Review

Application of ultrasound in combination with other technologies in food processing: A review

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ABSTRACT

The use of non-thermal processing technologies has been on the surge due to ever increasing demand for highest quality convenient foods containing the natural taste & flavor and being free of chemical additives and preservatives. Among the various non-thermal processing methods, ultrasound technology has proven to be very valuable. Ultrasound processing, being used alone or in combination with other processing methods, yields significant positive results on the quality of foods, thus has been considered efficacious. Food processes performed under the action of ultrasound are believed to be affected in part by cavitation phenomenon and mass transfer enhancement. It is considered to be an emerging and promising technology and has been applied efficiently in food processing industry for several processes such as freezing, filtration, drying, separation, emulsion, sterilization, and extraction. Various researches have opined that ultrasound leads to an increase in the performance of the process and improves the quality factors of the food. The present paper will discuss the mechanical, chemical and biochemical effects produced by the propagation of high intensity ultrasonic waves through the medium. This review outlines the current knowledge about application of ultrasound in food technology including processing, preservation and extraction. In addition, the several advantages of ultrasound processing, which when combined with other different technologies (such as microwave, supercritical CO₂, high pressure processing, enzymatic extraction, etc.) are being examined. These include an array of effects such as effective mixing, retention of food characteristics, faster energy and mass transfer, reduced thermal and concentration gradients, effective extraction, increased production, and efficient alternative to conventional techniques. Furthermore, the paper presents the necessary theoretical background and details of the technology, technique, and safety precautions about ultrasound.

1. Introduction

Food processing is the effective conversion of agricultural produce into consumer ready product with the objective of producing more appealing, shelf-stable, compact, and usable and value-added product [22], which can involve single or multiple operation. The raw food items can be processed using several conventional processes and preservation techniques namely drying, baking, boiling, salting, pickling, soaking, etc. which are still used commonly and efficiently. The most traditional food processing methods rely on the underlying theory of increasing heat in order to reduce microbial growth and retard growth of foodborne pathogens that make the food suitable for consumption [122]. Such thermal processing requires high energy, yield low productivity and involve time-consuming procedures that require high external heat input/consumption [19]. There are numerous food items that are susceptible to viral or bacterial intoxication that are not suitable for heat processing. Thus, these heat-sensitive food items on subjecting to thermal treatment can undergo changes at physical, chemical and microbial level including taste, color and textural modifications. This has to lead to the demand for extensive research and development in optimizing the existing technologies and to develop creative and efficient alternative techniques [116]. Some of the novel and innovative methods used in food processing are supercritical fluid extraction, high-pressure processing, pulsed electric field, cold plasma, ultrasound, and ultraviolet irradiation.

The utilization of new “green and innovative” techniques typically involves less time, water and energy in processing, pasteurization and extraction. These techniques are ultrasound-assisted processing [23,171], microwave processing [145], extrusion [77], supercritical fluid extraction and processing [133,140], controlled pressure drop
process [141], pulse electromagnetic field [95,139], subcritical water extraction [128], and high pressure [105]. Food technology is currently a rapid evolving field of applied research and industry, under extreme or non-classical conditions. The production efficiency can be increased by using better alternatives to conventional extraction, processing and preservation techniques, furthermore it can lead to environmental conservation through reduced water/solvent use, minimizing wastewater and removal of harmful contaminants from processing.

The Ultrasound technique can be proved as a vital technique to help achieve the aim of sustainable “green” chemistry and extraction. This technique in the field of chemical and food industry is well known for significantly influencing the processing rate of different processes used [22,51]. Ultrasound-Assisted Extraction (UAE) operates on the principle of acoustic cavitation that damages the plant matrix cell walls and hence helps in the release of bioactive compounds [171]. The ultrasound waves can propagate through any medium as a mechanical wave within a frequency range of 20 kHz to 100 MHz, by generating phases of expansions and compressions. It can induce the formation, development and implosion of cavitation bubbles in a liquid media, when a high acoustic force is applied, which is commonly used for enhancement of several food processing methods [166,193]. The spectrum of ultrasonic waves involves a variety of frequency range which commonly extends from more than the 20 kHz which is the audible range and up to 10 MHz which is less than the microwave frequencies. The magnitude of the frequency that is associated to the ultrasonic effect, i.e., between 20 and 100 kHz, is governed by physical effects and has a wide range of application in non-destructive analytical techniques whereas, chemical effects were observed in the range of frequency in between 200 and 500 kHz [171]. Ultrasound can be used in a wide range of application including processes like fermentation, emulsification, crystallization, reactions kinetics, and extraction technique.

Ultrasound system has an important role in extraction, which help in determining the key design parameters of the extraction process like acoustic energy density, ultrasonic intensity, ultrasonic power and the operation mode (e.g. pulsed or non-pulsed) [171]. The ultrasonic bath and ultrasound probe-type method are the two different types of UAE instruments which are widely used for ultrasound applications (Fig. 1). The system can ease down the process of extraction with high reproducibility, less solvent consumption, simpler manipulation and work up, highly pure final product, elimination of wastewater after treatment and less consumption of fossil energy than normally required for conventional extraction techniques like Soxhlet extraction and Clevenger distillation [36]. The system can effectively extract various compounds such as aromas, antioxidants, pigments and other organic compounds from food components both processed and formulated from a range of matrices (mostly animal tissue, yeasts, microalgae, food and plant materials).

This review paper outlines the principle involved in ultrasound technique and its application in various food processing operations (filtration, extraction, freezing, etc.). As there is lack of awareness about combination of ultrasound with other conventional and emerging food processing technologies, the paper will also highlight the effects of application of ultrasound treatment when combined with other processing techniques such as thermal, microwave, enzymatic extraction, high pressure processing, etc.

2. Application of ultrasound in various food processing operations

Ultrasound can be used in food processing for various operations like extraction, drying, filtration, emulsification, homogenization, etc. The various processes where ultrasound can be applied is listed in Table 1.

2.1. Extraction of valuable compounds from food materials

The extraction through various agri-food originated bioactive compounds which is largely dependent on the efficiency and effectiveness of the extraction methods selected [16,70,179]. Traditional or conventional extraction methods have been used for the extraction of bioactive compounds from various natural sources [134,156]. The extraction parameter is selected in a way that allows simplified separation of the bioactive components with high accuracy and selectivity.

The study conducted by da Rocha and Norena [49] extracted bioactive compounds from grape pomace using ultrasound treatment (250, 350, and 450 W for 5, 10, and 15 min) and observed that extraction performed for 10 min resulted in maximum anthocyanin content (45% more). Also, phenolics and anthocyanin were extracted from jabuticaba peels using ultrasound bath (at 25 and 40 kHz) and it was observed that maximum extraction took place at 25 kHz for10 min of exposure time [64]. Furthermore, similar studies were also conducted by Ochoa et al. [125] and Chakraborty et al. [33] for the extraction of bioactive compounds.

Numerous papers in the literatures have documented UAE application in relation to the reduced the extraction cycle in natural components that require longer hours or even days using traditional processes. Specific component classes like polyphenols, odorants minerals including organic substances are extracted utilizing varied matrix through ultrasound. The mechanical outcomes show maximum solvent penetration inside cells by enhancing the diffusion and cavitation effect, allowing rupture of cell walls besides releasing the compounds in their
reductions in the operation and extracted times, the quantity and energy that are ecologically and economically viable. The main advantages are however, several studies reported such UAE represents another derivative using shorter duration and low operating conditions [175].

medium [60, 70]. Higher yields are therefore obtained with this technology using shorter duration and low operating conditions [175]. However, several studies reported such UAE represents another derivative for traditional technique considering food and natural products that are ecologically and economically viable. The main advantages are reductions in the operation and extracted times, the quantity and energy of the solvent utilized during unit operations and CO₂ emissions [22, 36]. The UAE method has therefore employed towards modifying food items and in development of novel food items which cannot be achieved using conventional extraction techniques [13]. In addition, ultrasound eased the detection and quantifiable procedure in organ phosphorus and triazine pesticides of wine samples, through its sensitivity and versatile nature. Particularly pesticides were extracted utilizing liquid-liquid dispersion micro-extraction assisted by ultrasound [43]. A recent observation emphasized on the new methods of extraction implementation for phthalate ester (PAE) and subsequent examination of the GC-MS in the product matrix. Within this field, various literature was documented outlining various methods of sample preparation/extraction [148, 149]. In baby food items, ultrasound-based process vortex-assisted liquid-liquid microextraction joined with GC ion trap MS (GC / IT-MS) enabled to obtain phthalates, that may be an endocrine disruptor.

