



Advances in application of ultrasound in food processing: A review

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ABSTRACT

Food processing plays a crucial role in coping up with the challenges against food security by reducing wastage and preventing spoilage. The ultrasound technology has revolutionized the food processing industry with its wide application in various processes, serving as a sustainable and low-cost alternative. This non-destructive technology offers several advantages such as rapid processes, enhanced process efficiency, elimination of process steps, better quality product and retention of product characteristics (texture, nutrition value, organoleptic properties), improved shelf life. This review paper summarizes the various applications of ultrasound in different unit operations (filtration, freezing, thawing, brining, sterilization/pasteurization, cutting, etc.) and specific food divisions (meat, fruits and vegetables, cereals, dairy, etc.) along with the advantages and drawbacks of the technology. The further scope of industrial implementation of ultrasound has also been discussed.

1. Introduction

Food processing refers to the deliberate transformation of agriculture produce, through numerous unit operations into more palatable, shelf-stable, portable and useful, value-added products, safe for human consumption [1]. Various traditional processing and preservation methods such as drying, frying, smoking, salting, pickling, soaking, etc. are still abundantly and effectively used to process raw food products. The underlying principle for most of the traditional food processing methods depends on expending heat to diminish the growth of microorganisms and inhibit foodborne pathogens which render the food safe for consumption [2]. These thermal treatments consume high energy, providing a low production efficiency, and are highly time-consuming procedures, requiring large levels of external inputs [3]. There are a lot of food products that present a threat of bacterial or viral intoxication for which processing by heat may not be desirable. Such thermally sensitive food products on exposure to heat treatment may undergo physical, chemical, and microbial changes such as modification of flavor, color, and texture. This has generated a need for research and development into maximum utilization of the existing technologies and the emergence of innovative and effective alternate technologies [4]. The novel methods used in food processing, include high-pressure processing, cold plasma, pulsed electric field, supercritical fluid extraction, ultraviolet irradiation, and ultrasound.

Sound waves exceeding the audible frequency range i.e. greater than 20 kHz are termed as 'Ultrasound'. When the acoustic waves

propagate through a medium, they generate compressions and rarefaction (decompressions) in the medium particles. This, in turn, produces a high amount of energy, due to turbulence, and increase in mass transfer. The underlying principle is the reflection and scattering of sonic waves analogous to light waves [5]. Ultrasound is an emerging sustainable technology that enhances the rate of several processes in the food processing industry, and their efficiency. It can also be applied in combination with temperature (thermosonication) and pressure (manosonication) to produce a synergistic effect, which further enhances its efficacy [6]. Based on the intensity and frequency ultrasound waves used in food application can be categorized into two categories: low and high-intensity ultrasound.

The low intensity or high-frequency ultrasound waves also described as diagnostic waves and have a characteristic frequency greater than 100 kHz and intensities below 1 W/cm². These waves can be utilized for evaluating the structure (shape, size, and dimensions) of the food product, determining the composition of fresh food commodities such as meat and poultry, raw and fermented fisheries. It is employed as a tool for non-invasive and non-destructive analysis of food products during processing and storage. It is also instrumental in the quality regulation and control of freshly produced fruits and vegetables both during pre and post-harvest operations [7]. The principle of operation of low energy ultrasound that it effectively exploits the interaction between matter and high-frequency sound waves to obtain detailed information in context to the structure, dimensions, and composition of the product through which it disseminates. Also, attenuation occurs due

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to loss of energy in compression and decompression of waves [8]. The absorption mechanism associates with homogenous and scattering with heterogeneous materials which provide information regarding physicochemical attributes of the material [9].

The high intensity and low-frequency ultrasound waves are characterized as disruptive and thus, induce considerable effects on the physical, biochemical, and mechanical properties of food products in contrast to low power ultrasound. Their frequency ranges from 20 to 100 kHz while intensities are in the range of 10 to 1000 W/cm². This has wide application in emulsification, defoaming, regulation of microstructures, and modification of textural attributes of fatty products, sonocrystallization, and functional properties of food proteins. It also has significant applications in numerous unit operations of freezing, drying, tenderization, concentration, thawing [7,10]. High-intensity ultrasound is characterized by the induction of acoustic cavitation which is caused due to the production, subsequent growth, and sudden collapse of larger bubbles liberating a high amount of energy [11].

Different review have been done on the applications of ultrasound technology in extraction, preservation and processing of food commodities. However, a specific review covering the application of ultrasound in food industry for the processing of foods and enhancement of unit operation involved with further prospects for commercialization has not been presented. This review paper summarizes the various applications of ultrasound in different unit operations (filtration, freezing, thawing, brining, sterilization/pasteurization, cutting, etc.) and specific food divisions (meat, fruits and vegetables, cereals, dairy, etc.) along with, the advantages and drawbacks of the technology.

2. Generation of ultrasound

The most basic component employed in the generation of ultrasound is a transducer which converts electrical pulses into acoustic energy of required intensity [12]. There are two types of transducers i.e. magnetostrictive and piezoelectric are mainly used for the generation of ultrasound (Fig. 1). Magnetostrictive Transducers act as electro-acoustic transducers for the generation of ultrasonic waves. These transducers work on the principle of magnetostriction which is described as the subsequent alteration in length per unit length. This is caused by magnetization on the application of the magnetic field, provided the material used is magnetostrictive (Fig. 1). Piezoelectric Transducer deals with the inter-conversion of acoustic and electrical energies. The basic principle of a piezoelectric sensor/transducer is that when a quartz crystal or any piezoelectric material is subjected to a force, it generates electrical charges on its surface, which can be termed as piezoelectricity which may be responsible for the cleaning action

[13].

3. Methods of application of ultrasound

In the food industry, ultrasound can be applied for supplementing the unit operations or in the processing of the food product by either direct exposure or using an instrument such as Sonotrode or Ultrasonic water bath.

3.1. Sonotrode

The acoustic energy produced by the transducers can be directly applied to the products which undergo treatment, processing, or are analyzed for their composition or structure [14]. A sonotrode is a welder's tool, and thus in case of food processing is predominantly employed in cutting and slicing actions (Fig. 2). Ultrasonic slicing of cheese, biscuits, fruits, and vegetables, etc. results in perfectly cut and sliced products. Also, contrary to conventional slicing techniques, ultrasonic technology minimizes loss of product and augments productivity. It is an essential part of the ultrasonic cutting system, which consists of a generator that produces alternating current with the required frequency of ultrasound. The transducer then converts electric oscillations to mechanical displacements. An amplifier then transfers the vibrations (mechanical) as a sound wave to sonotrode [15].

