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An Update on Applications of Power Ultrasound in Drying Food: A Review

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Abstract: Ultrasound is sound waves with above the human hearing range frequency that is approximately 20 kHz. Application of power ultrasound in combination with other food processing methods including drying, is considered to be an emerging and promising technology. The use of novel non-thermal technologies, such as power ultrasound, is suitable to facilitate the drying of heat sensitive food materials. Ultrasound enhance heat and mas transfer which result in faster moisture removal during drying due to heating, vibration and synergistic effects. These effects could lead to product quality preservation in terms of color, texture, vitamin C and antioxidants content, by the use of milder drying conditions, and in some cases can promote better energy efficiency. In this article, after a brief review on the history of ultrasonic drying, different methods are categorized and combinations of ultrasound with novel drying methods and their effects on phytochemicals are discussed with the focus on the recently published articles. Studies showed that the quality of ultrasonically dried products was usually higher than conventionally dried products. However, the effect of ultrasonic drying on the texture and nutritional value of the products should be further investigated.
Keywords: Ultrasound; Drying; Heat and mass transfer; Product quality.

1. Introduction

Drying is one of the first methods of preserving food and it has become a common process in food industry. Drying is considered to be one of the most energy intensive industrial processes; researches have shown that thermal drying operations consume up to 25% of the industrial energy in developed countries [1]. During the drying process, water allocation is mainly controlled by mass transfer resistance (internal and external). The rate of the water movement inside the materials is affected by the internal resistance and the convective transference of vapor from the solid surface to the air is controlled by the external resistance. The food material characteristics define the internal resistance, while the external resistance mostly depends on the thickness of the diffusion boundary layer [2].

The conventional drying process limitations could also be partly overcome by utilizing novel technologies as additional energy sources, such as infrared radiation, microwave or power US, in order to reduce drying time and temperature [3].

Ultrasound (US) application is based on the use of acoustic waves energy with a frequency above the human hearing range which is approximately 20 kHz [4]. The US applications in food processing, can be categorized into replacing traditional technologies and/or assisting them. In the recent years, the efficiency of the US assisted processes is improved and the disadvantages of some of the traditional processing technologies are also enhanced by the use of US. These US applications in food processes include, but not limited to enhancement of dehydration, freezing, thawing, extracting and filtration [5]. Therefore, the aim of the application of US in combination with conventional and novel drying technologies is to reduce internal and external resistances in heat and mass transfer during the process to improve drying efficiency.

The conventional drying process limitations could also be partly overcome by utilizing novel technologies as additional energy sources, such as infrared radiation, microwave or power US, in order to reduce drying time and temperature [3].

The main effect of US waves is to produce mechanical effects both in the solid moist material and the air in the around the evaporation area and consequently and its application in drying process can strengthen the water removal without the need to use a high amount of thermal energy [6]. US waves enhance moisture removal from food materials in the drying process due to “heating effect”, “vibration effect”, and “synergistic effect”. The heating effect indicates that a portion of the US energy is adsorbed by the drying material and causes a temperature increase that rises water vapor pressure in the evaporation area and the vibration effect implies that rapid US vibration can cause turbulence in the air near the drying area in the evaporation region, thus enhances the mass and heat transfer processes. These effects can cause a synergistic effect to increase the drying efficiency [7].

The “sponge effect” in gas–solid systems are mainly related to the quick series of alternative compressions and expansions caused by the ultrasonic waves in the solid moist material and its surrounding air. Microscopic channels can also be created by this mechanical energy which will in turn facilitate internal water movement [8]. Moreover, microstreaming and high turbulence at the interfaces will occur as well [9].

Hot air drying in combination with power ultrasound has been applied for dehydration of different products, such as several fruits and vegetables, which has resulted in shorter drying times. Power ultrasound’s mechanical energy could help to decrease both the external and the internal mass transfer resistance in the drying medium without the need to use a high amount of thermal energy; so the combination of low temperature drying with US technology in order to dry heat-sensitive materials have become an area of interest for further studies [10].