Table 1

| Applications | Principle | Products | Advantages | References |
|-------------|-----------|----------|------------|------------|
| Filtration  | Vibrations| Liquid food products eg. Juices | Increase membrane permeation. Enhances filtration process. Requires less time. | [121] |
| Freezing/ Crystallization | Uniform heat transfer | Fruits & vegetables eg. potatoes | Improves freezing by better preservation of the microstructure. Improved diffusion. Requires less time and small crystal size. | [194] |
| Thawing     | Uniform heat transfer | Frozen Products eg. bighead carp | Rapid decrease in temperature. Reduction in time of thawing. Color preservation Inhibit the degradation of lipids. Enhanced quality of goods. Reduced dehydration of products | [98] |
| Drying      | Uniform heat transfer | Dehydrated food products | Mass transfer intensification. Shorter time for processing Organoleptic properties improved. | [190] |
| Foaming     | Dispersion of gas bubbles | Protein eg. pea | Enhances the potential for foaming. Decreases the stability of foam and the capacity to retain water. | [184] |
| Degassing/Dearreation | Agitation | Carbonic beverages | Decreases broken bottles and the overflow of liquor. Requiring less time. | [113] |
| Cooking     | Uniform heat transfer | Fruits & vegetables e.g. sweet potatoes | Enhanced retention of nutrients. Improved heat transfer rate. Enhances the properties of organoleptics. Increased tenderness | [162] |
| Emulsification | Cavitation Phenomenon | Mayonnaise | Improves rheological characteristics. Enhances the stability of emulsions. Less time needed. | [153] |
| Cutting     | Cavitation Phenomenon | Cheese, Bread | Precision in cutting operations. Less time needed. | [102] |
| Extraction  | Diffusion | Food and plant material eg. bioactive compounds | Clean cuts with reduced product loss. | [62] |
| Rehydration | Absorption | Mushroom Slices | Required less solvent Decrease in the rehydration time | [192] |

2.2. Filtration

In combination with different food unit operations, ultrasound was found to improve the processes. Filtration has long been used as an effective techniques for efficient separation of solids by mother’s liquor or liquid processing. Difficulty regarding fouling or polarization in concentration developed through filtrates or cake filter being deposited above the membrane surface as the main process matter. This issue caused the reduction in the efficiency of filtration. Ultrasound energy is therefore successful against such an issue [22]. When ultrasound is applied during the filtration process the accumulation of retentive layers occurs above the membrane layer that causes polarization, it concentration gets distorted, but the intrinsic membrane permeability is left undisturbed. These leads to increased flux and decreased resistant flow [35]. Acoustic filtration is employed efficiently to improve wastewater filtration of industries that can be generally regarded as a gruesome process [93]. Although, optimizing velocity in ultrasound is of utmost importance to avoid damages formed inside filters [22, 180]. Ultrasound combined with filters, improves the life of filter through prevention of membrane caking and clogging, enabling continuing cavity around filter surface [75]. Camara et al. [27] reported that lower frequency ultrasound could help with coordinating membrane foul by its ease in removing particles through the cake layer. By this way, the acoustic filtrated process increases efficiency in processed items and reduces safety concerns. All of the above-mentioned factors are important in promoting the filtration process and are developed being ultrasonic-assisted filtration methods by several companies that are an asset for pre-occurring vibration screens. Although, the growth in this area is reduced by the use of single transducers with low power capacity, which means that newer power transducers could enhance acoustic filtration and improve their ability for large-scale use with vibration amplifiers [44].

2.3. Emulsification

Dispersions and emulsions often contain surfactants for stabilization purposes. The surfactants retard the collection inside the liquid phase about the dispersed matter. The surfactants thereby develop an additional layer around every particle. Although similar surfactants, being substantially stabilized, encapsulates gaseous bubble suspended inside liquid stages. The surfactant consumed in this way, the emulsion or
products and the enhancement of the mechanical properties of emulsion or dispersion quality reduces with the obtainment of erroneous particle size measurements [70]. For decreasing the difficulty in stable gas bubbles, decrease the number of bubbles and favour emulsification, liquids particularly degassed through sonication. Ultrasound devices can produce acoustic cavitation which means the formation and the collapse of air bubbles in the system. The collapse of air bubbles can facilitate the releasing of reactive radicals promoting chemical reactions [96,165]. The collapse of a cavitation bubble between two immiscible liquids along the contact surface creates a higher stable emulsion, also in lower energy [28,67]. As the acoustic power increases, the mean size and bubble population increased. This could increase the shear forces generated on the collapse of bubbles, facilitating the disruption of oil droplets. These changes reduce the size of oil droplets and thereby improve emulsion stability [14].

Several research groups have used high intensity ultrasound to produce protein stabilized emulsions. For example, Li et al. [99] used high intensity ultrasound (frequency 20 kHZ, applied power 450 W for 6 min) to improve the emulsifying properties of chicken myofibrillar protein and enhanced the rheological properties and storage ability of the myofibrillar protein stabilized emulsion. Results showed that the highest storage value (G’ value) and contributed to the formation of better oil/water emulsion gel elasticity was observed at the 6 min ultrasound treatment. The Petrochemical, chemical, cosmetic, and pharmaceutical industries often exploit this influence. US lower frequencies along with higher energy waves are basically utilized in the food sector for generation of mayonnaise, emulsions fruit juices, ketchup, and homogenized milk [181]. Ultrasound is a viable and potential technology for the overall improvement of emulsifier processing efficiency in products and the enhancement of the mechanical properties of emulsifier products.

2.4. Separation

This technique is based on a new principle about particle separation; the elevation in energy that applied to a low-frequency emulsion in ultrasound waves (<30 kHz) was used to split the mixture into its water and oil sections [106,114]). Before it is marketed, however, this principle must be further developed, as ultrasound waves that are high in potential easily utilize the opposing effect by giving rise to a firmer emulsion or dispersion to form. In the dairy field, cleaning the tissues used for protein collection/partition is a crucial procedure towards purity and produce appropriate goods. It can be seen in research done by Luján-Facundo et al. [106], the ultrasound polished tissues efficiently, and its efficiency upsurge at bottom densities [70].

2.5. Alteration of viscosity

Ultrasound may increase and decrease the viscosity, and the impact is either permanent or temporary, depending on its intensity [131]. Also, the ultrasound assists in processes such as homogenisation, cell dispersion, emulsiﬁcation, intracellular content extraction, maturation, drying, enzyme activation and/or deactivation, and degassing. Ultrasound accelerates the fermentation of milk in the presence of bifidobacteria to manufacture yoghurt for the reason that cellulose separation is stimulated due to impulse galactosidase produced later the bacterial cells are demolished [154]. To form yoghurt more equivalent and adhesive, the ultrasound also disperses milk fat. Milk is a colloidal form composed of suspended fat globules in the solvent mixture, aﬂuent in soluble sugar, sodium chloride and proteins. Moisten and fat are non-miscible liquids that appear to detach, and an ultrasound milk cure creates equivalent and uniformly allotted fat globules that permit the use of milk in a myriad of farm products. A review by Candrapala et al. [34] on the outcome of the ultrasound on casein and calcium manifest that the casein micelles and the concentration of calcium did not adjust, while the thickness of milk shrunk.