3.2. Ultrasonic water bath

Ultrasonic water baths have been widely accepted methods for cleaning, and sanitation in the food and beverage processing operations. Ultrasonic waves produced by the equipment into the cleaning fluid render the food safe for consumption, usually employed in degreasing processes. Ultrasonic cleaners transform low-frequency AC into high-frequency sound waves via the piezoelectric transducer, which is attached either to the bottom of the processing vessel or submerged into the cleaning liquid. The transducer produces high-intensity waves into the solution, creating compression, which tears apart the liquid, resulting in millions of macroscopic cavities or bubbles, termed as 'cavitation' (Fig. 2). These bubbles, violently collapse in the cleaning solution with enormous energy at high temperature and pressure. Within a short span, this process eradicates the dirt from all products, submerged in the cleaning solution [16].

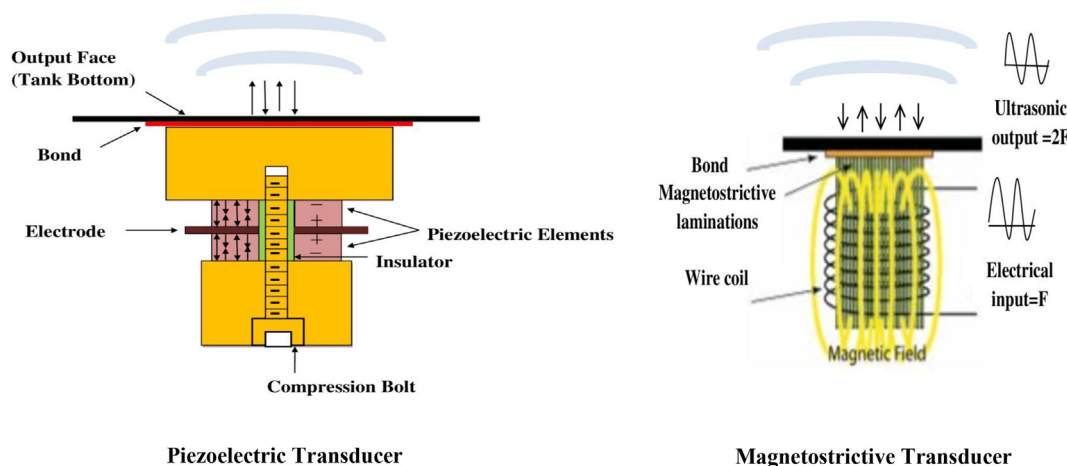


Fig. 1. Generation of ultrasound.

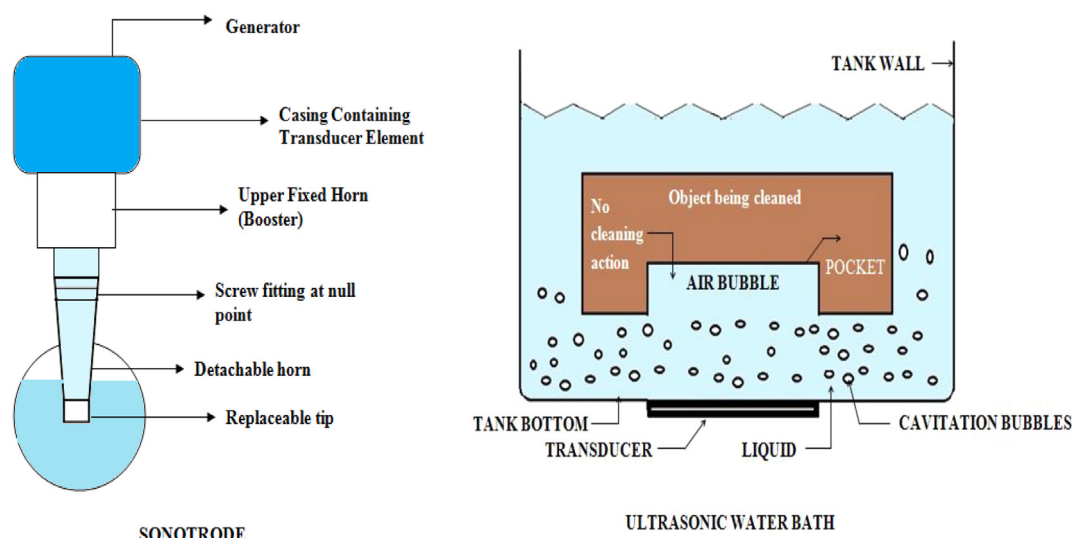


Fig. 2. Method of application of ultrasound.

4. Application of ultrasound in basic unit operations of the food industry

4.1. Filtration

Ultrasound has been found to enhance the processes when used in conjunction with various unit operations in the food industry (Table 1). Filtration has long been used as an important process in the food industry for efficient separation such as solids from their mother liquor or in the production of solid free liquid. The problems of fouling or concentration polarization caused by the deposition of the filtrate or filter cake on the membrane surface is a major issue in this process. These problems cause a reduction in filtration efficiency. However, ultrasound energy is effective against this issue [17]. On the application of ultrasound during the process of filtration, the retentate layers accumulated on the membrane surface causing concentration polarization, are disrupted while the membrane's intrinsic permeability remains unaffected. This results in an increase in flux and a decrease in flow resistance [18]. Acoustic filtration has been effectively used for the enhancement of industrial wastewater filtration which is usually considered to be a gruesome process [19]. However, the optimization of ultrasound velocity is extremely necessary for the prevention of any damage caused to the filters [20]. Ultrasound, when combined with filters, enhances the life of the filter, by preventing the caking and clogging of the membrane, enabled by continuous cavitation at the surface of the filter [21]. Camara et al. [22] stated that low frequency ultrasound can aid in controlling fouling of the membrane as it facilitates the removal of particles from the cake layer. Thus, acoustic filtration enhances the quality of the processed product and eliminates concern related to safety. All of the factors mentioned above are significant to commercialize the process of filtration and is being produced by several companies as ultrasonic-assisted filtration systems, which is an accessory to the pre-existing vibratory screens. However, the development in this field is limited due to single transducers with low power capacity and thus new power transducers can improve the acoustic filtration, and enhance its potential to be used at large scales, with vibration amplifiers [23].

