic liquid-based technique in synergy with spectrophotometry. Varying ultrasonication conditions were examined including; power ranging from 100 to 300 W, time (1–5 mins) and temperature (room to 60 °C). The extraction efficiency (EE) was found to increase with increasing US power; a trend attributed to the favored interactions between π–π stacking and hydrogen bonds. The US time followed a similar course at the initial treatment period (1–5 mins) but later decreased, an observation related to the likelihood of periodical deterioration of the complex formed as the ultrasonication treatment persisted. The EE was found to shown no significant correlation with the treatment temperatures. Their study showed that US treatment favored mass transfer for the microextraction. Ghoraba, Aibaghi, and Soleymanpour (2018) performed a microextraction study using an ultrasound-supported liquid-liquid dispersion for the synchronous diagnosis of experimentally-incorporated pesticide residues: azinphos-ethyl and bendiocarb in water, tomato, orange juice and potato samples. A water bath ultrasonication at 50 W power and 28 kHz frequency at room temperature was used for the microextraction of the pesticide residues in the samples. At varying conditions of US treatment time (1–10 mins), maximum EE was obtained at 3 mins which was accredited to favor a larger surface contact between the extractant and the aqueous samples. Their study showed that US improved the microextraction process remarkably.

Yilmaz (2018) developed an innovative and novel green sample preparation technique for the solvent-free microextraction of arsenic from flour and rice samples entailing the integrative usage of ultrasonication and water-phased enzymatic hydrolysis. The enzyme α-amylase functioned as a disintegrator of biomolecular bonds of triglycerides, sugars and proteins whereas a 5 mins ultrasonication at 640 W power, 35 kHz frequency and 37 °C temperature effected the breakage of the food matrices thus allowing the release of the arsenic and subsequent detection by inductively coupled plasma mass spectrometry.

Yao et al. (2018) contrived an unconventional microextraction technique involving ultrasound-supported, surfactant-intensified emulsification by the usage of 1-butyl-3-methylimidazolium tetrachloroferrate (a magnetic and ionic liquid) conjoined with solid-phase microextraction for the detection of the toxicants – lead and cadmium in food-grade vegetable oils and a subsequent anatomization using GFAAS (graphite furnace atomic absorption spectrometry). Their study entailed the use of an ultrasonic bath at 100 W power and 40 kHz frequency for an optimized duration of 5 mins. Ultrasonication aided the recovery of lead and cadmium from about 60 to 90%.

The more prominent use of ultrasonication in food microbiology is for the cavitative destruction of spoilage and/or pathogenic microorganisms. Nonetheless, ultrasonication is also applicable in favor of the growth of desirable microorganisms particularly in food fermentation processes (Terefe, Buckow, and Versteeg 2015). By the optimal manipulation of ultrasonication parameters such as energy, power and/or frequency, the cavitative destruction of microorganisms can be supplanted with their monitoring or improved metabolism through mechanism(s) such as; actuation of enzymes, improved sonoporative material transfer across microbial cell membranes and revamping of microbial processes (Novoa-Díaz et al. 2014; Ojha, Mason, et al. 2017).

De Lima Alves et al. (2017) performed a research study on the outcome of ultrasound treatment on the growth of inherent microorganisms (*Micrococcaceae* and lactic acid bacteria) in the fermented porcine product, the Italian salami. Their procedure involved the batch sonication of the fermented meats at 20 kHz frequency, 500 W power, 20 °C temperature for 0–9 mins. Their results from microbial enumeration subsequent to 0, 2, 15 and 120 days of storage showed that US remarkably improved the growth of intrinsic bacteria in contrast to unsonicated samples, with the 9 mins treatment giving the maximum population. They ascribed the US-induced increase to possible mechanisms such as deagglomeration of the microbes causing an increased viability, disintegration of macromolecules with a resulting improvement in nutrient availability and a destruction of competing microbes.

Liu, Yang, et al. (2018) employed ultrasonication to induce biological stress on *Lactobacillus acidophilus* with a consequent response of intensified β-glucosidase efficacy in biotransmutating soymilk isoflavones into aglycones. At its stationary growth phase, the LAB was irradiated with a 20 kHz, 40 W for a 2 mins and 1 day of re-incubation, an induced stress causing its β-glucosidase activity to increase by a factor of 1.82. The sonicated bacteria were subsequently used for the fermentation of soymilk which effected an increase in the aglycones fraction of its composite isoflavone from 21.8 to 97.9% after a 24 h period. Using the FESEM (field emission scanning electron microscope) morphology scan, they explained that ultrasonication, at optimal parameters inflicted stress-induced injuries to the bacterial cells. In response to these, the bacteria released the much desired β-glucosidase fermentation enzyme for repair of its surface injuries, thus increasing its activity. Their study showed that the activity of concomitant enzymes of desirable microorganisms in food systems can be augmented by US treatment.

The reflective property of soundwaves (including ultrasound) is the fundamental mechanism for the use of ultrasonication in the measurement of growth, population or fermentation metabolism of microorganisms.

Elvira et al. (2016) employed the backscattered ultrasonic echoes generated by *Saccharomyces cerevisiae* cells to measure their concentration in yeast culture solution. At 50 kHz ultrasonic frequency used in their study, echoes generated were used to characterize single-celled yeast cells at populations ranging from 10^2 to 10^7 cells/ml.

Phong et al. (2018) employed the mechanical, cavitative disruption of ultrasound on the cell walls of the food and feed grade microalgae: *Chlorella vulgaris* and *Chlorella sorokiniana* for the extraction of protein. Their results showed that the synergistic use of an alkaline (Pottasium hydroxide) and ultrasonication at 37 kHz for 1200 seconds effected the maximum protein recovery of approximately 14–26% and 31–37% from the biomasses of *Chlorella vulgaris* and *Chlorella sorokiniana* respectively. They illustrated that the combination of uniform cellular disruption by the chemical solvents used and the mechanically generated cellular cavities by the ultrasonication could have culminated such outputs.

Michelino et al. (2018) integrated the usage of high power ultrasonication and pressurization by supercritical carbon dioxide (SCO) for the inactivation of yeast, mold and bacterial microbes in coriander along with the dehydration activity of the composite techniques. At a pressure of 10 MPa and temperature of 40 to 50 °C, a 40 kHz ultrasonication of varying power between 0 and 80 W was initiated and the moisture content and quantification of the yeast, molds, mesophilic bacteria and their spores before and after the treatments was evaluated to determine its microbial outcome. Their study showed that at an optimal synergistic condition of 10 MPa pressure, 40 °C and ultrasonication power of 40 W, yeast and molds were negligible (at a population less than 2 log CFU/g), mesophilic bacteria decreased to about 4 Log and their spores to about 1 Log. Furthermore, the moisture content and water activity were found to significantly reduce by the combined treatment relative to the singular SCO treatment

Liu, Lu, et al. (2018) conducted a study to investigate the bactericidal potency of ultrasound on *E. coli*, a food-borne pathogen of public health importance. An ultrasonication treatment at 24 kHz and pulse duty proportion at 0.5 ranging from 0 to 15 mins with whey protein isolate at concentrations varying from 0% to 10% was carried on a colony of E. coli cells. Their study showed an expected decrease in the survival rate of the pathogen due to US treatment, however, on incorporation with WPI, the antioxidative, hydrophobicity and viscosity attributes of the dairy ingredient increased with an increase in the survival rate of the pathogen. They opined that the increasing WPI concentration possibly inhibited the spread of the bactericidal US wave.

The efficacy of ultrasonication in preservation of food products also depends on the packaging and storage conditions succeeding the US treatment. Piñon et al. (2018) in a study on chicken breast meat, applied an HIU of 9.6 W/cm^{-2} intensity at 40 kHz for periods ranging from 0 to 50 minutes with vacuum and aerobic packaging conditions with a subsequent chilling storage for 7 days. Their investigation showed that a 50 minutes ultrasound treatment considerably decreased the population of *Salmonella spp.* and *Staphlococcus aureus* in the samples. Albeit, ulrasonication with vacuum packaging was discovered to increase the population of lactic acid bacteria and mesophiles while anaerobic packaging was found to decrease the growth of psychrophilic microbes.

Vacuum packaging combined with ultrasound increases mesophiles and lactic acid bacteria in chicken meat. Anaerobic package conditions reduce the growth of psychrophiles. Ultrasound treatment followed by aerobic storage has no effect on the growth of *E. coli.* 50 min ultrasound treatment decreases *S. aureus* and *Salmonella* spp.-positive samples. High-intensity ultrasound is effective in the control of the growth of pathogenic bacteria.

The mechanochemical alterations initiated by ultrasonication such as sponge and heating effects, acoustic streaming, cavitation and free radical formation consequentially facilitates mass transfer, microporosity, formation of chemical bonds, cell membrane disruption and permeability, and micronutrient absorption and adsorption in food materials (Yilmaz and Bilek 2018; Bonto, Camacho, and Camacho 2018). These changes are underlying mechanisms by which ultrasound waves effect micronutrient fortification of foods.

Yilmaz and Bilek (2018) developed a vacuum-ultrasound device with the functionality of generating and propagating US waves at vacuum and normal conditions. At a fixed frequency of 35 kHz and varying working powers of 96–198 W, fresh cut apples were fortified with phenolics from carrot and calcium at normal and vacuum conditions. Their experimentation revealed that at vacuum condition and power of 130 W, the cellular conformation of the apple cells was least ruptured and the maximum micronutrient impregnation were obtained with increases in total flavonoids, total phenolics, total anthocyanins and calcium contents by 17.3, 11.8, 24.6 and 13.8% respectively. The overall antioxidative potentialities was improved by 23.6%.

Hasanvand, Fathi, and Bassiri (2018) conducted a study on the ultrasound-assisted encapsulation of Vitamin D3 for its improved usage in food fortification. Probe ultrasonication at 24 kHz and 450 W for time durations of 5 and 10 mins for the encapsulation of the vitamin with potato starch. Their study showed that ultrasonication resulted in the formation of hydrogen and van der Waals bonds between the vitamin and the starch.