Ultrasound treatment at various power input, temperature, and time can affect rheology properties and starch slurries. Chen et al. [39], applied the high power ultrasound treatment (0–45 °C, 242–968 W/cm², 2–16 min) on strawberry pulp. Authors observed that high power ultrasound treatment (605 W/cm² and 45 °C for 16 min) affects the rheological properties of strawberry pulp with an increase in the apparent viscosity, storage modulus (G’), and loss modulus (G”). Although the interaction of free Ca²⁺ and low-methylated pectin was promoted by high power ultrasound, the network structure of Ca²⁺ low-methylated pectin was formed, causing an increase in viscosity in the complex strawberry structure. Similarly, in ultrasound-treated (120 W for 20 min) starch gel, Kalinina et al., [86] found a decrease in viscosity; this effect being attributed to the reduction the amount of amylose in the starch gel with an increasing power and duration of ultrasonic exposure. It is therefore possible to use ultrasound to adjust the viscosity of starch solutions used in the food industry.

2.6. Drying

Ultrasound application in the drying procedure will stimulate drying rates for meat, fish, fruits and vegetables. This lowers the drying period, improves the warmth and mass transfer rate, maintain the characteristics of the product [91]. Ultrasound-assisted drying has been found to be an excellent substitute for traditional drying. The evaporation of liquid is enabled through the “sponge effect”, which increases the diffusion of the water from the inside to the product surface [143]. New micro channels are created by cavitation of water extracellular and intracellular. During the product combination ultrasound also influences air vibration, to remove the surface moisture [22,187].

Functioning on the implementations of sound waves for dehydrating indicates the limitation in dehydrate period at low air velocity and lower temperatures by about 20–30% [31]. In vacuum drying [169] and freeze drying [41], ultrasound participates to the upsurge drying ratio as compare to convective drying over conventional methods. Ultrasound application, when put at 0 to 200 W for 15–30 min, can make microchannels inside cell shape that give rise to impairment of the tissue [91]. The treatment of eggplant with ultrasound prior to dehydrating prominently lowers the drying time in addition to microstructure conservation [144]. Cruz et al. [48] stated that pre-drying with sound waves before the convective drying phase of grapes and plums inclines the amount of dehydration and drying kinetics besides improves the nature of the goods. Ultrasound proved efficacious in lowering the drying count because it increased mass transfer, consequently, effective drying by reducing power utilization also increasing the diffusivity of moisture [63]. As cavitation of the fluid media carrying the specimen [124], the mass transfer has been increased.

Kadam et al. [85] found that prior to drying, seaweed treated with ultrasound showed improved colour quality and decreased drying period and power costs. Pretreatment with ultrasound promotes weight control, water loss, shortened drying rate and solid gain development [127]. The influence on ultrasonic pretreatment prior to the drying of various parameters of ultrasound such as power, frequency, time, and amplitude, as well as drying kinetics and ultrasound-assisted efficiency were studied [22]. When food products are treated with ultrasound, they either gain or lose moisture. This happens because of the combined effect of gradient concentration between substance, ultrasound and liquid media [191]. The rate of drying is accelerated by the ultrasound application which may vary the result in certain cases. Ultrasound processing usually lowers the absorption of water, improves the colour of the substance and reduces the loss of nutrients: total phenolic content, flavonoid content, antioxidants activity, and vitamin C [81]. It was worth noting that ultrasound assisted dehydreadtion pretreatment significantly reduces the oil content of fried samples and improves product color.
2.7. Freezing and crystallization

Freezing and crystallization processes are interconnected. These are characterized by nucleation and then crystallization [137,152]. Conventional cooling is quicker when applying ultrasound, and offers uniform seeding, resulting in shorter dwelling time. The final crystal size decreases by the seeds and thus do not harm the cells [163]. An accelerated cooling can be achieved by improving heat transfer [22,97]. Ultrasonic cavitation occurs, which serves as nuclei for crystal formation or disruption of the present initial nuclei. Finer ice crystals are formed between the beginning of crystallization and ice formation which reduces the freezing time [42]. Even so, it reduces cell structure destruction. In ultrasound assisted freezing, the freezing process can be speed up because of the mass transfer, increase in heat and nucleation initiation [50]. Primary and secondary nucleation is the two major phases of ultrasound nucleation. Primary nucleation occurs when nucleation temperature which is less than the required freezing temperature, is reached. This step goes along with the release of latent heat in excess amounts. The high pressure generated by ultrasound (act as a driving force for nucleation) is recorded and result in the reduction of degree of supercooling [90]. When the size of the bubbles exceeds the critical threshold, which is required for nucleation then the bubbles produced by cavitation act as a nucleated nuclei. Microstreaming and eddies can result from the movement of stable cavitation bubbles, thus improving the transfer of mass and heat which resulting in nucleation. Cavitation bubbles and microflow induces shear force due to collapsing. More nucleation sites are produced when ultrasound shatters the dendrites of present ice into pieces [68].

Food stuff has been stored by ultrasound [50]. It is suitable for pharmaceuticals as well as high-value food products. Ultrasound is being used to crystallize food products such as triglyceride oils [90], milk fat [111], ice cream [117]. The additional advantage of ultrasound is that it allows for the prevention of crystal encrustation on cooling elements and ensuring the heat process during cooling [194].

2.8. Rehydration

Food items that have been dried for preservation are rehydrated through immersion in warm liquids before use. Rehydration process helps specify items towards function regeneration with recovered property. Rehydration method consist about 3 sequential procedures: absorption of water, leaching swells of the product, and soluble solids [173]. This is used as an indicator of any damage or disruption caused by the dehydration process. Some modifications in the reconstituted product’s properties are the result of differences in its structure and composition [110]. It has been documented that the rehydration level varies significantly above the level of structure or cell damage inside of the food material due to dehydration. Thereby, pretreatment was used prior rehydration process for reducing shrinkage that boost product properties and efficient optimization is achieved.

As a pretreatment, ultrasound has been used to dry, dehydrate and rehydrate products. Tao et al. [167] evaluated samples in white cabbage for 1131.1 W/m² that stated rehydration levels for sonicated samples were greater than those of the controls. Similar outcomes for dried green pepper have also been observed [164]. Rehydration ratio measures the capacity of the dried/dehydrated product to retain water, that is dependent primarily on pores distribution inside microstructure of items [170]. Rehydrated proportion aroused to be highest in case of sonication treated shiitake mushroom, which showed high capacity of water absorption, compared with controlled products with rest methods such as Blanching, freezing and osmotic dehydration for 4.58 value [192]. Aksoy et al. [2] have suggested in samples treated with ultrasound displayed high ratio of rehydration in case of minced flesh relative to control samples at 35 °C and 2.5 kHz. Similar results for the rehydration of ultrasound-treated dried carrots were reported [142]. Researchers have stated that ultrasound application may lead to the formation of pores and can develop higher internal stress [167]. Rojas et al. [146] reported that apple treatment with ethanol and ultrasound effectively increased the rehydration rate at 25 °C for 10 min.