4.2. Freezing and crystallization

The processes of freezing and crystallization are interlinked as both are characterized by the initial nucleation process with subsequent crystallization [24]. On the application of ultrasound, conventional cooling is more rapid and provides uniform seeding, leading to shorter

dwel time. More seeds reduce the final crystal size and thus cause less damage to the cells [25]. By improving heat transfer, accelerated cooling can be achieved [26]. Ultrasonic cavitation occurs and it acts as nuclei for the growth of crystals or disrupting the initial nuclei present. This leads to finer ice crystals and reduction in the time between the beginning of crystallization and ice formation, during freezing [27]. Therefore, it reduces the destruction of cell structure. In the case of ultrasound-assisted freezing, it has been observed that ultrasound can accelerate the process of freezing due to an increase in heat and mass transfer and initiation of nucleation [28]. Nucleation as a result of ultrasound consists of two major phases: primary and secondary nucleation. The initiation or primary nucleation occurs when nucleation temperature is achieved, which is less than the required temperature of freezing. Also, this phase is accompanied by the release of latent heat in large amounts. It is reported that the high pressure caused by ultrasound results in a decrease in the degree of supercooling which is the driving force for nucleation [29]. The bubbles produced due to cavitation, serve as the nuclei for nucleation, as the bubble size reaches the threshold critical required for nucleation. The motion of the stable cavitation bubbles can result in microstreaming and eddies, subsequently enhancing heat and mass transfer and resulting in nucleation. Ultrasound radiation ruptures the dendrites of the present ice into fragments during the secondary phase, which is due to the collapsing cavitation bubbles and microflow derived shear force, resulting in more sites for nucleation [10].

Ultrasound has been used to store a variety of foodstuffs [28]. For high-value food products as well as pharmaceuticals, ultrasonic freezing is suitable. Ultrasound has been applicable in the crystallization of food products such as triglyceride oils – vegetable oils [29], ice cream [30], and milk fat [31]. Ultrasound also provides an additional benefit as it enables the prevention of encrustation of the crystals on elements of cooling, thus, ensuring proper transfer of heat throughout the process of cooling [32].

4.3. Thawing

In order to increase the shelf life of products, freezing is a common and widely employed method whose success depends on the optimization of conditions of thawing [33]. The process of defrosting or thawing of products that are frozen is extremely slow as well as expensive in the food processing industry and thus, causes inconvenience in catering and other unit operations. During thawing the food is subjected to microbial, chemical, and physical changes [26]. Kissam et al. [34] observed that the application of ultrasound in the relaxation

Table 1
Application in of ultrasound in basic unit operations.

Applications	Principle	Products	Advantages	References
Filtration	Vibrations	Liquid food products eg. Juices	Increases membrane permeation. Requires less time. Enhances filtration process	[14]
Freezing / Crystallization	Uniform Heat Transfer	Milk products Fruits & Vegetables Meat	Improves freezing by better preservation of the microstructure. Requires less time and small crystal size. Improved diffusion. Rapid decrease in temperature.	[32]
Thawing	Uniform heat Transfer	Frozen products	Reduction in thawing time. Preserve color Inhibit lipid oxidation. Improved product quality.	[36]
Brining/Pickling		Cheese, meat, fish etc	Reduced product dehydration Low water activity and longer shelf life Required less sodium chloride Uniform distribution of salt in less time	[40,39]
Drying	Uniform Heat Transfer	Dehydrated Food Products	Intensification of mass transfer. Shorter processing time. Enhanced organoleptic properties.	[55]
Foaming	Dispersion of gas bubbles	Protein	Increased drying rate due to less resistance. Increases the foaming capacity	[59,62]
Degassing / Deaeration	Agitation	Carbonic beverages, aqueous solutions.	Reduces the foam stability and water retention capacity Reduces the bottles broken and beverage overflow Less time required	[66]
Cooking	Uniform Heat Transfer	Meat Products Vegetables	Requires less time Improved nutrient retention. Improved rate of heat transfer. Enhances organoleptic properties. Improved tenderization	[149,148]
Emulsification	Cavitation Phenomenon	Emulsions eg. Mayonnaise	Enhances rheological properties Improves emulsion stability Requires less time	[149]
Cutting	Cavitation Phenomenon	Soft Products eg. Cheese, Bread	Accuracy in cuts Requires less time Clean cuts with minimized product loss	[76]
Sterilization / Pasteurization	Uniform Heat Transfer	Milk, Juice	Reduced processing time Efficient microbial inactivation Low temperature requirements Low energy requirements	[77]
Extraction	Diffusion	Food and plant material	Increase the efficiency of extraction Reduces the time of extraction Less solvent required	[84,85]
Rehydration	Absorption	Dried vegetables, grains etc.	Reduction in time of rehydration	[95,94]

frequency range enhanced the rate of thawing in comparison to conductive heating alone. According to the experiments, cod blocks required about 71% lesser time by thawing through ultrasound-assisted immersion in water as compared to water immersion when ultrasound at 1500 Hz frequency and power of 60 W was applied. Ultrasound has also been used for the thawing of fish and meat where it was observed that thawing was attained at frequencies of 500 kHz [35].

Ultrasound energy can be absorbed by frozen products to accelerate the process of thawing and enhance product quality. If ultrasound is applied efficiently, it can improve the rate of thawing, avoiding heating of the surface and extreme product dehydration, as well as retain color and inhibit lipid oxidation. Ultrasound can be carried along with water immersion during the process of thawing [36].

4.4. Brining/Pickling

Brining has been used as a very common process in the preservation and manufacturing of foods, especially for cheese and meat. The drawbacks of traditional brining such as low efficiency and slow preservation of food can be overcome by the application of ultrasound. Food producers are interested in alternatives for traditional brining technologies [37]. Ultrasonication also acts as a method to produce pickled food products with a lesser amount of sodium chloride in comparison to presently available commercial pickles. Carcel et al. [38], studied brining of pork loin slices by immersing them in a

saturated solution and applying ultrasound during the process of brining. It was observed that the content of sodium chloride and water post-treatment were greater in the sonicated sample than the non-sonicated one. Furthermore, the acoustic treatment also reduces the time required for salting, the coloring of raw meat as well as crust formation [39]. This process also produces a product with uniform salt content. Sánchez et al. [40], found that the equilibrium of salt concentration in cheese treated with ultrasound cannot be attained at the initial stage of ripening as compared to conventional ripening. Though, cheese brined with ultrasonic assistance depicted a low water diffusivity that explained the low drying rate. In the case of brined meat products, it was observed that the rate of mass transfer was enhanced significantly by applying ultrasound on reaching a threshold magnitude of intensity [38]. Faster brining processes enable the control of bloating, structural damage, and enzymatic softening of brined foods. Contreras-Lopez et al. [41] observed that the application of high intensity acoustic energy increased the overall salt concentration in pork loins and retained its color and quality. The slices were more juicier and tender. Also, meat brining assisted by ultrasound enhances the mass transfer, moisture content and salt diffusion into beef [42]. Moreover, the higher rate of salt gain on the application of ultrasound reduces the gain of sodium chloride in the brine solution, thereby, reducing the requirement of desalting as a post-processing operation [18].