Macrotechnological applications of ultrasound

The macroscale implementation of ultrasound in food systems entails the physicochemical, nutritional, sensorial, mechanical and functional transformations imparted on them by the technique (Table 3). They are associated with the quality attributes consumers crave in their inspection of food products prior to their purchase and as such, food manufacturers place paramount attention and considerations on them.

Zhang et al. (2017) conducted a study on the modification effects on the physicochemical properties of myofibrillar protein gel subjected to high intensity ultrasound (HIU) treatment. The protein was isolated from chicken breast meat and its turbidity, solubility, particle size and zeta potential, surface hydrophobicity, and rheological characteristics were examined after ultrasonication at 20 kHz with

Table 3. Macroscale effects of ultrasonication in foods.

Food	US parameters	US functionality	Results					Other techniques and/or materials employed	References
Milk and Orange juice	40 and 60 W, 20 kHz, 30 and 60 mins, pH 7.4 and 4.0	Anti-microbial effects against E. coli effects on viscosity, pH, color and vitamin C		High power		Low power		Antimicrobial peptide Cercropin P1 at different concentrations	Fitriyanti and Narsimhan 2018
				Orange	Milk	Orange	Milk		
			Viscosity	–	–	–	–		
			L*	–	–	–	–		
			a*	–	–	+	–		
			b*	–	–	–	–		
			Protein	n.d	–	n.d	+		
			Vit. C	No effect	n.d	No effect	n.d		
			E. coli	–	–	–	–		
Sorghum kafirin and enzymatically digested sorghum gluten-like flour	0–20 ± 0.05 kHz, 40%, 10 mins	Improvement of physico-chemical properties	Kafirin	Improved extraction and anti-oxidative properties Improved solubility from 6.5 to 173.3 µg/mL				*In vitro* enzymatic digestion with pepsin and pancreatin. Fourier Transform Infrared Spectroscopy. Size exclusion chromatography	Sullivan, Pangloli, and Dia 2018
			Enzymatically-digested samples	DPPH scav.	ORAC	NOscav.(aft.10mins)	Protein content		
				+	+	+	+		
Germinated and dehulled red rice and brown rice	25 kHz, 16 W/L, 5 mins	Starch hydrolysis and improvement of functional properties		Red rice		Brown rice		Germination, Environmental Scanning Electron Microscopy (ESEM)	Ding et al. 2018
			Total starch content	Decrease by 4.01 mg/100 g; enhanced starch hydrolysis		No significant difference			
			Glucose content	Increased by 30.06 mg/100 g		Increased by 98.34 mg/100 g			
			Color (ΔE: average color difference)	Decrease		Increase			
			Viscosity properties (peak, trough and final)	Remarkable decrease		Less decrease			
Ginseng Berry extract	Ultrasonication for 10 h	Increase in the concentration of ginsenoside	Improved survival rate of liver-injured rats fed with ultrasound processed ginseng extract					HPLC. *In vivo* analysis	Nam et al. 2018
Cranberries	45 kHz, 150 W	Osmotic dehydration	Significant decrease in moisture content					Microwave vacuum. ESEM	Zielinska and Markowski 2018
Mandarin and orange juices	25 kHz, 700 W, 0.016 W/mL, 25 ± 4 °C and TSN: 55 ± 4 °C	Evualuation of ascorbic acid stability due to sonication treatments	Neither sonication or thermosonication treatments affected ascorbic acid content in fruit juices					Degassing of juices	Aguilar et al. 2017
Guava juice	20 kHz, 15 W/cm^2, 121 W/L, 3–9 mins, 25 °C	Impacts on it physical, structural and nutritive attributes			After US treatment			Optical microscopy	Campoli et al. 2018
			Serum cloudiness (at 660nm)		+				
			Pulp sedimentation index (%)		+				
			Lycopene content (µg/g)		–				
			Lycopene accesibility *in vitro (%)*		+				
			L*, a* and b*		Negligible effect				
Whey protein	20, 28 and 20/28 kHz, 250 W/L, 5–20 mins, Pulse: 10 sec on, 3 sec off.	Correlation between US frequency with the mechanical properties and microstructure			Mono: 20 kHz	Mono: 28 kHz	Duo: 20/28 kHz	Circular Dichroism (CD) spectrum analysis, Intrinsic fluorescence, Confocal laser scanning microscopy measurement (CLSM)	Cheng et al. 2019
			Storage modulus (MPa)		+	+	Varying		
			Hardness (N)		+	+	Varying		
			Water Holding Capacity (%)		+	+	+		
			α-Helix (%)		–	–	–		
			β-Sheet(%)		+	+	+		
			β-Turn (%)		+	+	+		
			Random coil (%)		+	+	+		
Beef (*Longissimus dorsi*) muscle	40 kHz, 11 W/cm^2, 60 min, 4 °C	Beef tenderization and its effects on the sensory and technological parameters			Control	14 days storage + US treatment		Texture profile analysis (TPA), SEM	Gonzalez et al. 2018
			pH		5.54	5.63			
			Chroma		20.93	21.84			
			Hue angle		32.02	36.66			
			Water Holding Capacity (%)		62.28	55.43			
			Shear force (N)		22.95	17.32			
			Hardness (N)		35.05 ± 2.10	27.61 ± 2.58			
			Cohesiveness		0.55 ± 0.06	0.50 ± 0.07			
			Sprigginess (mm)		0.49 ± 0.01	0.46 ± 0.02			
			Chewiness (N)		7.86 ± 0.72	6.68 ± 0.88			
			Fragmentability		0.05 ± 0.01	0.03 ± 0.01			
Extra Virgin Olive oil	20 kHz, 150 W/cm^2, 13.5 kJ/kg, 20 ± 1 °C	Qualitative and quantitative improvement			Air treatment	HPU + Air		Malaxation with oxygen	Iqdiam et al. 2019
			Oil Yield (%)		12.13 ± 0.02	13.34 ± 0.02			
			Oil Extractibility Index (%)		62.84 ± 0.1	69.11 ± 0.10			
			Free Fatty Acids (% oleic acid)		0.38 ± 0.01	0.39 ± 0.02			
			Peroxide Value (meq O_2/kg)		6.08 ± 0.03	6.11 ± 0.09			
			Bitterness (K-270nm)		0.13 ± 0.02	0.13 ± 0.01			
			Total polyphenols (mg/kg)		405 ± 4.32	403 ± 5.02			
			Total tocopherol (mg/kg)		321 ± 10.53	359 ± 15.51			
			Chlorophylls (mg/kg)		5.45 ± 0.51	7.12 ± 0.34			
			Carotenoids (mg/kg		5.73 ± 0.22	6.24 ± 0.33			

(*continued*)

Table 3. Continued.

Food	US parameters	US functionality	Results			Other techniques and/or materials employed	References
Giant squid (*Dosidicus gigas*)	20 kHz, 20%, 17 W, 0–3 mins, 0 − 3 °C	Impact on functional properties		Increasing US treatment time		Texture profile analysis	Hurtado et al. 2019
			Emulsifying activity index (m^2/g)	+			
			Emulsion stability index (min)	+			
			Foam stability (%)	No difference			
			Foaming capacity (%)	+			
				At 3 mins US			
			WHC (g H_2O/g protein)	+			
			Gel strength (N × cm/g protein)	+			
			Hardness (N/g protein)	+			
			Elasticity	+			
			Cohesiveness	+			
Salad dressing with lecithin (LT) emulsifier	80 W ultrasonic bath, 1 min	Impact on emulsion stability		In-pack sonication	Scaled-up homogenization	Dynamic and multiple light scattering analyses	Gavahian et al. 2018
			Viscosity (Pa.s)	0.0042 ± 0.0002,	0.0042 ± 0.0004		
			Span (μm)	1.42 ± 0.45	2.08 ± 0.01		

+: Increase; −: decrease; WHC: water holding capacity; DPPH: 2,2-diphenyl-1-picrylhydrazyl; ORAC: Oxygen Radical Absorbance Capacity

power ranging from 200 to 1000 W for 15 minutes with a pulse period of 5 seconds on and 1 second off. The particle size was found to reduce with increasing power with the 0 and 1000 W treatments having average readings of 2084.57 and 271.27 nm, respectively. All zeta potential results were found to be negative implying a lesser coagulation tendency and size uniformity. Turbidity readings followed an expected, similar trend changing from 0.234 to 0.121 for 0 and 1000 W preparations, respectively. These result orientations were discussed to arise from the immensely energetic ultrasonic waves imparting shear forces on the protein particles and resulting in their agitated rupturing. These also could be the rationale behind the increased surface hydrophobicity and solubility readings which were found to increase from about 22.5% to 88.5%, respectively.

Cheng et al. (2019) also researched on the influence of ultrasound on protein gels but from whey as the base material. Their study involved the comparison of two single and one simultaneous, double-frequency ultrasound treatment on the mechanical properties of whey protein gel. Single frequencies of 20 and 28 kHz and a double-frequency of 20/28 kHz frequency, at a power density of 250 W/L for 5–20 mins treatment time and pulse duration of 10 and 3 s for on and off modes. Their experimentation showed that the double treatment conferred more changes to the water-holding capacity, rheology and hardness of the protein gel owing to its propagation of a larger bubble temperature and shear force adequate in instigating structural changes in the protein gel more efficiently relative to the single frequency treatments.