Wang et al. [177] monitored kiwifruit from 0 to 30 min with ultrasound ranging 20 kHz and observed increase in rehydrated ratio that lowered the rehydration period for large ultrasonic tissue tunnels and pores. Ultrasound treated dehydrated osmotic samples, where rehydrated samples reported higher rehydration ratios due to microporous channel ultrasound forming [183]. Related findings have been documented in rehydrating dehydrated strawberries [6]. Kumar et al. [92] used pretreatment of ultrasound in spine gourd prior drying, in which rehydration kinetics produced a precise improvement for rehydration ratio that might be due to rehydration pretreatment formed cavity with capillary. Ultrasound has been shown to cause reduced rehydration times and is also used to rehydrate dried food grains. Miano et al. [115] suggested the ultrasound application to improve the mung beans hydration period that minimized the duration taken for processing as well. Additionally with no difference in starch properties, it successfully increases the bean germination rate, ideal for sprouting. Similar results for sorghum hydration were found, in which ultrasound increased the amount of liquid absorption and equilibrium moisture content (EMC) [130].

2.9. Preservation

Microbes along with enzymes are the major causes for food deterioration. The growth of microorganism in food products lead to deterioration in food qualities causing health problems. Enzymes that is present naturally in food breakdown fats by lipases or proteins by proteases [35,89]. To inactivate the microbial population and to affect the enzymatic activity, ultrasound has been reported that has been applied in many food products (juices, dairy products, water, meat, etc.) [129]. However, efficiency of ultrasound highly depends on the resistance level of the treated microbes / enzymes. Spores are more resistant than vegetative forms [112].

Gram-positive bacteria are more resistant than Gram-negative bacteria. The thickness and the constitution of their cell walls (cross-linking of peptidoglycan and teichoic acid) could explain their greater resistance to the ultrasonic field [126]. Viruses have a high degree of tolerance [88]. As for enzymes, due to a depolymerization effect, they are recorded to be inactivated via ultrasound. However, the effectiveness of this depolymerization varies [112]. When combined with other antimicrobial methods, ultrasound is also more efficient; thus, various authors have attempted to use it to enhance its impact on microbial and enzyme inactivation in combination with other antimicrobial methods [1,53]. Beneficial combinations include thermosonication (heat and ultrasound), manosonication (pressure and ultrasound), and [35,84].

3. Combination of ultrasound with other technologies

Altogether several methods were established affecting by UAE i.e. Fragmentation, erosion impact, sonoporation, local shear tension and plant structure destruction-detexturation. To explain, we have chosen to provide clear and separate proof of each influence. Yet most likely a mixture of effects occurs during the UAE. Perhaps these results are also sequential during the process of extraction. In addition, as a detailed mechanism about extreme mixture effect produced through ultrasound propagation inside liquid media provides the mass transfer enhancement increasing the movement of solute. The mixing effect occurs through acoustic streaming in the macroscopic scale, and acoustic microstreaming at a local stage [174]. The combinations of effects of mixing towards physical impact about ultrasound onto raw material can demonstrate improvement in ultrasonic extraction efficiency.

Understanding the potential mechanisms also points out that the extraction of the raw material has huge impacts. In addition, the pre-treatment methods employed to the raw materials for treatment
contribute in the efficiency of extraction like milling, flaking, drying which may influence the accessible extracted components [36]. A potential trend might be to determine whether an ultrasound effect generalization could be achieved based on the form of raw material.

3.1. Ultrasound combined with microwave technology

Combining UAE with microwave assisted extraction (MAE) is one of the most effective hybridized methods (UMAE) which provide quick and efficient extraction [157]. Several researchers have studied combination UMAE irradiation in natural extraction Cravotto and Binello, [45], but the considerate capability of the hybrid procedure is still not been appropriately utilized. We assume UMAE possess immense potential in academic as well as industrial research activities due to its highly efficiency and significantly shorter extraction period. This is a cost-efficient method for rapid sample preparation with newer process intensification strategies. Also, double simultaneous irradiation triggers additional along with synergistic effects towards vegetal matrix extraction phenomenon while non-metallic horns are only employed at moderate power. As defined in Cravotto and Cintas [46], horns made of Pyrex®, quartz or Peek® could be safely utilized till 90 W, beyond which material internal structure is destroyed irreversibly. But, it develops slight drawback as UMAE needs low marks of power by just two singly energy sources. Ultrasound significantly enhances the target extraction component via the cavitation phenomena. The effect of mechanical ultrasonication facilitates the withdrawal by plant body of soluble compounds by cell walls disruption promoting mass movement enabling access towards cell material by solvents. During the meantime, the entire sample is heated by microwave very fast triggering the movement of dissolved molecules. Simultaneously, irradiation improves the solvent penetration inside matrices promoting the solvation of analytes with typically increasing the solubility of target components.

García-Vaquero et al. [71] observed that UMAE extracted higher yield of phenolic compound and antioxidant from brown macroalgae as compared to UAE and MAE separately. Also, UMAE of flavonoid compounds extraction from Eucomia ulmoides leaves was studied by Wang et al. [178] and observed that UMAE extracted 2.454% high yield than ultrasound and microwave extraction. Cravotto et al., [47] successfully implemented UMAE as a complementing method for extracting oils through vegetable source i.e., soybean germ and docosahexaenoic acid (DHA)-abundant cultivated seaweed.

3.2. Ultrasound combined with supercritical fluid extraction

Supercritical fluid extraction (SFE) is a comparatively new technology for extraction depending upon the rise in solvation power of fluids (above their critical point). This results in extraction due to the combined effect of gas-like properties (mass transfer) and liquid-like properties (solvation) with diffusivity more than that of liquids [21]. Many researchers use CO₂ based due to user-friendly profile and higher extraction potential along with its inexpensive nature. SFE’s major benefits incorporate pre-concentration impacts, cleanliness with the assurance of higher yields, and simple operating procedure.

Liu et al. [103] showed promising results to obtain iberis amara seed oil using ultrasound pretreatment combined with supercritical CO₂ extraction. And result shows that combined treatment yield more than 25% oil as well as improves physiochemical properties and antioxidant activity of oil when compared with supercritical CO₂ extracted oil. Additionally, Gomez-Gomez et al. [74], studied the effect of supercritical CO₂ with high pressure ultrasound on the inactivation of more resistant microorganisms such as gram-positive bacteria or moulds as well as stability of the lipid emulsions. Castillo-zamudio et al. [32], also observed that when the supercritical CO₂ treatment combined with high pressure ultrasound were effective for inactivation of E. coli microbes and extend the shelf-life of dry cured ham. Supercritical fluid extraction has certain disadvantages like higher expenses to be incurred on equipment, and the complexity of separating polar components without the aid of CO₂ modifiers. Ultrasound also allows a wide range of compounds to be extracted using polar or non-polar solvents and much simpler equipment. The ultrasound treatment enhances the mass-flow of the target components from the solid phase to the extracting media [17].

3.3. Ultrasound combined with extrusion technology

Extraction is carried out by squeezing and expulsion for the making of sugar, wine and juices, or the drying out of bio-squander and in vegetable oil processing units. The squeezing procedure comprises a compression step to remove a liquid from the permeable matrix which contains the target compounds [100]. The fruit and vegetable tissue cells are encased by a membrane, and a cell wall situated in the centre lamella. The tough wall components protect the membranes and thus confining the extraction capacity by applying pressure [36]. To attain superior extricates (quality and quantity versus time) through process intensification level, the combination of squeezing with other technologies such as ultrasound can be examined in a research sense. The average extrusion force, for the most part, diminishes with an increase in the amplitude of the ultrasound producing stronger extrudability [38,118].

According to Zhang et al. [191], ultrasound was used as pretreatment as chemical free method to pretreat rice hull and enhance enzymatic hydrolysis for the production of fermentable sugars. Similar, study also conducted by Yang et al. [186], and observed that ultrasound pre-treatment yield 38.2% higher reducing sugar (381.59 mg/g rice hull) from pretreated rice hull compared to only by extrusion (276.11 mg/g rice hull). Some researcher also reported that ultrasound assisted extrusion technology had been used to improves the dispersion of nanoparticles in the polymer matrix [15].