4.5. Drying

The application of ultrasound in the drying process can accelerate the rate of drying of fruit, vegetables, meat, and fish. It reduces the drying time as well as enhances the rate of heat and mass transfer to preserve the product quality [43]. Ultrasonication has proven to be an effective alternative to the conventional drying process. The removal of water is facilitated by the phenomenon of “sponge effect”, improving the water diffusion from the interior to the surface of the product [44]. New microchannels are formed due to intracellular and extracellular cavitation of water. Also, ultrasound generates air turbulence at the air-product interface, to remove the moisture from the surface [45].

Research on the application of ultrasound in drying shows a reduction in drying time by about 20–30% at the low velocity of the air and reduced temperatures [46]. In addition to convective drying, ultrasound is also applicable for freeze-drying [47] and vacuum drying [48] to enhance the rate of drying over conventional methods. Ultrasound application, when applied for 15–30 min at 0 to 200 W, can create, within the cell structures, microchannels which cause tissue damage [43]. Ultrasound treatment of eggplant before drying significantly decreases the duration of drying and preservation of microstructure [49]. Cruz et al. [50], mentioned that pre dehydration using ultrasound before the process of convective drying of plums and grapes enhances the rate of drying and drying kinetics and also enhances the quality of the products. Ultrasonication has been effective in reducing the drying time due to an increase in mass transfer, resulting in, and efficient drying by reduction of energy consumption and an increase in moisture diffusivity [51]. The mass transfer was enhanced due to the cavitation of the liquid media containing the sample [52].

Kadam et al. [53] mentioned that seaweed treated with ultrasound before drying exhibited enhanced color quality and reduced drying time and cost of energy. Pre-treatment by ultrasound facilitates the reduction of weight, water loss, reduction in drying time, and an increase in solid gain [54]. The effects of varying ultrasound parameters such as time, power, frequency, and amplitude on ultrasonic pretreatment before drying well as ultrasound-assisted drying kinetics and quality have been studied. When treated with ultrasound the food products either loose or gain moisture due to the combined effect of the concentration gradient between the liquid media and product, and ultrasound [55]. The application of ultrasound increased the rate of drying; however, the results may vary in some cases. In general, ultrasound treatment reduces water activity, enhances product color, and decreases the loss of nutrients: flavonoid content, antioxidant activity, vitamin C, and total phenolic content [56].

4.6. Foaming

Ultrasound application enhances the foaming properties of proteins due to decreased particle size, better volume, and increased stability [57]. Sheng et al. [58], reported a significant improvement in egg white's foaming capacity after treatment with ultrasound at 360 W with a minor reduction of foam stability. The foaming properties were influenced by variations in protein structure. Conversely, an increase in capacity and foam stability after probe sonication was observed in soy protein; however, there was no noticeable improvement in the emulsification and foaming properties, after ultrasonic bath treatment at 500 kHz. It was also found that the functional properties of serum proteins, when treated with ultrasound at 20 kHz, affected their foaming capacity and solubility due to exposure to increased temperatures, as a result of sonication [59]. Xiong et al. [60], reported that interaction of pea proteins was promoted and a smooth film was formed at the air–water interface on the application of ultrasound which enhanced foam stability. These results suggest that ultrasound can be applied to modify pea protein isolate's foaming properties. Morales et al. [61], found that the treatment of soy protein isolate solution with ultrasound at high temperature (75–80 °C), improved the foaming

capacity by modifying the particle size of the protein isolate but did not change the stability of foam significantly. A synergistic effect of temperature and ultrasound was observed on foam stability. In the case of jaca protein isolate foaming capacity increased whereas foam stability and water retention capacity decreased due to an increase in ultrasound intensity [62]. Foam stability and foam capacity of proteins of wheat gluten when sonicated gradually increased with the increase in the power of treatment [63].

4.7. Degassing / Deaeration

A liquid is composed of a mixed concentration of gases such as nitrogen, oxygen, and carbon dioxide. The commonly used methods for the process of degassing are by reducing the pressure or by boiling while acoustics treatment can perform this function with minimum temperature change. Upon application of ultrasound the gas bubble vibrates rapidly due to which they come close to each other and grow to an effectively larger size which enables them to elevate through the liquid, against gravitational forces, to reach the surface [64]. This technique can be applied in the degassing of carbonic beverages in the food industry like in the case of beer before bottling, also called defobbing [65]. In the manufacturing of carbonic beverages, the major purpose is the displacement of gas from the surface of the liquid, avoiding any organoleptic damage to the product by oxygen or bacteria. This process includes the coupling of a transducer to the external side of a bottle, which results in degassing. In comparison to mechanical agitation, the acoustic method reduces the count of bottles broken and beverage overflow. In the process of fermentation of sake wine and beer, exposure to ultrasound at low intensity reduced the time taken by about 36 to 50% [66]. The degassing operation assisted by ultrasound is faster especially in aqueous systems, but the elimination of gas is tougher in highly viscous products such as molten chocolate.

4.8. Depolymerization

Ultrasound depolymerization is actively used to depolymerize starch and such researches can be traced to 1933 [67]. Exposure to ultrasound at a low power causes a temporary reduction in viscosities of polymeric liquids but high ultrasound power results in depolymerization and a permanent change in rheology which are useful in food processing [68]. Recent studies have focused on polymer degradation by ultrasonic treatment, including organic substances (nitrobenzene, polyethylene, dyes, aniline) which would slowly develop into a biopolymer (starch, protein, carrageenan) [69]. The cavitation effect of ultrasound induces the depolymerization through two mechanisms: 1. Chemical degradation due to the chemical reactions between high energy molecules and biopolymer molecules eg. Generation of free hydroxyl radicals from cavitation and 2. Mechanical degradation due to collapsing cavitation bubbles in a biopolymer [70]. Exposure to ultrasound also finds great potential in the conversion of raw materials of biomass such as the polymeric carbohydrates to beneficial low weight molecules [71]. A comparative study between ultrasound and some other innovative technologies such as microwave radiation and γ -radiation proved ultrasound to be the most suitable for the procedures for depolymerization of xyloglucan [72] and hyaluronan [73]. A recent study proposed a mechanism of reaction for depolymerization by ultrasound, describing that ether bond cleavage and use of suitable solvent can enhance the process. It also showed that the depolymerization of lignin can be improved by acoustic cavitation [74].