Bevilacqua et al. (2019) performed an advanced microbiological study on the ultrasonic attenuation of the probiotics: *Acidipropionibacterium jensenii* and *Propionibacterium freudenreichii* and its denouement on their hydrophobicity and biofilm stability. A low power ultrasound of 40 and 60% net power, 2 s pulse and treatment duration of 4–8 mins. The biofilm stability of the probiotic propionibacteria as estimated by the population of the immobile, sessile cells 7 days subsequent to ultrasonication was found to be 5.53 log cfu/cm^2 and 2.62 log cfu/cm^2 for the control of *Acidipropionibacterium jensenii* and for the *Propionibacterium freudenreichii*, 4.11 log cfu/cm^2 for sonicated and 3.02 log cfu/cm^2 for control. The elucidation for the results were the possible influence of ultrasound in elevated metabolism with a consequent surface adhesion, improved nutrient translocation and enhanced auto-aggregation. The change in biofilm stability sequentially marked up the hydrophobicity of the probiotics with the *A. jensenii* increasing from 17.03 to 32.11% and the *P. freudenreichii*, 15.45 to 27.12%.

Hurtado et al. (2019) examined the modification of the functional characteristics of the protein concentrate obtained from giant squid mantle by ultrasonication process time. A 20 kHz and 17 W ultrasound was employed for 0–90 seconds for emulsion stability index (ESI), foam stability and foaming capacity and 0–3 mins for gelling properties. The steadfastness of the emulsion as shown by the ESI values were found to markedly increase for 90 s ultrasonication, an outcome attributed to the US-induced favorable orientation of the protein. The foaming capacity followed a similar course but with less increase, while the foam stability was found to be independent of the US treatment time. Gelation properties such as water holding capacity (WHC) and texture were examined. A 3 mins US treatment showed the highest WHC which was linked to the fractional unfolding of the protein and a better exposure of the polar amino acid to water. Textural properties such as gel hardness, strength, cohesiveness and elasticity were all found to increase by 10, 32, 108 and 27% respectively. These augmentations were copulated with improved cross-linkages in the protein network, eventuating in more elastic, cohesive and harder gels.

Ultrasonication treatment of foods can alter the sensorial properties of such foods through mechanisms such as: initiation of certain biochemical reactions and disruption of food cells and release of sensory-changing constituents, (Aguilar et al. 2017). There is no fixed trend for sensory parameters of foods with regards to ultrasound treatments as different foods have shown different courses in terms of color, taste and consistency in several studies, all of which have been affiliated to the inherent constituents of each food.

Campoli et al. (2018) examined the color of guava juice subsequent to its treatment with a 20 kHz and 1000 W ultrasound for 0 to 9 min and storage for 14 days at 25 °C. They reported that though the sonication increased the lycopene content of the juice, it had no significant values on the color parameters, as sonicated and control samples showed little variations. Kwaw et al. (2018), in a study regarding the effects of ultrasonication on the sensorial properties of fermented mulberry juice reported incongruous findings. In their study, two different US frequencies viz 22 and 24 kHz were adopted and two different process times (10 and 20 mins) for each frequency. Their research showed that the hunter L* and b* values decreased with increasing sonication parameters. They opined that the increase in the total anthocyanin content instigated by the ultrasonication procedure decreased the luminosity of the juice, thereby reflecting in the lower readings obtained.

Han, Chung, and Lim (2019) inspected the significance of ultrasonicated preparation on the sensorial properties of mayonnaise containing octenylsuccinylated corn starch and octenylsuccinylated dextrin (OSA). At US conditions of 135 W power, 42 kHz frequency and treatment period of 1 h, the texture, oily taste, flavor and color were examined after 50 (OSCS-50) and 70 (OSA-70) mins sonication relative to unsonicated OSCS samples. Their readings showed a higher acceptability preference for OSA − 50 and 70 than OSA, precisely 5.15 ± 0.11, 5.57 ± 0.15 and 4.37 ± 0.33 respectively. A similar course followed for all sensory parameters, howbeit, for flavor and texture, the 70 mins treatment had higher values than OSA − 50 and the opposite for color and oily taste. The impactful dissolution of degraded or partially gelatinized molecules by US treatment was a probable reason for the results obtained.

Iqdiam et al. (2019) analyzed the improvement associated with high power ultrasonication in synergy with malaxative oxygen control on the sensorial constitution of extra virgin olive oil. The combination of high-power ultrasound (13.5 kJ kg^{-1}, 20 kHz and 150 W) with oxygen at 2, 5, 10% concentrations was tested and the overall acceptability, pungency, bitterness, greenness and ripeness were subjectively examined by experienced panelists. The outcome of the experimentation showed that the ultrasonication had no appreciable correlation with the sensorial attributes. The outcome of the sensory tests, especially for the overall acceptance, pungency and bitterness readings, were rather associated with the change in oxygen headspace concentration during malaxation which could have initiated an accruement in the total polyphenolic components like o-diphenols and the derivatives of ligstroside and oleuropein.

Gonzalez et al. (2018) productively applied ultrasonication at high intensity for the tenderization of stored beef meat and studied its technological and sensorial characteristics. HIU with values of 11 W/cm^2 and 40 kHz were used on vacuum packed *Longissimus dorsi* beef muscles already stored at 4 C for different durations of 0, 7 and 14 days. HIU was found to have a desirable, increasing impact on the pH values with 0.05 units more than the control beef samples. They explained that the HIU cavitation effect could have induced the disengagement of deaminases and proteolytic enzymes which eventually decreased the acidic protein groups or possibly as a result of HIU-induced ionic release from cellular organelles to the cytoplasm thus causing alterations in the location of ionic performances. Storage duration, not ultrasonication, was observed to affect the water holding capacity of the beef samples. For color attributes, lightness and hue angle were found to increase with the HIU treatment, redness and chroma decreased while yellowness was unaffected. For the subjective color tests, sonicated samples were reported as being more pinkish. With regards to texture profile analysis, sonicated samples showed lower hardness and fragmentablility. HIU was disserted to induce macromolecular mutations possibly in the enzymes and causing them to be more proficient in their reactions that affect cellular integrity. Other textural qualities such as chewiness, adhesiveness, cohesiveness and springiness were found to be independent of ultrasonication. Subjective analyses showed that the HIU treatment imparted an intense beefy flavor on the samples irrespective of the storage duration. These outputs were allied to complex chemical and metabolic reactions altered by the HIU-aided release of enzyme from cellular components.

Limitations to the use of ultrasonic treatment in food processing

Ultrasonication has its numerous benefits in food processing as already discussed. However, certain constraints regarding ultrasonication equipment and foods processed are potential rationales behind the difficulty in its conventional adoption on the industrial scale (Figure 3).

Regarding food materials processed with ultrasonication, the detriments of undesirable alterations to food nutrients and the improper inactivation of unwanted enzymes and microorganisms are prominent disadvantages. The sonochemical cavitations propagated by ultrasound generates free radicals which have been found to induce the catalysis of

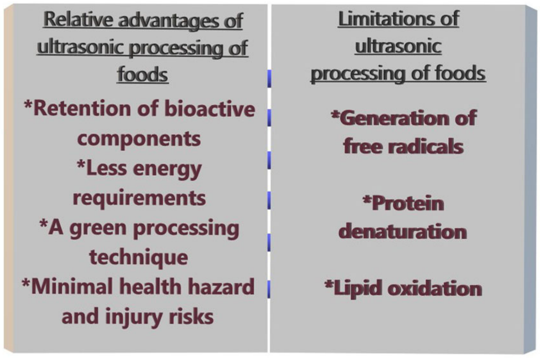

Figure 3. Advantages and limitations of ultrasonic processing relative to conventional techniques.

unsought reactions responsible for the damage of amino acids, proteins and fats and possibly lead to the syntheses of new polymers that negatively alter the texture of the final product and depreciate its value (Arvanitoyannis, Kotsanopoulos, and Savva 2017). A substantial example is in the appropriation of ultrasound for the homogenization and/or emulsification of milk with an undesired but resulting lipid oxidation and protein denaturation (Bhandari and Zisu 2016). An efficient panacea to these issues will include an adequate planning of the ultrasonication treatment through an efficient optimization of all process parameters (Arvanitoyannis, Kotsanopoulos, and Savva 2017). Conditions of sonication frequency, duration, temperature and pressure as applicable should be optimally selected for desired outputs.

Ultrasonic equipment also bears the concern of the overall scalability and costs, with the notable ones associated with purchase and energy of utilization. The scalability has been related to the transducer section of the ultrasound system due to its relationship with power conversion and it implies the peak power for each transducer (Patist and Bates 2008). The commonly used transducers in ultrasound systems are the piezoelectric and the magnetostrictive transducers: the piezoelectric converts electric charges into ultrasonic forms while the magnetostrictive converts magnetic fields to ultrasonic modes. The piezoelectric types are preferred commercially due to their better scalability. Though the ultrasound has no moving parts which would imply lower maintenance costs, the use of high-power ultrasound for example for continuous industrial scale processes as substitute for energy-intensive operations such as milling and homogenization would require its inherent costs. For a range of operations such as defoaming, emulsification, extrusion, extraction and waste treatment processes, investment costs could range from over 100,000 to over 600,000 US Dollars yearly (Patist and Bates 2008). The design and fabrication of ultrasound equipment that require relatively lower amount of energy and from affordable materials would doubtlessly prove effective to these concerns.

Furthermore, the subject of ultrasound-induced corrosion is of uttermost concern especially in the food industry where corrosion-prone metals are used for the fabrication of various plant and equipment components as pipes, casings etc. Though ultrasonication is more prominently used for inspection of corrosion, its aftermath in inducing corrosion is a potential limitation to its usage. Ultrasonication-related occurrences such as mass transportation and acoustic cavitation which are potential in inducing interfacial electrochemical reactions on metal surfaces with their subsequent corrosion. Proper consideration should be given to parameters such as ultrasound power, area of the probe tip and distance between the probe and the metal surface (Morais and Brett 2002). Conversely, ultrasound can be used for the green syntheses of anti-corrosion compounds such as pyrazolo[3,4-b] pyridines, calcium zinc phosphate pigment and magnesium zinc molybdate which can be applied as coatings (Verma, Quraishic and Ebensoa, 2018). Nonetheless, a proactive approach would be to use ultrasound for early detection of corrosions and implement necessary maintenance operations.