3.4. Ultrasound combined with Soxhlet extraction

The Soxhlet extraction is customarily utilized to expel fats and oils from their matrix. This framework was designed in 1879 and has been broadly utilized in different areas such as environment, agricultural/food products and indeed pharmaceuticals [4,52,104,119]. Its idea is generally straightforward as it iteratively permeates condensed vapours from a heated solvent, generally n-hexane. Furthermore, the Soxhlet extraction has a few downsides such as long working time (a few hours), huge sums of solvents, vapourisation and a concentration step fundamental towards the end of the extraction. Only a few forms within the theory/literature have recorded the combining of Soxhlet x extraction with evolved strategies, such as ultrasound, to quicken the extraction of fat and oil [36].

Al Juhaimi et al. [3] found that ultrasounds as pretreatment before Soxhlet of peanut oil has been observed with 51.50% extraction yield in 10 min along with slight changes in fatty acid composition i.e. reduction of oleic acid content from 57.10% to 56.69% after 30 min. Furthermore, the combined study of ultrasound and Soxhlet method has been developed to take benefits of both techniques by reducing the number of Soxhlet cycles, the processing time, temperature, and solvent consumption [9]. The Luque de Castro and Chemat groups [59,108] have created unique Sono-Soxhlet procedures. Ultrasound is presented into the exterior or inside of the extraction chamber to extend the extraction of solid material and the transport of compounds from the solid matrix to solvent. Sono-Soxhlet consolidates the benefits of extraction performed with Soxhlet (same extraction by a new dissolvable) and boosts ultrasound mass exchange (diminishing of extraction time). The strategy makes sure that the specimen is collected completely, effortlessly and precisely. This strategy was moreover utilized for extricating the oil content and the fatty acid (FA) composition of oleaginous beans, wiener lipids, cheese fat and pastry shop items.
3.5. Ultrasound combined with Clevenger distillation

The conventional strategy of segregating unstable compounds like essential oils from plant material (herbs, flavours, barks, fruits, etc.) is alembic distillation which is additionally called Clevenger distillation in chemistry research facilities [109,132]. This process is carried out by the iterative refining and heating of the fragrant matrix, which ordinarily needs huge sums of water and energy. Extraction times can vary between 6 and 24 h. Fragrant plants were exposed to boiling water or steam discharge their essential oils by dissipation amid distillation. Recuperation of the essential oil is made sure by refining two immiscible fluids, that’s, water along with essential oil. It was based on the thought that the overall vapour pressures break-even with the air pressure at boiling point. And the constituents of essential oil, for which boiling happens ordinarily between 200 °C and 300 °C, are vaporized at a temperature near to water. When vapours of boiling water and essential oil are condensed, they are both put away and isolated in a framework called the “Florentine flask.” The essential oil drifts at the top, being lighter than water, whereas water goes to the down and isolates.

With the development of a flavour and scent processing units and the expanding request for more natural items, the need for modern strategies of extraction has gone up. The combination of ultrasound with Clevenger or alembic refining has in recent times pulled in expanding interest. This drive to the creation of Sono-Clevenger [135] pointed specifically at extricating essential oils from plant materials. Sono-Clevenger is a starting combination of ultrasonic cavitation at ambient or diminished pressure and Clevenger refining. It points to provide comparable yields to those gotten through conventional hydrodistillation in any case with diminished extraction times and enhanced yields. Unlike customary Clevenger refining, the thermally delicate crude materials are preserved with this technique. The findings of this study are summarised in that ultrasonic extraction under optimum conditions had a significant impact at an energy, economic and environmental level, increasing the viability of the oil and fat industry in contrast to the conventional process.

3.6. Ultrasound combined with osmotic dehydration

Utilizing sound waves with osmotic dehydration yields in higher wastage of water and gain of solute at a lesser temperature of the solution, indeed as protecting the attributes like flavour, colour and temperature-sensitive nutrients [116,138]. This is often due to the increase in porosity of the cell wall (lower resistance) as a result of minuscule channels, which enhanced water and solute transport.

The usage of ultrasound to dry out the apples osmotically has been found to accelerate the mass transfer rate of “water out” and “solute in” 117% and 137% separately due to ultrasound pretreatment [30]. The comparison of Ultrasound treatment with pulsed-vacuum treatment, yielded in excessive moisture losses and reduces gain of solid in cases of apple fruit [54]. The prominent reduction of firm texture was because of ultrasonic treatment compared with specimen treated with pulsed vacuum and could be credited to extreme cell distortion and structure damages [54]. Additionally, Deng and Zhao [54] too detailed that ultrasonic treatment brought about in the more Tg (glass transition temperature), a reduce water activity, rehydration rate, and water content a more extreme rupturing of the structure, as well as fewer crevices and calcium take-up than pulsed vacuum. Stojanovic and Silva [160] also stated that ultrasound application improved the diffusion rates of moisture throughout osmotic dehydration of rabbit eye blueberries; though, this is related to the loss of anthocyanins and phenolics. In the case of melon dehydration through osmosis, the moisture diffusivity was found to decrease at the start of the process (for less than 30 min) due to involvement of sugar. In contrast, it enhanced when the process continued for longer durations (over 1 h) due to the rupturing of cellulase [66]. Gabaldon-Leyva et al. [69] also observed that more moisture losses and the absorption of soluble solids during bell pepper processing resulted as a case of ultrasonic treatment.

Recently, Behir et al. [20] reported the effect of ultrasound assisted osmotic dehydration on the pomegranate seeds. The result showed that the ultrasound pretreatment involves a reduction in the osmotic solution temperature and favoring a reduction in the process cost. Also, the texture of ultrasound assisted osmotic dehydration sample showed more hardness and their microstructure compared to the fresh and osmotic dehydrated sample. Bozkir et al. [25], evaluated the effect of ultrasound assisted osmotic dehydration on the drying behavior and quality properties of persimmon fruit. Ultrasound assisted osmotic dehydration demonstrated a significantly shortened the drying time, increased drying rates, and a 21% increase in effective water diffusivity by 30 min and caused the fewest changes to the quality characteristics of persimmon. The effect of ultrasonic pre-treatment on osmotic dehydration of kiwi slices was investigated by Frithani and Dash [136]. Ultrasound pre-treatment caused increased water losses along with limited solid gain as well. In addition, ultrasound pretreatment shows the effective moisture diffusivities with no shrinkage condition i.e. 3.864 × 10⁻¹⁰.

Ultrasound treatment is utilized in cheese and meat bringing items. Within the case of cheese brining, when ultrasound was used, the rate of expulsion of water and sodium chloride increased [151]. While within the case of pork loin (longissimusdorsi) amid brining, the ultimate moisture content was considerably excessive than the beginning moisture content and the sodium chloride content was in accordance with the quality of ultrasonic treatment used [30].