4.9. Cutting

Ultrasound has improved the overall processing of food by enhancing the cutting process. Acoustic equipment presents a novel methodology for slicing or cutting a wide variety of foods during production, minimizing the wastage of products and lesser costs for maintenance.

Ultrasonic cutting employs a knife blade which is coupled with a source of ultrasound connected by a shaft [19]. The tool used for cutting is available in various shapes, each of which can be considered to be an ultrasonic horn which is a part of the entire ultrasonic resonating system. Cutting under the superimposition of vibrations of ultrasound competes directly with technologies such as conventional techniques using knives or saws and water jet cutting at high velocity. Ultrasonic cutting requires low energy [75]. The characteristics of ultrasonic cutting are dependent on the condition and type of food, that is, thawed or frozen. Cutting of fragile and heterogeneous foods such as pastry, cakes, and other bakery products or cheese or sticky products is one of the widespread applications. Ultrasound also helps improve hygiene, as vibrations prevent product adherence on the blades, thus, decreasing the development of microorganisms on the product surface, that is, ultrasonic vibrations enable 'auto - cleaning' of the blades. The repetitiveness and accuracy of the cut cause a decrease in losses due to cracks or crumbs relative to cutting and provide a better weight standardization and portion dimensions [76].

4.10. Sterilization/ pasteurization

Thermal sterilization and pasteurization are commonly used conventional techniques for the inactivation of enzymes and microorganisms in foods. There is considerable loss of nutrients, development of off-flavors and deterioration of functional properties of foods through thermal processing. By the virtue of cavitation effects, ultrasound helps to eliminate these ill effects of thermal sterilization [77]. Ultrasound-assisted pasteurization has found to be very effective against *E. coli*, *Listeria monocytogenes* and *Pseudomonas fluorescens* with no ill effect on casein or total protein content of the milk pasteurized [78]. The killing of microbes is due to thinning of the cell membrane, production of free radicals, and localized heating. Ultrasound alone or in combination with temperature and pressure has found to be effective in inactivating enzymes like polyphenoloxidases, peroxidases, lipooxygenase and pectin methyltransferase and arresting the degradation of vegetables and fruit juices and milk products [79]. Recent studies have shown that ultrasound combined with thermal treatment can inactivate the *Clostridium perfringens* spores in the slurry of beef. Thermosonication can result in a significant reduction of D95 value [80]. It also accelerates the sterilization rate of food and thus reduces the intensity and time required for heat treatment and the damage caused. Ultrasound minimizes the loss of flavor, enhances homogeneity, effective savings of energy [81].

4.11. Extraction

Extraction is a major unit operation used for the effective separation and production of various oils, bioactive compounds and molecules from their matrices. Soxhlet extraction, heat reflux, and maceration are the commonly used conventional techniques for extraction, which require large amounts of solvent, labor, and are energy and cost-intensive [82]. Ultrasound-assisted extraction is an effective alternative that overcomes the drawbacks of traditional technologies with enhanced yields [83]. Ultrasonic implosion and cavitation rupture the cell walls, enhancing the mass transfer from solid to liquid phase. Also, within the tissues, microchannels are created on an ultrasound application which enhances the solvent penetration into the solid matrix which increases mass transfer [84]. Thus, Ultrasound aided extraction contributes to efficient recovery of compounds in lesser time, energy, and solvent requirements, add an added advantage of low-temperature extraction, for temperature-sensitive food products [82].

Ultrasonic assisted extraction is usually performed under continuous wave mode and pulse mode technique is employed over long term extraction. It is generally preferred for the extraction of bioactive compounds due to its versatility, easy operation, the scope of industrial application, with an ability to use less solvent and retain the biological activity [85]. However, the extraction efficiency is greatly affected by

ultrasonic power, frequency, solvent, and the matrix to solvent employed.[86]. Recently the ultrasonic assisted extraction has been extensively employed for the extraction of bioactive compounds from food and food wastes. Ochoa et al. [87] extracted anthocyanins from purple yam employing ultrasonic homogenizer at 750 W in pulse mode and observed that extraction performed at 30°C for 10 min resulted in higher anthocyanin content than the conventional method. Bioactive compounds were extracted from grape pomace using ultrasound (250, 350, and 450 W) for 5, 10, and 15 min and it was observed that maximum extraction (45% of anthocyanins) took place at 10 min of exposure time [88]. Phenolics and anthocyanins were also extracted from jabuticaba peels in an ultrasonic water bath at 25 and 40 kHz and maximum extraction were observed when exposed for 10 min at 25KHz [89]. Bioactive compounds were extracted from a bitter melon using ultrasound, employing different time, temperature, and solvent solid ratio combinations using water as a solvent and observed that the maximum extraction was observed at 68.4°C for a 12 min exposure time [90].

4.12. Rehydration

Food products are dried to preserve them for a longer period of time and need to be rehydrated before use, by means of hot water immersion. Rehydration enables the product to regain its characteristics and restore its properties. The process of rehydration is composed of three consecutive processes: water is absorbed, the product swells and soluble solids are leached [91]. It is treated as a measure of injury or disruptions caused due to the process of dehydration. Any changes in the properties of the reconstituted product are a result of variation in its composition and structure [92]. It is well known that the extent of rehydration, greatly depends on the extent of structural or cellular disruption in the product due to dehydration. Thus, pretreatments can be employed prior to rehydration to prevent shrinkage and enhance product characteristics and optimize quality.