Concluding notes and future anticipations

The reality of achieving an environment with its natural profile conserved lies in the effective will and decisions of stakeholders (industrial and individuals alike) globally to adopt principles and procedures in this regard. Moreover, industrial food brands with targets beyond the scopes of profit acquisition but improvement of global nutrient supply must deem it fit to embrace processing methodologies of lesser detrimental effects to the bioactive composition of foods processed.

Ultrasonication offers the synergistic balance of meeting both needs. In addition to its superlative advantages of being cost effective with regards to industrial floor spacing, investment and running costs, it causes no harm to the environment, has no remarkably-known deleterious effect(s) on human health and poses less risk of injury to lives.

In all scales of food processing viz nanotechnological, microtechnological and macrotechnological, ultrasonication has proven to be suitable or even more efficacious relative to the conventional processing methods used in these regards. As an emerging technology, it can be used in solitude or as a composite with other techniques for the actualization of food processing objectives. In subsequent times, it promises to be a unit operation used conventionally for basic and crucial food handling and processing procedures. Industrially, ultrasonication could be potentially applicable from raw material reception to processing, quality checks, packaging and final product distribution through innovative means. The proper synergism between scientific experimentations and industrialization of ultrasound treatment for food and other applicable fields would irrefutably benefit all parties and conserve the earth's environment.

References

Abral, H., V. Lawrensius, D. Handayani, and E. Sugiarti. 2018. Preparation of nano-sized particles from bacterial cellulose using ultrasonication and their characterization. *Carbohydrate Polymers* 191:161–7. doi: 10.1016/j.carbpol.2018.03.026.

Adhikari, B. M., V. P. Tung, T. Truong, N. Bansal, and B. Bhandari. 2019. Impact of in-situ CO_2 nano-bubbles generation on freezing parameters of selected liquid foods. *Food Biophysics* 15:97–112. doi: 10.1007/s11483-019-09604-z.

Aditya, N. P., and S. Ko. 2015. Solid lipid nanoparticles (SLNs): delivery N.P. Aditya, S. Ko, Solid lipid nanoparticles (SLNs): Delivery vehicles for food bioactives. *RSC Advances* 5 (39):30902–11. doi: 10.1039/C4RA17127F.

Aguilar, K., A. Garvín, A. Ibarz, and P. E. D. Augusto. 2017. Ascorbic acid stability in fruit juices during thermosonication. *Ultrasonics Sonochemistry* 37:375–81. doi: 10.1016/j.ultsonch.2017.01.029.

Ali, A. M. M., H. Kishimura, and S. Benjakul. 2018. Extraction efficiency and characteristics of acid and pepsin soluble collagens from the skin of golden carp (*Probarbus jullieni*) as affected by ultrasonication. *Process Biochemistry* 66:237–44. doi: 10.1016/j.procbio.2018.01.003.

Altunay, N., A. Elik, and R. Gürkan. 2018. Extraction and reliable determination of acrylamide from thermally processed foods using ionic liquid-based ultrasound-assisted selective microextraction combined with spectrophotometry. *Food Additives & Contaminants: Part A* 35 (2):222–32. doi: 10.1080/19440049.2017.1394585.

Amirante, R., and M. L. Clodoveo. 2017. Developments in the design and construction of continuous full-scale ultrasonic devices for the EVOO industry. *European Journal of Lipid Science and Technology* 119 (6):1600438. doi: 10.1002/ejlt.201600438.

Appis, A. W., M. J. Tracy, and S. B. Feinstein. 2015. Update on the safety and efficacy of commercial ultrasound contrast agents in cardiac applications. *Echo Research and Practice* 22:R55–62. https://dx.doi.org/10.1530%2FERP-15-0018. doi: 10.1530/ERP-15-0018.

Arvanitoyannis, I. S., K. V. Kotsanopoulos, and A. G. Savva. 2017. Use of ultrasounds in the food industry—methods and effects on quality, safety and organoleptic characteristics of foods: A review. *Critical Reviews in Food Science and Nutrition* 57 (1):109–28. doi: 10.1080/10408398.2013.860514.

Babazadeh, A., B. Ghanbarzadeh, and H. Hamishehkar. 2016. Novel nanostructured lipid carriers as a promising food grade delivery system for rutin. *Journal of Functional Foods* 26:167–75. doi: 10.1016/j.jff.2016.07.017.

Balthazar, C. F., A. Santillo, J. T. Guimarães, V. Bevilacqua, M. R. Corbo, M. Caroprese, R. Marino, E. A. Esmerino, M. C. Silva, R. S. L. Raices, et al. 2018. Ultrasound processing of fresh and frozen semi-skimmed sheep milk and its effects on microbiological and physical-chemical quality. *Ultrasonics Sonochemistry* 51:241–48. doi: 10.1016/j.ultsonch.2018.10.017.

Bartkiene, E., V. Bartkevics, L. E. Ikkere, I. Pugajeva, P. Zavistanaviciute, V. Lele, M. Ruzauskas, J. Bernatoniene, V. Jakstas, D. Klupsaite, et al. 2018. The effects of ultrasonication, fermentation with *Lactobacillus sp.*, and dehydration on the chemical composition and microbial contamination of bovine colostrum. *Journal of Dairy Science* 101 (8):6787–98. doi: 10.3168/jds.2018-14692.

Bellary, A. N., and N. K. Rastogi. 2015. Ways and means for the infusion of bioactive constituents in solid foods. *Critical Reviews in Food Science and Nutrition* 51:705–22. doi: 10.1080/10408398.2012.757545.

Bevilacqua, A., A. Racioppo, M. Sinigaglia, B. Speranza, D. Campaniello, and M. R. Corbo. 2019. A low-power ultrasound attenuation improves the stability of biofilm and hydrophobicity of *Propionibacterium freudenreichii subsp. freudenreichii* DSM 20271 and *Acidipropionibacterium jensenii* DSM 20535. *Food Microbiology* 78:104–9. doi: 10.1016/j.fm.2018.10.010.

Bharathi, V. S. K., J. A. Moses, and C. Anandharamakrishnan. 2018. Nano and microencapsulation using food grade polymers. In: *Polymers for Food Applications*. Singapore: Springer. doi: 10.1007/978-3-319-94625-2_14.

Bhandari, B., and B. Zisu. 2016. Effect of ultrasound treatment on the evolution of solubility of milk protein concentrate powder. In *Handbook of ultrasonics and sonochemistry*. Singapore: Springer. doi: 10.1007/978-981-287-278-4_70.

Biswas, M. C., B. J. Tiimob, W. Abdela, S. Jeelani, and V. K. Rangari. 2019. Nano silica-carbon-silver ternary hybrid induced antimicrobial composite films for food packaging application. *Food Packaging and Shelf Life* 19:104–13. doi: 10.1016/j.fpsl.2018.12.003.

Bochicchio, S., A. A. Barba, G. Grassi, and G. Lamberti. 2016. Vitamin delivery: Carriers based on nanoliposomes produced via ultrasonic irradiation. *LWT - Food Science and Technology* 69:9–16. doi: 10.1016/j.lwt.2016.01.025.

Bonto, A. P., K. S. I. Camacho, and D. H. Camacho. 2018. Increased vitamin B5 uptake capacity of ultrasonic treated milled rice: A new method for rice fortification. *LWT - Food Science and Technology* 95:32–9. doi: 10.1016/j.lwt.2018.04.062.

Campoli, S. S., M. L. Rojas, J. E. P. G. do Amaral, S. G. Canniatti-Brazaca, and P. E. D. Augusto. 2018. Ultrasound processing of guava juice: Effect on structure, physical properties and lycopene *in vitro* accessibility. *Food Chemistry* 268:594–601. doi: 10.1016/j.foodchem.2018.06.127.

Campone, L., R. Celano, A. L. Piccinelli, I. Pagano, N. Cicero, R. D. Sanzo, S. Carabetta, M. Russo, and L. Rastrelli. 2019. Ultrasound assisted dispersive liquid-liquid microextraction for fast and accurate analysis of chloramphenicol in honey. *Food Research International* 115:572–9. doi: 10.1016/j.foodres.2018.09.006.

Castro, L., and F. P. Capote. 2007. Ultrasound assistance to heterogeneous systems. In: *Analytical Applications of Ultrasound*. Netherlands: Elsevier.

Çelik, D. A., M. A. Amer, D. F. Novoa-Díaz, J. A. Chávez, A. Turó, M. J. García-Hernández, and J. Salazar. 2018. Design and implementation of an ultrasonic sensor for rapid monitoring of industrial malolactic fermentation of wines. *Instrumentation Science & Technology* 46 (4):387–407. doi: 10.1080/10739149.2017.1394878.

Chandrapala, J., B. Zisu, S. Kentish, and M. Ashokkumar. 2012. The effects of high-intensity ultrasound on the structural and functional properties of α-Lactalbumin, β-Lactoglobulin and their mixtures. *Food Research International* 482:940–3. doi: 10.1016/j.foodres.2012.02.021.

Chemat, F., Z. Huma, and M. K. Khan. 2011. Applications of ultrasound in food technology: Processing, preservation and extraction. *Ultrasonics Sonochemistry* 18:813–35. doi: 10.1016/j.ultsonch.2010.11.023.

Chemat, F., N. Rombaut, A. Meullemiestre, M. Turk, S. Perino, A. S. Fabiano-Tixier, and M. Abert-Vian. 2017. Review of green food processing techniques. Preservation, transformation, and extraction. *Innovative Food Science & Emerging Technologies* 41:357–77. doi: 10.1016/j.ifset.2017.04.016.

Cheng, Y., P. O. Donkor, X. Ren, J. Wu, K. Agyemang, I. Ayim, and H. Ma. 2019. Effect of ultrasound pretreatment with mono-frequency and simultaneous dual frequency on the mechanical properties and microstructure of whey protein emulsion gels. *Food Hydrocolloids.* 89:434–42. doi: 10.1016/j.foodhyd.2018.11.007.