3.7. Ultrasound combined with enzymatic extraction

Since current time, combined ultrasound with enzyme-assisted separation process in bioactive components, referred as Ultrasound assisted enzymatic extraction (UAEE), has been explored in certain researches [8,37,61,107,120,159]. The UAEE is known to be combined complementary strategies of extraction, providing a few extra points of interest. Enzymes encourage recuperation through the degradation and rupture of cell wall and films within enzyme-assisted extraction (EAE). Enzymes, in any case, such as cell walls, don’t hydrolyze the matrix totally [29,182]. UAEE enhances the process of enzymatic extraction, as the cavity process is stimulated by ultrasonic power which easily break down the matrices, to permit enzyme aided reactions along with consequent discharge of targeted components. Contrary to this, the mass migration of solvents, target particles, and enzymes itself inside or in the exterior of the media can’t be improved by enzymes alone. Hence, in EAE, other physical iterations such as shaking can be utilized to make strides in mass exchange, among which UAE is a perfect choice for its mass transfer enhancement, as it were not for exterior but moreover interior of the matrices [35,83]. Apart from this, ultrasonic power within the UAE raised matrix surfaces and area of contact among stages, will uncover the enzymes to more substrates within the EAE treatment and contribute to the exposing of more target compounds. Several researches have emphasized about increase in enzymatic reaction rates in EAE due to ultrasonic treatment which can upgrade enzyme-substratum collisions and allow a better rate of discharge [25,29]. A few other types of research have shown that through certain conditions, low-frequency ultrasound was competent in progressing the operation of cellulase [5,123]. In a few cases, on the other side, the enzymatic reaction within the EAE might increase the effect of ultrasound within the UAEE in return. As said over, the impact of ultrasound would be significantly affected by the viscosity of the extraction system. While separating constituents, the consistency of the extraction process might be enhanced, especially when water is utilized as a dissolving agent due to the discharge of a few untargeted compounds, such as certain hydrocolloids. A few particular enzymes may corrupt numerous of these untargeted compounds, bringing down the viscosity and resulting in about the negative viscous impact upon improvement of ultrasonic treatment. UAEE is utilized for extracting polysaccharides from...
numerous plant resources, like epimedium leaves [40], wheat brans [176], pumpkin [182], blackcurrant [185] and Ginkgo biloba clears out [188], in which UAEE has illustrated its capacity to boost production. Wu et al. [182] found out that with EAE and UAEE on the recovery of pumpkin polysaccharides. The investigation demonstrated that when enzymes and ultrasound were utilized at the same time (ultrasonic illumination with dynamic proteins) or in the arrangement (ultrasonic light with inert enzymes) for sample, superior recovery of polysaccharides was accomplished in comparison to only EAE and traditional water extraction method or only using UAE. Collectively with the best polysaccharide production around 4.33 ± 0.15 percent were obtained through synchronous UAEE handle. Moreover, to remove arabinoxylan from wheat bran, Wang et al. [176] utilized UAEE with UAE in the sequential arrangement. Building on ultrasound enhanced viability in enzyme treated with UAEE delivered high extracted yields (14.26 ± 0.17%) of arabinoxylan by wheat bran correlating to either EAE or UAE only, they found out. Amiri-Rigi et al. [8] utilized UAEE to extract lycopene from residues of tomatoes within the tomato industry - Tchabo et al. [168] inspected impact of UAEE and EAE for extracting phytochemical component (flavonoid, phenolic, anthocyanin, etc.). In this study, extraction is performed using UAE in combination with EAE and after that application of micro-emulsification extraction in tomatoes residue brought about improved partition in lycopenes when UAEE method is employed. A better extraction and productivity was observed using final products of phyto-bioactive mulberry components in UAEE extracted samples in comparison for UAE, EAE or conventional extracted procedures. They observed an increment using final products of phyto-bioactive mulberry components with better productivity in UAEE extracted in comparison for UAE, EAE or conventional extracted procedures. Amigh and Dinani [7] performed an enzymatic treatment to recover oil from date seed. To enhance the extraction performance of oil from date seeds, these same authors applied the simultaneous combination of ultrasound and enzymes. The results showed that strategy allows increasing the extraction yield of oil by using the sample to solvent ratio of 1:3 in comparison to the treatment using only enzymes. Similarly, the enzymatic extraction after ultrasonication pretreatment has also been reported for increasing the extracted oil contents from peanut seed powder [76]. Bora, Handique and Sit [24] combined enzymatic treatment with ultrasound treatment for extraction of juice from banana pulp and observed that juice yield increased while viscosity of the juice decreased. The total soluble solids and clarity of the juice obtained by the combined treatment was also higher.

3.8. Ultrasound combined with high pressure processing

The applied pressure within extent ranging about 100–1000 MPa at room temperature forms high-pressure processing (HPP) [82,161]. Mainly it is utilized for deactivation of pathogens along with vegetative microbes, yeasts including molds, but pressure treatment alone cannot accomplish noteworthy inactivation of spores and lower of enzymatic activity of certain enzymes [79]. Depending on the type of food, treatment durations can shift from 2 to 30 min in industrial applications [72]. In case where pressure is employed with surrounding temperatures, due to adiabatic heating, a 3 to 9 °C/100 MPa temperature enhancement takes place (that depends on the pressure transferring liquid along with treatment period) [18].

When it is forced to fluid material, the high-intensity ultrasound actuates production of heat. In this manner, ultrasound applications are planned as an HHP pre-treatment that has been designed at 5–8 °C processing temperature, and the temperature fluctuations should be kept minimal due to ultrasound treatment. Apart from this, ultrasound treatment, in combination with high-pressure treatment, ought to cause a reduction in microbial activity. It is reported that the ultrasound-high pressure treatment (US-HPP) has insignificant impacts on the nutritional quality and taste of food.

Zhang et al. [189] studied the effect of the combined pretreatment of ultrahigh pressure and ultrasound (UHP-US) on the properties of vacuum freeze dried strawberry slices compared to UHP and US pretreatment alone. The results shows that UHP-US treatment reduced the drying duration and energy consumption as well as improves the quality more pronouncedly. Gomes et al. [73] showed promising results for prebiotic cranberry juice when US-HPP processes were used for processing. Solid conservation of fructo-oligosaccharides (FOS) was gotten after the treatment. No basic changes after treatment appeared during the instrumental colour examination, soluble solids, pH, organic acids, bioactive components and antioxidant ability. In order to decide the fitting conditions for ultrasound-high pressure treatment (US-HPP) to fulfill, Lee et al. [94] performed the test with respect to the temperature increment and E. coli. A somewhat increased level of E. coli inactivation took place as a result of combining US-HPP.

The application of US-HPP yields higher inactivation of microbes and enzymes and can be taken as another approach for food conservation.

A summary of the various techniques combined with ultrasound for food processing is presented in Table 2.

3.9. Ultrasound combined with liquid/ solid phase micro-extraction

Solid-phase micro-extraction (SPME) and Liquid-phase micro-extraction (LPME) are the most common and widespread pretreatment methodologies. LPME is an easy and user-friendly procedure, but it always takes time and involves vast amounts of samples and organic solvents [78]. The SPME approach is based on the fundamental concepts of sorbent analyte absorption or adsorption [55] and recent developments in this area are often concerned with the use of new sorbent materials [10].

The combination of ultrasound with LPME/SPME can bring several advantages such as high extraction efficiency, high reproducibility, low time and solvent consumption, easy operation, low cost and low pollution to environment. This combination is applied for determination and preconcentration of many kinds of compounds such as heavy metals [172], organic drugs [147], food dyes [11,150] and hazardous dyes [57] from water, juice, etc.

The Azure B adsorption percentage onto CNTs/ZnO@Ni2P-NCs at various ultrasound time (2–10 min) was investigated from aqueous solution [58] and observed that 98.84% Azure B adsorption were achieved at 8.2 min sonication time using 0.031 g of CNTs/ZnO@Ni2P-NCs, 26.1 mg L−1 initial Az-B concentration, and pH 6.3. Dil et al., [56], studied the effect of ultrasound-assisted dispersive SPME for the determination of Methyl Green (MG) and Rose Bengal (RB) dyes in water and industrial wastewater in silverzinc oxide nanoparticles loaded on activated carbon (Ag-ZnO-NC). The result showed that 3.3 min ultrasonication recovers 99.37 and 99.27% of MG and RB, respectively at 4.8 min. The combination of ultrasound with LPME/SPME can bring several advantages such as high extraction efficiency, high reproducibility, low time and solvent consumption, easy operation, low cost and low pollution to environment. This combination is applied for determination and preconcentration of many kinds of compounds such as heavy metals [172], organic drugs [147], food dyes [11,150] and hazardous dyes [57] from water, juice, etc.