Ultrasound has been used as a pretreatment for drying, dehydration as well as rehydration operations. Tao et al. [93] sonicated white cabbage samples at 1131.1 W/m² and observed that the sonicated samples had higher rehydration rates as compared to control samples. Similar results were also observed for dried green pepper [94]. Rehydration ratio is the measure of the ability of absorption of water by the dried/dehydrated product, which mainly depends on the distribution of pores in the product's microstructure [95]. The rehydration ratio was observed to be highest for sonicated shiitake mushroom in comparison to control samples and other techniques like freezing, blanching, and osmotic dehydration with a value of 4.58, which depicted a great ability of water absorption [96]. Aksoy et al. [97] also reported, that ultrasound treated samples showed higher rehydration ratio for minced meat at 35 °C and 25 KHz in comparison to control samples. Similar results were reported for rehydration of dried carrot treated with ultrasound [98]. Researchers have reported that application of ultrasound can lead to pore formation and develop higher internal stress [93]. Rojas et al. [99] observed that the treatment of apple with ethanol and ultrasound for 10 min at 25°C efficiently increased the rate of rehydration. Wang et al. [100] treated kiwifruit with ultrasound for 0–30 min at 20 KHz and showed that the treatment enhanced the rehydration ratio and reduced the rehydration time attributed to the larger tunnels or spaces in tissues created by ultrasound. Osmotically dehydrated samples treated with ultrasound where rehydrated showed higher rehydration ratios due to the formation of microporous channels due to ultrasound [101]. Similar results were obtained for the rehydration of dehydrated strawberry samples [102]. Kumar et al. [103] applied ultrasound pretreatment on spine gourd before drying, and the rehydration kinetics depicted sharp increment in the rehydration ratio which could be attributed to the rehydration of cavities and capillaries formed during the pre-treatment. Ultrasound is also employed on rehydration of dried food grains and found to cause a reduction in time of

Table 2
Application of ultrasound in food industry.

Category	Products	Advantage	Reference
Meat Industry	Chicken, Beef, Pork, Rabbit meat	Enhances tenderness; Improves water dynamics of tissue; Increase in water holding capacity; Color enhancement; pH escalation & antimicrobial effect; Shortens aging period	[110,109,117]
Fruits & Vegetables	Fresh and minimally processed fruits and vegetables, Juice, Purees, Edible and refined vegetable oil	Reduction of microbial load. (Sterilization & Disinfection); Changes in color; Enzyme inactivation & Desensitization; Enhances drying characteristics; Purity and quality evaluation of oils	[123,132]
Cereal Products	Flour dough, Bakery products (Bread, Biscuits, Crackers, Wafers, Batters (Donuts, pancakes)	Evaluation of dough and batter properties: texture & rheology, density, volume index. Increase firmness enhances texture and color component, Improves sensory and visual aspects.	[128,131,134]
Dairy Industry	Milk, Yogurt, Cheese, Ice Cream	Microbial Inactivation, Homogenization, Reduction of fat globules Enhancement of organoleptic properties and nutritional quality, Reduction in time for cheese ripening and fermentation,	[138,137]
Emulsions	Mayonnaise, Dressings, Creams, Oil emulsions	Increase in the stability index, emulsion capacity, activity index of emulsions	[141,140]

rehydration. Miano et al. [104] suggested that the application of ultrasound enhanced the process of mung bean hydration and also reduced the time required for the process. It also, successfully increase the rate of germination of the bean, desirable for sprouting, with no variation in the properties of starch. Similar results were observed for the hydration of sorghum, where ultrasound enhanced the rate of water uptake and equilibrium moisture content [105].

5. Application of ultrasound in food industry

5.1. Meat industry

The application of ultrasound treatment has been observed to be effective in the processing of various food products (Table 2). The use of ultrasound in the meat industry began with the assessment of fat and muscle of living cattle around the 1950 s. Low-intensity ultrasound is commonly used in improving the taste, tenderness, and quality which are important to achieve consumer acceptability. Recent studies indicate the prospective application of high-intensity ultrasound on fresh meat [106], mostly in tenderizing [107], brining of meat [38], cooking [18], thawing [35], freezing [108] and bacterial inhibition [109]. The most recent research which aims to explain the influence on meat products by the application of high-intensity ultrasound focuses on bovine muscles, predominantly, Semitendinosus and Longissimus [109,109–112]. These studies majorly focus on the microscopic changes, changes in salt dynamics, water, and texture of the meat tissue, on the application of high-intensity ultrasound. Also, oxidative stability, sensory characteristics, and color are important traits of meat influenced by ultrasound. There is a remarkable effect of ultrasound on the tenderness and water dynamics of the tissue [82].

The effect of ultrasound on pH was analyzed and it was reported, that the pH of meat can escalate from the initial value before rigor mortis, on ultrasound treatment (10 W/cm² 2.6 MHz). This could be attributed to the release of ion into the cytoplasm from the cells or by changes in the protein structure which leads to variations in the arrangement of ionic functionalities bringing about a change in pH of muscles [113]. Ultrasound is instrumental in increasing meat tenderness and shortening the period of aging, without any effect on other parameters of quality [107,114]. This is attributed to the rupture of the myofibrillar structure of the protein, collagen macromolecules fragmentation, protein migration, and others which accelerates proteolysis accompanied by an increase in troponin -T and desmin degradation when meat is subjected to ultrasonic treatment [111]. Cavitation generates shock waves that damage the muscular structure. High-intensity ultrasound increases the absorption of water and NaCl in cured meat. The space between fibers is directly proportional to the ultrasonic intensity and high concentrations of salt are strongly related to the rupture of myofibrils [115]. Marinades of meat consist of salts in

two forms, that is, wet and dry. It was observed that the intensity of applied ultrasound determines its effect on pork during wet marination. Ultrasound results in the formation of bubbles, hitting the tissues, leading to microinjections of the solution of brine into the product. This explains the increase of salt content in meat treated with ultrasound [36]. The water dynamics of meat which is treated with ultrasound is a point of disagreement as some authors report an increase in water holding capacity [110] while others report a decrease [116]. The variation can be a result of the method of ultrasound, time, and intensities used for treatment [106].

The color of meat is an important attribute for consumer acceptance. In the case of fresh beef, cherry red color is acceptable. Peña-González et al. [107], suggested that there is no effect of ultrasound on the color of meat as the generation of heat accompanied is not enough for protein or pigment denaturation. In contrast, [113] upon evaluation of meat after being treated with ultrasound found that the color varied from lighter, less red to more orangish-yellow color and less bright than control. Thus, ultrasound enhances the total variations in color, limiting oxymyoglobin, and metmyoglobin formation.

Ultrasound contributes to the antimicrobial effect as well as increases the shelf life of meat products due to the cavitation in liquid media [115]. The antimicrobial effect is also dependent on the time of contact with microorganisms, the type of microorganisms, the quantity of food and its composition, and the temperature of treatment [117]. Ultrasound also finds its application in the freezing of meat products where it can cause the induction of nucleation at increased temperatures during the process. This could be used in the control of distributions of ice crystals, their size as well as the requirement of time in frozen foods [35]. Ultrasonication can also cause ice crystal fragmentation, increasing the number of nuclei and size reduction of crystals.