Dasgupta, N., and S. Ranjan. 2018. Nanotechnology in Food Sector. In: *An introduction to food grade nanoemulsions. Environmental chemistry for a sustainable world*. Singapore: Springer. doi: 10.1007/978-981-10-6986-4_1D.

Jhala, D., H. Rather, and R. Vasita. 2018. Nano-delivery of food-derived biomolecules: An overview. functional food and human health. In *Functional food and human health*, eds. V. Rani and U. Yadav, 447–470. Singapore: Springer. doi: 10.1007/978-981-13-1123-9_20.

De Lima Alves, L., M. Stefanello da Silva, D. R. Martins Flores, D. Rodrigues Athayde, A. Roggia Ruviaro, D. da Silva Brum, V. Sabrina, F. Batista, R. O. Mello, C. R. de Menezes, et al. 2018. Effect of ultrasound on the physicochemical and microbiological characteristics of Italian salami. *Food Research International* 106:363–73. doi: 10.1016/j.foodres.2017.12.074.

De Souza, H. J. B., R. V. Fernandes, S. V. de Borges, P. H. C. Felix, L. C. Viana, A. M. T. Lago, and D. A. Botrel. 2018. Utility of blended polymeric formulations containing cellulose nanofibrils for encapsulation and controlled release of sweet orange essential oil. *Food and Bioprocess Technology* 11 (6):1188–98. doi: 10.1007/s11947-018-2082-9.

Ding, J., G. G. Hou, M. Dong, S. Xiong, S. Zhao, and H. Feng. 2018. Physicochemical properties of germinated dehulled rice flour and energy requirement in germination as affected by ultrasound treatment. *Ultrasonics Sonochemistry* 41:484–91. doi: 10.1016/j.ultsonch.2017.10.010.

Dong, W., G. Stomackin, X. Lin, G. K. Martin, and T. T. Jung. 2019. Distortion product otoacoustic emissions: Sensitive measures of tympanic -membrane perforation and healing processes in a gerbil model. *Hearing Research* 378:3–12. doi: 10.1016/j.heares.2019.01.015.

Elvira, L., P. Vera, F. J. Cañadas, S. K. Shukla, and F. Montero. 2016. Concentration measurement of yeast suspensions using high frequency ultrasound backscattering. *Ultrasonics* 64:151–61. doi: 10.1016/j.ultras.2015.08.009.

EPA. 2017. Basics of green Chemistry. Accessed October 15. 2019. https://www.epa.gov/greenchemistry/basics-green-chemistry.

Ercan, S. S., and C. Soysal. 2013. Use of ultrasound in food preservation. *Natural Science* 05 (08):5–13. doi: 10.4236/ns.2013.58A2002.

Fan, L., F. Hou, A. I. Muhammad, L. V. Ruiling, R. B. Watharkar, M. Guo, T. Ding, and D. Liu. 2019. Synergistic inactivation and mechanism of thermal and ultrasound treatments against *Bacillus subtilis* spores. *Food Research International* 116:1094–102. doi: 10.1016/j.foodres.2018.09.052.

Fitriyanti, M., and G. Narsimhan. 2018. Synergistic effect of low power ultrasonication on antimicrobial activity of cecropin P1 against *E. coli* in food systems. *LWT - Food Science and Technology* 96:175–81. doi: 10.1016/j.lwt.2018.05.016.

Gallardo, J. M., I. Ortea, and M. Carrera. 2013. Proteomics and its applications for food authentication and food-technology research. *TrAC Trends in Analytical Chemistry* 52:135–41. doi: 10.1016/j.trac.2013.05.019.

Gavahian, M., R. Farhoosh, K. Javidnia, F. Shahidi, M. T. Golmakani, and A. Farahnaky. 2017. Effects of electrolyte concentration and ultrasound pretreatment on ohmic-assisted hydrodistillation of essential oils from *Mentha piperita L. International Journal of Food Engineering* 13 (10):10. doi: 10.1515/ijfe-2017-0010.

Gavahian, M., S. Sastry, and A. Farahnaky. 2020. Ohmic heating as a promising technique for extraction of herbal essential oils: Understanding mechanisms, recent findings, and associated challenges. *Advanced Food and Nutrition Research* 91:227–73. doi: 10.1016/bs.afnr.2019.09.001..

Gavahian, M., Y. M. Chen, A. M. Khaneghah, F. J. Barba, and B. B. Yang. 2018. In-pack sonication technique for edible emulsions: Understanding the impact of acacia gum and lecithin emulsifiers and ultrasound homogenization on salad dressing emulsions stability. *Food Hydrocolloids* 83:79–87. doi: 10.1016/j.foodhyd.2018.04.039.

Gavahian, M., Y. H. Chu, and A. Farahnaky. 2019. Effects of ohmic and microwave cooking on textural softening and physical properties of rice. *Journal of Food Engineering* 243:114–24. doi: 10.1016/j.jfoodeng.2018.09.010.

Ghanbarzadeh, B., A. Babazadeh, and H. Hamishehkar. 2016. Nano-phytosome as a potential food-grade delivery system. *Food Bioscience* 15:126–35. doi: 10.1016/j.fbio.2016.07.006.

Ghoraba, Z., B. Aibaghi, and A. Soleymanpour. 2018. Ultrasound-assisted dispersive liquid-liquid microextraction followed by ion mobility spectrometry for the simultaneous determination of bendiocarb and azinphos-ethyl in water, soil, food and beverage samples. *Ecotoxicology and Environmental Safety* 165:459–66. doi: 10.1016/j.ecoenv.2018.09.021.

Ghosh, S. 2017. Thermosonication as an upcoming technology in the dairy industry: An overview. *Journal of Advanced Dairy Research* 5 (3):189–91. doi: 10.4172/2329-888X.1000189.

Gonzalez, P. E., A. D. Alarcon-Rojo, I. Garcia-Galicia, L. Carrillo-Lopez, and M. Huerta-Jimenez. 2018. Ultrasound as a potential process to tenderize beef: Sensory and technological parameters. *Ultrasonics Sonochemistry* 53:131–41. doi: 10.1016/j.ultsonch.2018.12.045.

Gul, O., F. T. Saricaoglu, A. Besir, I. Atalar, and F. Yazici. 2018. Effect of ultrasound treatment on the properties of nano-emulsion films obtained from hazelnut meal protein and clove essential oil. *Ultrasonics Sonochemistry* 41:466–74. doi: 10.1016/j.ultsonch.2017.10.011.

Gutiérrez, T. J., and K. Álvarez. 2017. Biopolymers as microencapsulation materials in the food industry. In *Advances in physicochemical properties of biopolymers: part 2*, eds. M. Masuelli and D. Renard, 296–322. Sharjah, UAE: Bentham Science Publishers. doi: 10.2174/9781681085449117010009. EE.UU. ISBN: 978-1-68108-545-6. eISBN: 978-1-68108-544-9

Hadian, Z., M. A. Sahari, H. R. Moghimi, and M. Barzegar. 2014. Formulation, characterization and optimization of liposomes containing eicosapentaenoic and docosahexaenoic acids; a methodology approach. *Iranian Journal of Pharmaceutical Research* 132:393–404.

Han, J. A., H. J. Chung, and S. T. Lim. 2019. Physical and emulsifying properties of OSA-corn dextrin with various manufacturing methods. *Food Hydrocolloids* 89:563–9. doi: 10.1016/j.foodhyd.2018.11.014.

Hasanvand, E., M. Fathi, and A. Bassiri. 2018. Production and characterization of vitamin D3 loaded starch nanoparticles: Effect of amylose to amylopectin ratio and sonication parameters. *Journal of Food Science and Technology* 55 (4):1314–24. doi: 10.1007/s13197-018-3042-0.

Hoseinnejad, M., S. M. Jafari, and I. Katouzian. 2017. Inorganic and metal nanoparticles and their antimicrobial activity in food packaging applications. *Critical Reviews in Microbiology* 442:161–81. doi: 10.1080/1040841X.2017.1332001.

Huang, L., X. Ding, Y. Li, and H. Ma. 2019. The aggregation, structures and emulsifying properties of soybean protein isolate induced by ultrasound and acid. *Food Chemistry* 279:114–9. doi: 10.1016/j.foodchem.2018.11.147.

Hurtado, V. S., L. S. López-Bermúdez, O. A. Higuera-Barraza, C. L. Del Toro-Sanchez, S. Ruiz-Cruz, M. G. Suárez-Jiménez, and E. Marquez-Rios. 2019. Effect of ultrasonication time on the functional properties of giant squid (*Dosidicus gigas*) mantle protein concentrate. *Food Bioscience* 27:1–5. doi: 10.1016/j.fbio.2018.11.003.

Iqdiam, B. M., M. O. Abuagela, S. M. Marshall, Y. Yagiz, R. Goodrich-Schneider, G. L. Baker, B. A. Welt, and M. R. Marshall. 2019. Combining high power ultrasound pre-treatment with malaxation oxygen control to improve quantity and quality of extra virgin olive oil. *Journal of Food Engineering* 244:1–10. doi: 10.1016/j.jfoodeng.2018.09.013.

Jiang, T., X. Guo, A. Lin, H. Wu, C. Sun, J. Feng, and J. S. Kanwal. 2019. Bats increase vocal amplitude and decrease vocal complexity to mitigate noise interference during social communication. *Animal Cognition* 22 (2):199–212. doi: 10.1007/s10071-018-01235-0.

Carpenter, J., S. George, and V. K. Saharan. 2018. A comparative study of batch and recirculating flow ultrasonication system for preparation of multilayer olive oil in water emulsion stabilized with whey protein isolate and sodium alginate. *Chemical Engineering and Processing* 125:131–49. doi: 10.1016/j.cep.2018.01.006.