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4. Challenges in ultrasound processing of food

The problems exist with non-standardized documentation of methodology and control parameters until the widespread implementation of the technology. Standardized documentation in terms of energy consumption, types of tests and volumes of samples would promote techno-economic evaluation before industrial implementation. Nonetheless, significant research and development activities are required to understand, simplify and implement this dynamic method to its maximum potential. The system must be rigorously tested and proven safe before it is commercially viable.

Many of the studies focus on the ultrasonic frequency (20 or 40 kHz) that is commercially available. It is necessary to study the use of different ultrasonic frequencies along with various parameters such as...
acoustic power, time of treatment and temperature.

The ultrasound method is used to find its used in several applications, such as assessing emulsions droplet size and ability to concentrate, observing the concentration of suspensions and aqueous phase, monitoring fat crystallization, and monitoring of creaming profiles in emulsions and suspensions; in particular for online observation of these properties throughout processing. It is a fast, accurate, non-invasive, and non-destructive method which can be implemented to a condensed or optically opaque device. This can also be quickly modified for online measurements, which would be responsible for monitoring operations in the food processing industry.

The occurrence of tiny air bubbles in a solution can so much inhibit ultrasound that an ultrasound wave can’t spread through the sample at times. This issue can be solved by taking measurements of reflection instead of transmission, although the signal from the air bubbles can interfere with other parts. A lot of information about the thermophysical properties such as densities, compressibility, heat capacity and thermal conductivity of a material is required to make theoretical predictions of its ultrasonic properties. Therefore, theoretical analysis of the data from systems with several components of unknown properties is scanty.

Ultrasonic of low intensity is quite economical and finds its application in the agricultural/food sector. For several years it has been recognized the utility of high-intensity ultrasound to modify the physical and chemical properties of food. However, it was only recently that manufactures started adapting laboratory-scale technology to large-scale processing operations. The increased use of high-intensity ultrasound is primarily based on the availability of low-cost instrumentation, which has been shown to have substantial benefits over alternative technologies.

Most food products have a very high attenuation level, including plant tissues, aerated products, and certain semi-crystalline foods (chocolates), which can make measurement extremely difficult. Because of cleaning, fouling, and other practical constraints the use of a shorter path length might not be feasible in a real method. The use of low-frequency decreases the resolution of spaces. For certain cases, multiple sample variables shift at the same time, and this will influence the ultrasonic properties. The simple sensor is not sufficient in this case, because it results in large and difficult peaks to overcome. If it is challenging to get very accurate and uniform control of temperature throughout the sample, additional errors may be introduced in further measurement. The occurrence of air in the sample results in tremendous impedance mismatch between air bubbles and other food products, which allows air bubbles to reflect and a very fast dispersal. Ultrasound can also be used as a tool for the detection of included air which is not readily apparent otherwise.

### Table 2

| Technique       | Characteristics                              | Target product | Result                                                                 | References |
|-----------------|----------------------------------------------|----------------|------------------------------------------------------------------------|------------|
| Supercritical CO₂ | Extraction temperature, 5 °C; extraction time, 0.5 h; Pressure, 5 MPa | Adlay oil and coixenolide | Ultrasonic helps to increase the 14% extraction yield of adlay oil and coixenolide. | [80]       |
| Microwave       | microwave power, 98 W; extracting time, 367 s; the ratio of solvent to tomato paste, 10:6:1 | Lycopene from tomatoes | Shorter extraction time, less volume of the solvents needed and higher lycopene yield. | [101]      |
| Microwave       | Ultrasound frequency, 19 kHz; microwave power, 80 W | Soybean germ oil | Extraction times were reduced up to 10-fold. | [46]       |
| Osmotic Dehydration | 8% salt/50.1% sucrose; temperature, 50 °C; frequency, 130 kHz. | Cranberry | Decreased time of osmotic dehydration from 9 h to 40 min. | [155]      |
| Osmotic Dehydration | 15% salt/50% sugar solution; temperature, 45 °C; time, 30 min | Potatoes | Increase the efficiency and speed on osmotic dehydration. Improved the quality of fried potatoes by reducing oil and moisture content. | [87]       |
| Osmotic Drying  | Ultrasound time, 20 min                     | Pineapple | Increased the water diffusivity by 45.1%. Decrease up to 31% on the drying time. | [65]       |
| High Pressure Processing | ultrasonic treatment for 5 min (600 and 1200 W/L) followed by HPP for 5 min (450 MPa). | Cranberry Juice | The retention of organic acids was high (greater than 90%), An increase in anthocyanin content up to 24%. | [73]       |
| Soxhlet         | Ultrasound amplitude, 45%; duty cycle of ultrasonic exposure, 5 s; temperature of water-bath, 75 °C; ultrasonic time, 10 s; the height of the probe, 9 cm; inclination angle, 45° | oleaginous seeds such as sunflower, rape and soybean seeds | Reduction in apparent viscosity of PP by 42.8%; Depress the elastic effect and the extruding swell ratio. | [38]       |
| Extrusion       | rotation speed: 10 rpm; temperature: 190 °C; 200 W ultrasonic wave | polypropylene (PP) melts | Maintains the flavor of essential oil. | [108]      |
| Extrusion       | Extrusion speed, 40 mm/s; frequency, 20 kHz; amplitude: 10 m | Extrusion Force | The extrusion force and the material flow stress were reduced by 14%. | [118]      |
| Enzyme          | Ultrasound power, 50 W; temperature 25 °C; time, 30 s; Enzyme (9 µL/g tomato industrial waste powder); time, 60 min; pH 4.5; temperature, 45 °C | Lycopene from tomato | Highest extraction of lycopene. Reduction in the sonication time. | [8]        |
| Clevenger       | Ultrasonic frequency, 26 kHz; ultrasound power, 200 W | Essential Oil | Reduced the time required to achieve yield from 80 min to 20 min. Maintain the flavor of essential oil. | [135]      |
5. Future of ultrasound processing

One of the major accomplishments in the field of innovative extraction techniques has been the emergence of ultrasound-assisted extraction techniques that effectively uses knowledge’s into technology and consumer goods. A technique that has been developed to keep the production wheel running is the use of ultrasonic technology to extract food and natural extracts. Ultrasound-assisted extraction uses physical and chemical phenomena which differ basically from those used in conventional extraction methods. The method of ultrasound extraction will produce concentrated extracts that are free of any residual solvents, contaminants or artifacts. The modern ultrasound model, developed till date, offers net yield and selectivity benefits, improves extraction time, extracts health and productivity, is easily integrated into the industry, and is environmentally friendly. These days, selection of technique to be used for extraction of desired compound from a particular plant should depend on the balance between extraction effectiveness and reproducibility, ease of operation, along with consideration of time, cost, protection and degree of automation. This overview addressed the existing significance of the principle of ultrasound extraction in the chemistry of natural products. A comprehensive review of present as well as past literature demonstrates the utility of this laboratory- and industrial-scale extraction method. We anticipate that this review will broaden the reach of laboratory and industrial/commercial success for possible applications of ultrasound technology in food and natural products extraction.

6. Conclusion

Ultrasound technique has demonstrated its potential for preservation, extraction, and processing in the food industry. In the agricultural/food industry, ultrasound is progressively used to improve different processes and has become an extremely promising tool on the manufacturing front. When used in addition to other food preservation methods, it enhances the effectiveness of the process. It has many benefits over other pre-existing technologies and, which when combined with them, helps to resolve their own limitations. The combination of ultrasound with different food processing technologies can improve process efficiency, reduce the time required for various processing operations, improvement in the overall rate of extraction and yield. Ultrasound has promised a revolutionary future with its capacity to increase productivity and decrease the time needed for different processing operations. The full food processing operations may be carried out with the help of ultrasound within few minutes or seconds, along with a reduction in total processing costs, delivering high final product purity levels, eliminating wastewater treatment, and post-processing with least resources. The lack of expertise, awareness, and inability to give up the conventional procedures prevents ultrasound from being adopted and commercialized at industrial levels. The knowledge that ultrasound technology can be combined with other existing and novel technologies will create awareness for commercial application of this technology and help in development of environmentally friendly technologies for industries particularly food industries.