5.2. Fruits and vegetables

Fresh fruits and vegetables are prone to accelerated deterioration and maintaining their quality is very challenging in the food industry. Ultrasound is observed to be an emerging technology in reducing the rate of both pre and post-harvest losses. It is complicated to interpret ultrasound data in fruits and vegetables because the pores and voids present in them cause scattering of ultrasound and thus have an attenuating effect on them [118]. Research suggests that the firmness of fresh fruits and vegetables can be influenced by the application of ultrasound, varying with the intensity. Also, changes in color were observed in some cases which could be attributed to the probable inactivation of phenolperoxidase and polyphenol oxidase enzymes. These enzymes are responsible for the color variations in frozen and raw vegetables and also, browning reactions. Sonication also imparts an antimicrobial effect which could be due to free radical formation and cavitation [119]. Mizrach et al. [120], gave a detailed description of the

different changes, both physicochemical and physiological involved in maturation and growth, harvesting, and storage period (shelf life). Also, how harvesting time and shelf life can be indirectly assessed by linking the outcomes of physiological measurements such as dry weight percentage, firmness, total soluble solids, mealiness, acidity, and oil content with ultrasound. In another study, the sugar content and maturity of plum fruits was estimated by the measurement of ultrasound attenuation in the tissues of fruit-related with the plum firmness [118]. The viscosity and sugar content of orange juice which had been reconstituted was measured by employing a non-contact ultrasonic process, which operated either in through-transmission or pulse-echo mode [121]. Velocity measurements of ultrasound can also be employed for evaluating purity, quality, and oil composition. A study measured ultrasound attenuation and velocity in some Moroccan oils like argan oil, olive oil, and commercial cooking oils using the pulse-echo technique. Acoustical data was determined by the processing of data for the oils such as absorption loss coefficient, celerity, acoustical impedance, compressibility modulus, and density [122]. Acoustic energy also helps in the extraction of pesticide residue by virtue of its chemical and physical effects significantly. This method of cleaning is effective for fresh fruits and vegetables as it requires less time, retains color and nutrients, maintains texture and is safe to be used in the food industry [123]. Chen et al. [124] also stated that application of ultrasound on fresh produce can inhibit or limit the formation of biofilms or microbes. The blunt enzymes generated due to ultrasound reduce weight loss in substances sensitive to heat. It also helps in the curing and tenderization of fresh vegetables.

5.3. Cereal products

There exist a variety of cereal-based products like biscuits, breakfast cereals, and bars, bakery products, of which bread being the major product. Ross et al. [125], displayed a strong relationship between rheology and ultrasonic attenuation and velocity. This was done by examining the extent to which three varied flour doughs were mixed using conventional rheology and ultrasonic techniques, which provided the proof of application of ultrasound in quality control of dough. Another study depicted the application of ultrasound in the characterization of the fermentation phase during bread making [126]. Skaf et al. [127], formulated a low-frequency ultrasound method that consists of two big sensors so that continuous chemical and physical evolution of dough during fermentation could be overcome. This enabled the evaluation of dough's physical properties, critical time determination and technical parameters influencing the dough development process. Porosity is an important physical-mechanical property that is correlated directly to quality aspects of bakery products. Air incorporation is necessary during the mixing of bread dough and maintenance of dough until formulation, to optimize the rheology and texture of the bread. These air bubbles greatly affect the sound attenuation and velocity which depends on the frequency of waves [126]. Petrauskas [128], employed a rapid and low cost, through transmission ultrasonic velocity technique to monitor the alteration in the consistency of wheat dough which is caused due to proteins and starch gelatinization. For the evaluation of the textural properties of products of bread, low frequency, the direct ultrasonic measurement process is suitable which is non-destructive and rapid. Ultrasound can also enhance dough firmness, bread texture as well as the color component. It also results in the superior quality of products with excellent visual and sensory properties [129]. It was observed that ultrasound treatment decreases the surface hydrophobicity of wheat flour dough and puts in order the secondary structure of gliadin, gluten and glutenin. It also improved gluten's structural properties [130]. In another study [131], mentioned that acoustic treatment on quinoa flour, modified its functional properties due to variations in degradation of starch and non starch components.

Biscuits and other products made of cereals are generally

characterized by crispiness. Acoustic envelop detector was established by Leeds University which assessed the crispiness based on the behavior of displacement/force of food products and acoustic attenuation [132]. Ultrasound can also be used to evaluate batter properties such as viscosity, rheology, and density and cake properties such as symmetry, height, density, volume index which can be employed in products like waffles, donuts, pancakes, and cupcakes [133]. Fox et al. [134], described the application and established the design of an ultrasound system at a low cost to monitor the batters as they are mixed for their specific purpose. To measure the acoustic impedance of batters, the changes in their compressibility were monitored. Substantial relationships were attained between the consistency of batters and acoustic impedance in further measurements of ultrasound [135].

5.4. Dairy industry

Ultrasound is an efficient technology, which enables nutrient retention, leading to increased shelf life and better quality dairy product. It is less costly, rapid, and simple for application [136]. In the dairy industry, it has been beneficial in microbial inactivation. The intracellular cavitation causes damage to the cellular membrane of microorganisms generation of free radicals and damage to DNA [137]. High-intensity ultrasound is capable of enhancing probiotic strain viability for starter cultures used for the manufacturing of culture milk and its products. It also fastens lactose hydrolysis by the release of the enzyme, lactase, and acid production stimulation, thus reducing fermentation time. Ultrasound treatment enhances the organoleptic properties of fermented milk products along with their nutritional qualities due to an increase in bioactive peptides and oligosaccharides, reducing lactose content [56].

Ultrasound also causes a reduction in time required for cheese ripening, by releasing intracellular enzymes, accelerating the breakdown of protein structure, and enhances the textural, organoleptic properties and nutritional characteristics [135]. The application of high-intensity ultrasound has been observed to decrease the size of fat globules in the production of yogurt, improving viscosity, decreasing syneresis, increasing the gel strength, and acceleration of fermentation. It also contributes to a firm and stable formation of a gel by denaturation of whey proteins, division of casein micelles, and recombination of protein fraction to produce a firmer yogurt [136]. The treatment of ice cream mix during the manufacturing process by ultrasound, while freezing, enhances the textural and organoleptic properties of ice cream. This is attributed to the enhancement of nucleation, formation of uniform and smaller crystals of ice, and improved rates of heat and mass transfer caused by cavitations. In cavitations, the bubbles explode which leads to an increase in pressure locally, promoting nucleation of ice and break down of large crystals [138].