Jokar, M., and R. Abdul Rahman. 2014. Study of silver ion migration from melt-blended and layered deposited silver polyethylene nanocomposite into food simulants and apple juice. *Food Additives & Contaminants: Part A* 31 (4):734–42. doi: 10.1080/19440049.2013.878812.

Jones, K., K. Pfeifer, and G. Castillo. 2019. Trends in the global food system and implications for institutional foodservice. In *Institutions as conscious food consumers*, eds. S. E. Thottathil, A. M. Goger, 21–46. Cambridge, MA: Academic Press. doi: 10.1016/B978-0-12-813617-1.00002-2.

Jones, O. G., J. Adamcik, S. Handschin, S. Bolisetty, and R. Mezzenga. 2010. Fibrillation of β-lactoglobulin at low pH in the presence of a complexing anionic polysaccharide. *Langmuir* 2622:17449–58. doi: 10.1021/la1026619.

Kassem, A., J. Meade, K. McGill, C. Walsh, J. Gibbons, J. Lyng, and P. Whyte. 2018. An investigation of high intensity ultrasonication and chemical immersion treatments on *Campylobacter jejuni* and spoilage bacteria in chicken. *Innovative Food Science & Emerging Technologies* 45:298–305. doi: 10.1016/j.ifset.2017.10.015.

Kehinde, B. A., and P. Sharma. 2020. Recently isolated antidiabetic hydrolysates and peptides from multiple food sources: A review. *Critical Reviews in Food Science and Nutrition* 6 (2):322–40. doi: 10.1080/10408398.2018.1528206.

Kermasha, S., S. Aziz, J. Gill, and R. Neufeld. 2018. Microencapsulation of esterified krill oil, using complex coacervation. *Journal of Microencapsulation* 35 (1):36–48. doi: 10.1080/02652048.2017.1413148.

Kim, H. K., Y. H. Kim, Y. E. Kim, S. K. Jung, N. H. Lee, and K. M. Song. 2018. Effects of salts on ultrasonic extraction of protein from porcine myocardium. *Food and Bioproducts Processing* 108:12–7. doi: 10.1016/j.fbp.2017.12.002.

Kumar, R., K. Kaur, S. K. Pandey, R. Kumar, S. Uppal, and S. K. Mehta. 2018. Fabrication of benzylisothiocynate encapsulated nanoemulsion through ultrasonication: Augmentation of anticancer and antimicrobial attributes. *Journal of Molecular Liquids* 263:324–33. doi: 10.1016/j.molliq.2018.04.110.

Kumari, B., B. K. Tiwari, M. B. Hossain, D. K. Rai, and N. P. Brunton. 2017. Ultrasound-assisted extraction of polyphenols from potato peels: Profiling and kinetic modelling. *International Journal of Food Science & Technology* 526:1432–9. doi: 10.1111/ijfs.13404.

Kwaw, E., Y. Ma, W. Tchabo, A. S. Sackey, M. T. Apaliya, L. Xiao, M. Wu, and F. Sarpong. 2018. Impact of ultrasonication and pulsed light treatments on phenolics concentration and antioxidant activities of lactic-acid-fermented mulberry juice. *LWT- Food Science and Technology* 92:61–6. doi: 10.1016/j.lwt.2018.02.016.

Lafarga, T., P. Colás-Medà, M. Abadias, I. Aguiló-Aguayo, G. Bobo, and I. Viñas. 2019. Strategies to reduce microbial risk and improve quality of fresh and processed strawberries: A review. *Innovative Food Science & Emerging Technologies* 52:197–212. doi: 10.1016/j.ifset.2018.12.012.

Leinenga, G., C. Langton, R. Nisbet, and J. Götz. 2016. Ultrasound treatment of neurological diseases — Current and emerging applications. *Nature Reviews Neurology* 123:161–74. doi: 10.1038/nrneurol.2016.13.

Leong, T., P. Juliano, and K. Knoerzer. 2017. Advances in ultrasonic and megasonic processing of foods. *Food Engineering Reviews* 93:237–56. doi: 10.1007/s12393-017-9167-5.

Leong, T. S. H., M. Zhou, D. Zhou, M. Ashokkumar, and G. J. O. Martin. 2018. The formation of double emulsions in skim milk using minimal food-grade emulsifiers – A comparison between ultrasonic and high pressure homogenisation efficiencies. *Journal of Food Engineering* 219:81–92. doi: 10.1016/j.jfoodeng.2017.09.018.

Liao, H., L. Jiang, Y. Cheng, X. Liao, and R. Zhang. 2018. Application of nisin-assisted thermosonication processing for preservation and quality retention of fresh apple juice. *Ultrasonics Sonochemistry* 42:244–9. doi: 10.1016/j.ultsonch.2017.11.020.

Lindon, J. C., G. E. Tranter, and D. Koppenaal. 2016. *Encyclopedia of spectroscopy and spectrometry*. Netherlands: Elsevier Science. ISBN 9780128032251 https://books.google.co.in/books?id=G3nHCgAAQBAJ.

Liu, L., Z. Lu, L. Li, B. Li, X. Zhang, X. Zhang, and Z. Xu. 2018. Physical relation and mechanism of ultrasonic bactericidal activity on pathogenic *E. coli* with WPI. *Microbial Pathogenesis* 117:73–9. doi: 10.1016/j.micpath.2018.02.007.

Liu, W. S., C. Y. Yang, and T. J. Fang. 2018. Strategic ultrasound-induced stress response of lactic acid bacteria on enhancement of β-glucosidase activity for bioconversion of isoflavones in soymilk. *Journal of Microbiological Methods* 148:145–50. doi: 10.1016/j.mimet.2018.04.006.

López-Pedrouso, M., C. Pérez-Santaescolástica, D. Franco, J. Carballo, J. V. Garcia-Perez, J. Benedito, C. Zapata, and J. M. Lorenzo. 2019. Proteomic footprint of ultrasound intensification on sliced dry-cured ham subjected to mild thermal conditions. *Journal of Proteomics* 193:123–30. doi: 10.1016/j.jprot.2018.10.002.

Lu, Z. H., N. Belanger, E. Donner, and Q. Liu. 2018. Debranching of pea starch using pullulanase and ultrasonication synergistically to enhance slowly digestible and resistant starch. *Food Chemistry* 268:533–41. doi: 10.1016/j.foodchem.2018.06.115.

Maher, O. K. 2018. Nanomedicine and nanotechnology for heart failure research, diagnosis, and treatment. In *Heart failure in the child and young adult*, 779–84. Netherlands: Elsevier. doi: 10.1016/b978-0-12-802393-8.00060-0.

Mahmoudi, M.,. H. R. Kalhor, S. Laurent, and I. Lynch. 2013. Protein fibrillation and nanoparticle interactions: Opportunities and challenges. *Nanoscale* 5 (7):2570. doi: 10.1039/c3nr33193h.

Majid, I., G. A. Nayik, and V. Nanda. 2015. Ultrasonication and food technology: A review. *Cogent Food and Agriculture* 1 (1071022). doi: 10.1080/23311932.2015.1071022.

Marei, G., E. Rabea, and M. Badawy. 2018. Preparation and characterizations of chitosan/citral nanoemulsions and their antimicrobial activity. *Applied Food Biotechnology* 52:69–78. doi: 10.22037/afb.v5i2.19005.

McHugh, T. H. 2016. Putting ultrasound to use in food processing. Food Technology Magazine, December 2016. Accessed February 22, 2020. https://www.ift.org/news-and-publications/food-technology-magazine/issues/2016/december/columns/processing-ultrasound-use-in-food-processing.

Michelino, F., A. Zambon, M. T. Vizzotto, S. Cozzi, and S. Spilimbergo. 2018. High power ultrasound combined with supercritical carbon dioxide for the drying and microbial inactivation of coriander. *Journal of CO2 Utilization* 24:516–21. doi: 10.1016/j.jcou.2018.02.010.

Minakawa, A. F. K., P. C. S. Faria-Tischer, and S. Mali. 2019. Simple ultrasound method to obtain starch micro- and nanoparticles from cassava, corn and yam starches. *Food Chemistry* 283:11–8. doi: 10.1016/j.foodchem.2019.01.015.

Misra, N. N., A. Martynenko, F. Chemat, L. Paniwnyk, F. J. Barba, and A. R. Jambrak. 2018. Thermodynamics, transport phenomena and electrochemistry of external field assisted non-thermal food technologies. *Critical Reviews in Food Science and Nutrition* 58 (11):1832–63. doi: 10.1080/10408398.2017.1287660.

Misra, N. N., M. Koubaa, S. Roohinejad, P. Juliano, H. Alpas, R. S. Inácio, A. J. Saraiva, and F. J. Barba. 2017. Landmarks in the historical development of twenty first century food processing technologies. *Food Research International* 97:318–39. doi: 10.1016/j.foodres.2017.05.001.

Mizielińska, M.,. U. Kowalska, M. Jarosz, and P. A. Sumińska. 2018. Comparison of the effects of packaging containing nano zno or polylysine on the microbial purity and texture of cod (*Gadus morhua*) fillets. *Nanomaterials* 8 (3):158. doi: 10.3390/nano8030158.

Morais, N. L. P., and C. M. A. Brett. 2002. Influence of ultrasound on the corrosion of aluminium. *Key Engineering Materials* 230-232:412–5. doi: 10.4028/www.scientific.net/KEM.230-232.412.

Nadar, S. S., and V. K. Rathod. 2017. Ultrasound assisted intensification of enzyme activity and its properties: A mini-review. *World Journal of Microbiology and Biotechnology* 33 (9):170. doi: 10.1007/s11274-017-2322-6.

Nam, Y., J. Bae, J. H. Jeong, S. K. Ko, and U. D. Sohn. 2018. Protective effect of ultrasonication-processed ginseng berry extract on the D-galactosamine/lipopolysaccharide-induced liver injury model in rats. *Journal of Ginseng Research* 42 (4):540–8. doi: 10.1016/j.jgr.2017.07.007.