References

[1] E. Adal, Microbial inactivation by ultrasound in the food industry, in: Technological Developments in Food Preservation, Processing, and Storage, IGI Global, 2020, pp. 86–96.
[2] A. Aksoy, S. Karasu, A. Akciçek, S. Kayacan, Effects of different drying methods on drying kinetics, microstructure, color, and the rehydration ratio of minced meat, Foods 8 (6) (2020) 369.
[3] F. Al Juhaime, N. Uslu, Influence of ultrasonic-assisted pretreatment on oil content and fatty acid composition of hazelnut, peanut and black cumin seeds, J. Food Process. Preserv. 42 (1) (2018) e13335.
[4] G.R. Alara, U.H. Abdurrahman, C.J. Ikegbe, Sonohlet extraction of phenolic compounds from Veronica cinearea leaves and its antioxidant activity, J. Appl. Res. Med. Aromat. Plants 11 (2018) 12–17.
[5] M. Aliyu, M.J. Hefner, Effects of ultrasound energy on degradation of cellulose in food, Ultrason. Sonochem. 43 (4) (2020) 265–268.
[6] E. Amami, W. Khezami, S. Mezrigui, L.S. Badwaik, A.K. Bejar, C.T. Perez, Osmotic dehydration pretreatments on drying and quality properties of dates, Food Res. Int. 106 (2019) 1
[7] A. Asfaram, M. Ghaedi, A. Goudarzi, Optimization of ultrasound-assisted dispersive solid-phase microextraction based on nanoparticles followed by spectrophotometry for the simultaneous determination of dyes using experimental design, Ultrason. Sonochem. 32 (2016) 467–471.
[8] A. Asfaram, M. Ghaedi, A. Hadi, G. Javadian, M. Zolafi, F. Sadeghi, Synthesis of Fe3O4@Gd2O3 NPs magnetic nanocomposite for sonochemical-assisted sorption and pre-concentration of trace Allura Red from aqueous samples prior to HPLC–UV detection: CCD–RSM design, Ultrason. Sonochem. 44 (2018) 240–250.
[9] A. Asfaram, M. Ghaedi, A. Goudarzi, Cu-and SnO2 nanoparticles loaded on activated carbon for efficient ultrasound assisted dispersive SPME spectrophotometric detection of quercetin in Nasturtium officinale extract and fruit juice samples: CCD–RSM design, Ultrason. Sonochem. 47 (2018) 1–9.
[10] M. Ashokkumar, Ultrasonic food processing, Alternatives Conventional Food Process. 53 (2018) 316.
[11] M. Ashokkumar, F. Cavallieri, F. Chemat, K. Okitsu, A. Sambandam, K. Yatsui, et al., Handbook of Ultrasonics and Sonochemistry. Handbook of Ultrasonics and Sonochemistry, Springer, US, 2016.
[12] C.A. Avila-Orta, P. González-Morones, D. Agüero-Valdez, A. González-Sánchez, J. G. Martínez-Colunga, J.M.A. Mata-Padilla, V.J. Cruz-Delgado, Ultrasound-assisted melt extraction of polymer nanocomposites, in: Nanocomposites-Recent Developments, IntechOpen, 2018.
[13] J. Azimir, I.S.M. Zaidul, M.M. Rah Man, K.M. Sharif, A. Mohamed, F. Sahena, et al., Techniques for extraction of bioactive compounds from plant materials: a review, J. Food Eng. 117 (4) (2013) 426–436.
[14] S. Balachandran, S.E. Kentish, R. Mawson, M. Ashokkumar, Ultrasonic enhancement of the supercritical extraction from ginger, Ultrason. Sonochem. 13 (6) (2006) 471–479.
[15] V.M. Balasubramaniam, E.Y. Ting, C.M. Stewart, J.A. Robbins, Recommended laboratory-practices for conducting high-pressure microwave inactivation experiments, Innov. Food Sci. Emerg. Technol. 5 (3) (2004) 299–306.
[16] F.J. Barba, Microalgae and seaweed for food applications: challenges and perspectives, Food Res. Int. (Ottawa, Ont.) 99 (Pt 3) (2017) 969.
[17] R. Behin, M.A. Bouaziz, R. Ettaih, M. Sehilli, S. Sahinine, C. Blecker, H. Attia, Optimization of ultrasound-assisted osmotic dehydration of pomegranate seeds (Punica granatum L.) using response surface methodology, J. Food Process. Preserv. 44 (9) (2020) e146577.
[18] F.W.F. Bezerra, M.S. De Oliveira, P.N. Bezerra, V.M.B. Cunha, M.P. Silva, W.A. da Costa, R.C. Junior, Extraction of bioactive compounds, in: Green Sustainable Process for Chemical and Environmental Engineering and Science, Elsevier, 2015, pp. 149–167.
[19] X. Bhargava, R.S. Moh, K. Kumar, V.S. Shanrana, Advances in application of ultrasound in food processing: a review, Ultrason. Sonochem. 51 (2019) 111–119.
[20] M.M.M. Bindes, M.H.M. Reis, V.L. Cardoso, D.C. Boffito, Ultrasound-assisted extraction of bioactive compounds from green tea leaves and clarification with ultrasound in food processing: a review, Ultrason. Sonochem. 105293 (2020).
[21] S.J. Bora, J. Handique, N. Sit, Effect of ultrasound and enzymatic pre-treatment on yield and properties of banana juice, Ultrason. Sonochem. 37 (2017) 445–451.
[22] H. Bozkar, A.B. Ergin, E. Serdar, G. Metin, T. Bayyal, Influence of ultrasound and osmotic dehydration pretreatments on drying and quality properties of persimmon fruit, Ultrason. Sonochem. 54 (2019) 135–141.
[23] E. Bracey, R.A. Steenbing, B.E. Brooker, Relating the microstructure of enzyme dispersions in organic solvents to their kinetic behavior, Enzyme Microb. Technol. 22 (3) (1998) 147–151.
[24] H.W. Camara, H. Doan, A. Lohi, In-situ ultrasound-assisted control of polymeric membrane fouling, Ultrasonics 106206 (2020).

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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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D.W. Sun, Z. Hu, CFD simulation of coupled heat and mass transfer through gas chromatography-ion trap/mass spectrometry, J. Chromatogr. A 1474 (2016) 1–7.

K.V. Ilkska, R. Manasseh, R. Mawson, M. Ashokkumar, Ultrasonic recovery and modification of food ingredients, in: Ultrasonics Technology for Food and Bioprocessing, Springer, New York, NY, 2011, pp. 345–368.

M. Vinatour, An overview of the ultrasound assisted extraction of bioactive principles from herbs, Ultrason. Sonochem. 8 (3) (2001) 303–313.

Z. Hu, Y. Wang, B. Sun, Y. Liu, H. Zhang, Optimization of ultrasound-assisted enzymatic extraction of arabinobioxyran from wheat bran, Food Chem. 150 (2014) 482–488.

J. Hao, W.H. Xiao, J.H. Ye, J. Wang, V. Raghuvan, Ultrasonic pretreatment to enhance drying kinetics of kiwifruit (Actinidia delicosa) slices: pros and cons, Food Bioprocess Technol. 12 (5) (2019) 865–876.

I. Cieplak, J. Biskupski, C. Pajak, P. Biernacki, E. Popielska, J. Bobrowska, S. Kowalski, M. Stasiak, The effect of high power ultrasound on milk homogenization and functionality, Int. J. Food Sci. Technol. 44 (2009) 939–946.