5.5. Emulsions

Emulsion and fats like mayonnaise, dressings, cream, etc can be characterized by low-intensity ultrasound. Low-intensity ultrasound acts as a powerful analytical technique for the assessment of chemical and physical properties such as solid fat content, oil content, hardness, crystallization, oil composition, and crystallization [139]. Ultrasound exhibits an efficient alternate for enhancement of the capacity of emulsification. Currently, the application of ultrasound represents an interesting alternative to improve the emulsifying capacity [57]. Zhu et al. [140], suggested that the activity index of emulsification, stability index of emulsification and solubility depicted an increase post sonication. Thus, presenting ultrasound as a tool for improvement of the techno-functional properties of proteins of walnut. On the other hand [60], suggested that the emulsification activity and capacity of foaming were enhanced, however, the rate of adsorption decreased due to increasing particle size, which acts negatively towards the emulsifying activity. Carpenter and Saharan [141], reported that the emulsion of

mustard oil prepared by applying ultrasound showed lasting stability, under ambient conditions, even after a storage period of 3 months, without any noticeable proof of phase separation or formation of cream. Lower droplet size and greater stability of emulsion were observed at 40% amplitude against cremation in comparison to the ones prepared at 20% and 30% amplitude. On the application of ultrasound at 20 kHz and 80 W cm⁻² [139], reported a change in the index of emulsifying activity and enhanced index of emulsion stability. Albano and Nicoletti [141], observed that emulsion stability of pectin mixture and concentrate of whey protein was enhanced by sonication and thus can be applied in low-fat systems. Conversely [142], suggested that the pectin extract from the peel of sour orange showed an increase in emulsion stability at reduced temperatures. The capacity of the interaction of proteins of giant squid mantle with other proteins and oil was enhanced upon sonication along with the properties of emulsification [57]. The index of emulsification of samples showed an increase with an increase in treatment time of ultrasonication and the index of emulsion stability was reported to increase significantly when treatment was applied for 1 min [143]. Thus, the overall emulsion stability can be enhanced by ultrasound treatment.

5.6. Honey

Natural pure honey can be easily adulterated by the addition of substances like chalk, starch, gelatine, sucrose, water, commercial glucose, and various other substances. Thus, to detect adulteration and check the quality, various analytical procedures and techniques have been employed for the compositional analysis of honey [144]. Low power ultrasound has also found its application in the determination of mechanical and physical properties of honey. Singh & Dwivedi [145], suggested that changes in ultrasonic velocity, in turn, caused changes in various physical properties of honey-like viscosity, homogeneity, and density caused by adulteration. It can thus act as an effective means for adulteration detection in honey and ensure the authenticity of pure and natural honey. It can also be used for comparison between different kinds of honey by measurement of moisture content, viscosity, and high-frequency dynamic shear rheology [146].

6. Advantages and disadvantages

Ultrasound is an eco-friendly, green technology that has proficiently enhanced various processes in the food industry. Also, it acts as an excellent substitute for several heat-based, conventional technologies that are detrimental to product quality. Ultrasound effectively contributes to meat tenderization and curing, firmness of fruits and vegetables, better mixing of doughs, microbial inactivation, homogenization, sterilization, and pasteurization and emulsification. Ultrasonication results in the production of a better quality product at lower temperatures, with an improved rate of heat and mass transfer. Ultrasound speeds up the filtration process, increasing the life of the filter, accelerates freezing, and results in smaller crystal size, faster drying, and thawing operations. Ultrasound provides a rapid processing technique, limiting the production cost. It improves process efficiency by eliminating the need for process steps and increased product yield. Also, the quality and purity of the final product are improved, by enhancing its organoleptic properties, firmness, and texture. It also aids in the retention of the product's nutritional characteristics and increasing the product shelf life.

Ultrasound, when applied at high intensities generates heat due to an escalation in temperature, which has detrimental effects on the organoleptic and nutritional characteristics of the food product. Also, the effectiveness of ultrasound against microbial and enzymatic inactivations has not been completely successful. However, the synergistic effect along with temperature and pressure may cause inactivation. Also, high power ultrasound may cause adverse physical and chemical effects on foods. The free radicals generated due to cavitation result in lipid

oxidation accompanied by off-flavors and odors, protein denaturation and reduction in total phenolic contents due to ascorbic acid degradation. The synergistic application of ultrasound with temperature and pressure also results in the formation of free radicals which catalyze reaction that may damage the protein structure and thus adversely affect the texture of the food product. Thus, the intensity and synergy of ultrasound need to be optimized before application.

7. Future prospects

Through the years, several research studies have proved the efficacy of ultrasound in the replacement, enhancement, and improvement of various conventional processing techniques in the food industry. However, the combination of ultrasound with other techniques generates better results on the overall quality of the final product and could be the focus of further research. The further development for the application of ultrasound on an industrial level requires the optimization of parameters and ground-level research to analyze the effect of acoustic treatment on the bulk production of food. The research on a larger scale should also consider the safety aspects and adverse effects of ultrasound on humans. Also, an immense amount of energy is required for the commercialization and industrialization of ultrasound which presents an obstruction in its application in the food industry. Therefore, research on ultrasound should be specifically focused on implementation on an industrial scale.

8. Conclusion

Ultrasound has proven its abilities in the food industry into preservation, extraction, and processing. Ultrasound is being increasingly used to enhance various processes in the food industry and has become an extremely promising technology on the processing front. It becomes more powerful when used in combination with other techniques for the preservation of food. It has several advantages over other pre-existing or conventional technologies and helps cope up or overcome their shortcomings when coupled along with them. Ultrasound with its abilities to increase efficiency and reduce the time required for various processing operations has promised a progressive future. In midst of ultrasound, full-fledged processing unit operations can be accomplished within minutes or seconds, along with a reduction in the overall cost of processing, providing high purity levels of the final product, eradicating wastewater treatment, post-processing with a minimum of energy. The lack of knowledge, understanding, and reluctance to let go of traditional practices, prevents the implementation and commercialization of ultrasound at industrial levels.

Authors contributions

Nitya Bhargava studied the literature and drafted this manuscript; Rahul S Mor monitored and directed the manuscript preparation; Vijay Singh Sharanagat, Kshitiz Kumar supervised the framework and content. The final edited manuscript was proofread and accepted by all the authors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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