Naseri, N.,. H. Valizadeh, and P. Zakeri-Milani. 2015. Solid lipid nanoparticles and nanostructured lipid carriers: Structure, preparation and application. *Advanced Pharmaceutical Bulletin* 5 (3):305–13. doi: 10.15171/apb.2015.043.

Nazzaro, F., F. Fratianni, and R. Coppola. 2012. Microtechnology and nanotechnology in food science. In *Green technologies in food production and processing. Food engineering series*, eds. J. Boye and Y. Arcand. Boston, MA: Springer. doi: 10.1007/978-1-4614-1587-9_17.

Noorbakhsh-Soltani, S. M., M. M. Zerafat, and S. Sabbaghi. 2018. A comparative study of gelatin and starch-based nano-composite films modified by nano-cellulose and chitosan for food packaging applications. *Carbohydrate Polymers* 189:48–55. doi: 10.1016/j.carbpol.2018.02.012.

Novoa-Díaz, D., J. M. Rodríguez-Nogales, J. M. Fernández-Fernández, E. Vila-Crespo, J. García-Álvarez, J. Amer, M. A. J. Chávez, A. Turó, M. J. García-Hernández, and J. Salazar. 2014. Ultrasonic monitoring of malolactic fermentation in red wines. *Ultrasonics* 54 (6):1575–80. doi: 10.1016/j.ultras.2014.04.004.

Ojha, K. S., T. J. Mason, C. P. O'Donnell, J. P. Kerry, and B. K. Tiwari. 2017. Ultrasound technology for food fermentation applications. *Ultrasonics Sonochemistry* 34:410–7. doi: 10.1016/j.ultsonch.2016.06.001.

Ojha, K. S., C. A. Perussello, C. Á. García, J. P. Kerry, D. Pando, and B. K. Tiwari. 2017. Ultrasonic-assisted incorporation of nano-encapsulated omega-3 fatty acids to enhance the fatty acid profile of pork meat. *Meat Science* 132:99–106. doi: 10.1016/j.meatsci.2017.04.260.

Oliveira, M., and A. V. Machado. Preparation of polymer-based nanocomposites by different routes. 2013. Accessed September 4, 2018. https://repositorium.sdum.uminho.pt/bitstream/1822/26120/1/Chapter.pdf.

Öztürk, B. 2017. Nanoemulsions for food fortification with lipophilic vitamins: Production challenges, stability, and bioavailability. *European Journal of Lipid Science and Technology* 119 (7):1500539. doi: 10.1002/ejlt.201500539.

Palanisamy, N., B. Seale, A. Turner, and Y. Hemar. 2019. Low frequency ultrasound inactivation of thermophilic bacilli (*Geobacillus spp.*) and (*Anoxybacillus flavithermus*) in the presence of sodium hydroxide and hydrogen peroxide. *Ultrasonics Sonochemistry* 51:325–31. doi: 10.1016/j.ultsonch.2018.09.025.

Papaioannou, E. H., M. L. Kyriakides, and A. J. Karabelas. 2016. Natural origin lycopene and its 'green' downstream processing. *Critical Reviews in Food Science and Nutrition* 56 (4):686–709. doi: 10.1080/10408398.2013.817381.

Patist, A., and D. Bates. 2008. Ultrasonic innovations in the food industry: From the laboratory to commercial production. *Innovative Food Science & Emerging Technologies* 9 (2):147–54. doi: 10.1016/j.ifset.2007.07.004.

Phong, W. N., P. L. Show, C. F. Le, Y. Tao, J. S. Chang, and T. C. Ling. 2018. Improving cell disruption efficiency to facilitate protein release from microalgae using chemical and mechanical integrated method. *Biochemical Engineering Journal* 135:83–90. doi: 10.1016/j.bej.2018.04.002.

Piñon, M. I., A. D. Alarcon-Rojo, I. Garcia-Galicia, L. Carrillo-Lopez, and M. Huerta-Jimenez. 2018. Microbiological properties of poultry breast meat treated with high-intensity ultrasound. *Ultrasonics* :105680. doi: 10.1016/j.ultras.2018.01.001.

Pojić, M., A. Mišan, and B. Tiwari. 2018. Eco-innovative technologies for extraction of proteins for human consumption from renewable protein sources of plant origin. *Trends in Food Science & Technology* 75:93–104. doi: 10.1016/j.tifs.2018.03.010.

Pyatkovskyy, T. I., M. V. Shynkaryk, H. M. Mohamed, A. E. Yousef, and S. K. Sastry. 2018. Effects of combined high pressure (HPP), pulsed electric field (PEF) and sonication treatments on inactivation of *Listeria innocua*. *Journal of Food Engineering* 233:49–56. doi: 10.1016/j.jfoodeng.2018.04.002.

Rafiee, Z., and S. M. Jafari. 2018. Application of lipid nanocarriers for the food industry. *Reference Series in Phytochemistry* :1–43. doi: 10.1007/978-3-319-54528-8_93-1.

Raju, S., and S. C. Deka. 2018. Influence of thermosonication treatments on bioactive compounds and sensory quality of fruit (Haematocarpus validus) juice. *Journal of Food Processing and Preservation* 42 (8):e13701. doi: 10.1111/jfpp.13701.

Rana, A., Meena and Shweta. 2017. Ultrasonic processing and its use in food industry: A review. *International Journal of Chemical Studies* 5 (6):1961–68.

Ray, L., and K. C. Gupta. 2018. Role of nanotechnology in skin remedies. *Photocarcinogenesis and Photoprotection*: 141–157. doi: 10.1007/978-981-10-5493-8_13K.O.

Rojo, A. D. A., E. P. González, I. G. Galicia, L. C. López, M. H. Jiménez, R. R. Villagrana, and H. J. Vidales. 2018. Ultrasound application to improve meat quality. *Descriptive Food Science*. doi: 10.5772/intechopen.77973.

Shabana, S.,. R. Prasansha, I. Kalinina, I. Potoroko, U. Bagale, and S. H. Shirish. 2019. Ultrasound assisted acid hydrolyzed structure modification and loading of antioxidants on potato starch nanoparticles. *Ultrasonics Sonochemistry* 51:444–50. doi: 10.1016/j.ultsonch.2018.07.023.

Shankar, S., A. A. Oun, and J. W. Rhim. 2018. Preparation of antimicrobial hybrid nano-materials using regenerated cellulose and metallic nanoparticles. *International Journal of Biological Macromolecules* 107:17–27. doi: 10.1016/j.ijbiomac.2017.08.129.

Shao, Y., C. Wu, T. Wu, Y. Li, S. Chen, C. Yuan, and Y. Hu. 2018. Eugenol-chitosan nanoemulsions by ultrasound-mediated emulsification: Formulation, characterization and antimicrobial activity. *Carbohydrate Polymers* 193:144–52. doi: 10.1016/j.carbpol.2018.03.101.

Shekar, H. S., A. J. Rajamma, and S. Shivallyboregowda. 2018. Ultrasound-induced microencapsulation of simvastatin for gastric retention and controlled delivery. *Indian Journal of Pharmaceutical Sciences* 80 (4):647–56.

Singh, A., S. Benjakul, and K. Kijroongrojana. 2018. Effect of ultrasonication on physicochemical and foaming properties of squid ovary powder. *Food Hydrocolloids.* 77:286–96. doi: 10.1016/j.foodhyd.2017.10.005.

Sinha, S., A. Srivastava, T. Mehrotra, and R. Singh. 2018. *A review on the dairy industry waste water characteristics, its impact on environment and treatment possibilities*, 73–84. Switzerland: Springer Briefs in Environmental Science. doi: 10.1007/978-3-319-99398-0_6.

Sivagami, K., D. Anand, G. Divyapriya, and I. Nambi. 2019. Treatment of petroleum oil spill sludge using the combined ultrasound and Fenton oxidation process. *Ultrasonics Sonochemistry* 51:340–9. doi: 10.1016/j.ultsonch.2018.09.007.

Song, J., W. Tian, X. Xu, Y. Wang, and Z. Li. 2019. Thermal performance of a novel ultrasonic evaporator based on machine learning algorithms. *Applied Thermal Engineering* 148:438–46. doi: 10.1016/j.applthermaleng.2018.11.083.

Soria, A. C., and M. Villamiel. 2010. Effect of ultrasound on the technological properties and bioactivity of food: A review. *Trends in Food Science & Technology* 21 (7):323–31. doi: 10.1016/j.tifs.2010.04.003.

Stanic-Vucinic, D., M. Stojadinovic, M. Atanaskovic-Markovic, J. Ognjenovic, H. Gronlund, M. van Hage, R. Lantto, A. I. Sancho, and T. C. Velickovic. 2012. Structural changes and allergenic properties of β-lactoglobulin upon exposure to high-intensity ultrasound. *Molecular Nutrition & Food Research* 56 (12):1894–905. doi: 10.1002/mnfr.201200179.

Stefanović, A. B., J. R. Jovanović, M. B. Dojčinović, S. M. Lević, V. A. Nedović, B. M. Bugarski, and Z. D. Knežević-Jugović. 2017. Effect of the controlled high-intensity ultrasound on improving functionality and structural changes of egg white proteins. *Food and Bioprocess Technology* 10 (7):1224–39. doi: 10.1007/s11947-017-1884-5.

Strain, G. M., A. J. Rosado Martinez, K. A. McGee, and C. L. McMillan. 2016. Distortion product otoacoustic emissions in geriatric dogs. *The Veterinary Journal* 216:101–6. doi: 10.1016/j.tvjl.2016.07.010.

Sullivan, A. C., P. Pangloli, and V. P. Dia. 2018. Impact of ultrasonication on the physicochemical properties of sorghum kafirin and *in vitro* pepsin-pancreatin digestibility of sorghum gluten-like flour. *Food Chemistry* 240:1121–30. doi: 10.1016/j.foodchem.2017.08.046.

Syed, I., and P. Sarkar. 2018. Ultrasonication-assisted formation and characterization of geraniol and carvacrol-loaded emulsions for enhanced antimicrobial activity against food-borne pathogens. *Chemical Papers* 72 (10):2659–72. doi: 10.1007/s11696-018-0501-z.

Tao, Y., and D. W. Sun. 2015. Enhancement of food processes by ultrasound: A review. *Critical Reviews in Food Science and Nutrition* 55 (4):570–94. doi: 10.1080/10408398.2012.667849.

Teodoro, R. A. R., E. L. do Carmo, S. V. Borges, D. A. Botrel, G. R. Marques, P. H. Campelo-Felix, E. K. Silva, and R. V. Fernandes. 2018. Effects of ultrasonication on the characteristics of emulsions and microparticles containing Indian clove essential oil. *Drying Technology* 37 (9):1162–72. doi: 10.1080/07373937.2018.1492611.

Ter, H. G. 2011. Ultrasonic imaging: Safety considerations. *Interface Focus* 1 (4):686–97. https://dx.doi.org/10.1098%2Frsfs.2011.0029.

Terefe, N. S., R. Buckow, and C. Versteeg. 2015. Quality-related enzymes in plant-based products: Effects of novel food-processing technologies part 3: Ultrasonic Processing. *Critical Reviews in Food Science and Nutrition* 55:147–58. doi: 10.1080/10408398.2011.586134.

The Washington Post. 2019. How to combat climate change. Accessed February 26, 2019. https://www.washingtonpost.com/news/opinions/wp/2019/01/02/feature/opinion-here-are-11-climate-change-policies-to-fight-for-in-2019/?noredirect=onutm_term=.9f876f8ed9fc.

Tiwari, B. K. 2015. Ultrasound: A clean, green extraction technology. *TrAC Trends in Analytical Chemistry* 71:100–9. doi: 10.1016/j.trac.2015.04.013.

Tiwari, B. K., K. Muthukumarappan, C. P. O'Donnell, and P. J. Cullen. 2008. Effects of sonication on the kinetics of orange juice quality parameters. *Journal of Agricultural and Food Chemistry* 567:2423–8. doi: 10.1021/jf073503y.

Tran, T. T. T., K. T. Nguyen, and V. V. M. Le. 2018. Effects of ultrasonication variables on the activity and properties of alpha amylase preparation. *Biotechnology Progress* 34 (3):702–10. doi: 10.1002/btpr.2613.

Vasile, C. 2018. Polymeric nanocomposites and nanocoatings for food packaging: A review. *Materials (Basel, Switzerland)* 11 (10):1834. doi: 10.3390/ma11101834.

Verma, C., M. A. Quraishi, and E. E. Ebenso. 2018. Microwave and ultrasound irradiations for the synthesis of environmentally sustainable corrosion inhibitors: An overview. *Sustainable Chemistry and Pharmacy* 10:134–47. doi: 10.1016/j.scp.2018.11.001.

Waingankar, N., E. Goldenberg, and B. Gilbert. 2015. *History of ultrasound*, 1–9. New Dehli: Jaypee Brothers Medical Publishers. doi: 10.1007/978-1-4614-7744-0_1.

Wang, L., Xia, Q. Y., and Y. Li 2018. Label free-based proteomic analysis of proteins in Bacillus cereus spores regulated by high pressure processing and slightly acidic electrolyzed water treatment. *Food Control* 90:392–400. doi: 10.1016/j.foodcont.2018.03.015.

Wen, L., Z. Zhang, D. Rai, D. Sun, and B. K. Tiwari. 2019. Ultrasound-assisted extraction UAE) of bioactive compounds from coffee silverskin: Impact on phenolic content, antioxidant activity, and morphological characteristics. *Journal of Food Process Engineering* 42 (6):e13191. doi: 10.1111/jfpe.13191.

Wu, X. F., M. Zhang, B. Adhikari, and J. Sun. 2017. Recent developments in novel freezing and thawing technologies applied to foods. *Critical Reviews in Food Science and Nutrition* 57 (17):3620–31. doi: 10.1080/10408398.2015.1132670.

Yao, L., H. Liu, X. Wang, W. Xu, Y. Zhu, H. Wang, L. Pang, and C. Lin. 2018. Ultrasound-assisted surfactant-enhanced emulsification microextraction using a magnetic ionic liquid coupled with micro-solid phase extraction for the determination of cadmium and lead in edible vegetable oils. *Food Chemistry* 256:212–8. doi: 10.1016/j.foodchem.2018.02.132.

Yildiz, G., J. Andrade, N. E. Engeseth, and H. Feng. 2017. Functionalizing soy protein nano-aggregates with pH-shifting and mano-thermo-sonication. *Journal of Colloid and Interface Science* 505:836–46. doi: 10.1016/j.jcis.2017.06.088.

Yildiz, G., J. Ding, J. Andrade, N. J. Engeseth, and H. Feng. 2018. Effect of plant protein-polysaccharide complexes produced by mano-thermo-sonication and pH-shifting on the structure and stability of oil-in-water emulsions. *Innovative Food Science & Emerging Technologies* 47:317–25. doi: 10.1016/j.ifset.2018.03.005.

Yildiz, G., J. Ding, S. Gaur, J. Andrade, N. E. Engeseth, and H. Feng. 2018. Microencapsulation of docosahexaenoic acid (DHA) with four wall materials including pea protein-modified starch complex. *International Journal of Biological Macromolecules* 114:935–41. doi: 10.1016/j.ijbiomac.2018.03.175.

Yilmaz, E. 2018. Use of hydrolytic enzymes as green and effective extraction agents for ultrasound assisted-enzyme based hydrolytic water phase microextraction of arsenic in food samples. *Talanta* 189:302–7. doi: 10.1016/j.talanta.2018.07.006.

Yilmaz, F. M., and E. S. Bilek. 2018. Ultrasound-assisted vacuum impregnation on the fortification of fresh-cut apple with calcium and black carrot phenolics. *Ultrasonics Sonochemistry* 48:509–16. doi: 10.1016/j.ultsonch.2018.07.007.

Yu, Y., L. Zhang, T. Li, N. Wu, L. Jiang, X. Ji, and H. Huang. 2018. How nitrogen sources influence *Mortierella alpina* aging: From the lipid droplet proteome to the whole-cell proteome and metabolome. *Journal of Proteomics* 179:140–9. doi: 10.1016/j.jprot.2018.03.014.

Yusaf, T., and R. A. Al-Juboori. 2014. Alternative methods of microorganism disruption for agricultural applications. *Applied Energy* 114:909–23. doi: 10.1016/j.apenergy.2013.08.085

Zhang, J., S. Li, F. F. An, J. Liu, S. Jin, J. C. Zhang, P. C. Wang, X. Zhang, C. S. Lee, and X. J. Liang. 2015. Self-carried curcumin nanoparticles for *in vitro* and *in vivo* cancer therapy with real-time monitoring of drug release. *Nanoscale* 7 (32):13503–10. doi: 10.1039/C5NR03259H.

Zhang, L., N. Gao, Y. Yin, L. Yang, Y. Xie, Y. Chen, P. Dai, and T. Zhang. 2016. Bone conduction hearing in congenital aural atresia. *European Archives of Oto-Rhino-Laryngology* 273 (7):1697–703. doi: 10.1007/s00405-015-3727-1.

Zhang, P., Z. Zhu, and D. W. Sun. 2018. Using power ultrasound to accelerate food freezing processes: Effects on freezing efficiency and food microstructure. *Critical Reviews in Food Science and Nutrition* 58 (16):2842–53. doi: 10.1080/10408398.2018.1482528.

Zhang, Z. H., L. H. Wang, X. A. Zeng, Z. Han, and C. S. Brennan. 2018. Non-thermal technologies and its current and future application in the food industry: A review. *International Journal of Food Science & Technology* 54:1–13. doi: 10.1111/ijfs.13903.

Zhang, Z., J. M. Regenstein, P. Zhou, and Y. Yang. 2017. Effects of high intensity ultrasound modification on physicochemical property and water in myofibrillar protein gel. *Ultrasonics Sonochemistry* 34: 960–7. doi: 10.1016/j.ultsonch.2016.08.008.

Zhao, D., Li, L. D. Xu, B. Sheng, D. Qin, J. Chen, L. B. Li, and X. Zhang. 2018. Application of ultrasound pretreatment and glycation in regulating the heat-induced amyloid-like aggregation of β-lactoglobulin. *Food Hydrocolloids.* 80:122–9. doi: 10.1016/j.foodhyd.2018.02.001.

Zhong, X., Y. Zhang, G. Huang, Y. Ouyang, D. Liao, J. Peng, and W. Huang. 2018. Proteomic analysis of stachyose contribution to the growth of *Lactobacillus acidophilus* CICC22162. *Food & Function* 9 (5):2979–88. doi: 10.1039/C8FO00528A.

Zielinska, M., and M. Markowski. 2018. Effect of microwave-vacuum, ultrasonication, and freezing on mass transfer kinetics and diffusivity during osmotic dehydration of cranberries. *Drying Technology* 36 (10):1158–69. doi: 10.1080/07373937.2017.1390476.

Zou, Y., K. Zhang, H. Bian, M. Zhang, C. Sun, W. Xu, and D. Wang. 2018. Rapid tenderizing of goose breast muscle based on actomyosin dissociation by low-frequency ultrasonication. *Process Biochemistry* 65:115–22. doi: 10.1016/j.procbio.2017.11.010.

Zounr, R. A., M. Tuzen, N. Deligonul, and M. Y. Khuhawar. 2018. A highly selective and sensitive ultrasonic assisted dispersive liquid phase microextraction based on deep eutectic solvent for determination of cadmium in food and water samples prior to electrothermal atomic absorption spectrometry. *Food Chemistry* 253: 277–83. doi: 10.1016/j.foodchem.2018.01.167.