The cavitation phenomenon could also help to eliminate the most strongly attached water molecules which helps achieve very low moisture contents in ultrasonically dried products [11]. Because of creating pressure differences, microstreaming at the boundaries and oscillating viscosities, US can change the diffusion boundary layer. Likewise, external resistance to mass transfer can also be reduced by the increase in bulk transport in the sample which is a result of the agitation in the fluid produced by US. Furthermore, pressure change in the material which is a result of compressions and expansions caused by US waves, can produce micro-channels that facilitate the fluid transport; which means that removal of the moisture from the inside of the sample hastens by the sponge effect formed as a result of these pressure changes. So, the internal resistance to mass transfer is affected by all of these factors. The heat transfer coefficient can also be increased by US treatment, which because of higher heat transfer can as well hasten the moisture removal [12].

Musielak et al., in a recent review stated that US technology has not found a wide range of applications in food drying industry in spite of numerus studies on US applications and its proven mechanism of improving drying process. They reviewed the designs of different US assisted dryers and their mechanisms and concluded that the main limitation for industrial application of US technology in food drying industry is the lack of operational technology to generate the needed scale of airborne power US [13].

Therefore, it can be inferred that US application can be effective in constant rate and falling rate period of the drying process. Since in the constant rate period, the evaporation happens on the surface of the moist material, the effect of US in causing air turbulence accelerate the drying process and in the falling rate period, mechanical effects of the US on the moist material can increase the drying rate [14].

In the following sections, after a brief review on the history of US assisted drying, different methods of utilizing US waves to assist drying process are categorized into direct contact US, airborne US, intermittent US and the use of US as a pretreatment for drying fruits and vegetables. Additionally, the combination of US technology with novel drying methods including fluidized bed dryer, low temperature drying and vacuum drying are looked over and finally the effects of US assisted drying on phytochemicals and vitamins are discussed with the focus on the recently published articles.

2. History of drying by ultrasound

The first researchers who considered ultrasound for dehydration was Burger, F. J. and Sollnerl, K. who conducted their experiments in 1936. They claimed that with the help of US they have removed 0.5 - l.0 cm3 of water from 100 cm3 of wet quartz sand. Further studies showed that US application was also effective in drying sugar and the changes that US waves exert on diffusion currents was considered to be one of the mechanisms of US assisted drying. Studies have concluded that in the range of capillary moisture, application of intense US vibrations can hasten drying because (a) it increases the diffusivity and decreases the viscosity; (b) it creates and heats up the bubbles locally and subsequently creates a pressure which presses out the moisture; (c) because of creating alternating pressure, it causes pressure drops so that the water in the capillary channels moves towards the surface [15]. Industrial developments in the areas related to reducing energy consumption have caused a new quest for new energy efficient methods of drying that are more economically feasible. US irradiation improved the drying speed even in some drying methods that the temperature is usually close to the ambient temperature. Results of US assisted drying of fibrous materials and suspended particles in air have also been desirable. US in combination with other dehydrating techniques demonstrated synergistic effects which offers interesting possibilities for US assisted drying [16].

The application of US energy by using the stepped-plate transducers directly coupled to the food samples has proven to be very effective method for drying food. By using the new US technology, final moisture content of less than 1% have become achievable and it is also possible to reduce the drying time significantly. Because of the new high efficiency US systems, not only the energy consumption is reduced, but also the product color and phytochemicals is well conserved and the products can be rehydrated over 70% [17].

US has so far been used for improving dehydration in solid–gas systems (e.g. drying of onions). US has also been used in solid–liquid systems like the treatment of submerged products in hypertonic salt solutions for meat or cheese or fruits in sugar solutions. In these methods, mass transfer will be increased when the US power reaches a specific threshold value for the product [18].

In another study on US assisted drying, kinetics of air drying of persimmon cylinders were determined with and without application of high-intensity US (154.3 dB and 21.8 kHz) and under various drying air velocities. During dehydration of persimmons, high-intensity US affected the mass transfer process mainly in the low range of air velocities (less than 4 m/s). The drying rate was increased at the lowest air velocities using high-intensity US which influenced external and internal resistances. In such US assisted drying methods, air velocity has a reciprocal effect so that higher air velocities reduce the external resistance but at the same time acoustic field inside the drying chamber is disturbed by high air velocity and US effects on drying kinetics weakens [2, 19].

Sabarez et al., (2012) applied ultrasound in a drying process by transferring the US energy using the product tray as the US transmitting surface with solid contacts to the product. They stated that US application in conventional hot air drying process can significantly reduce the processing time and energy consumption, without adversely affecting the product quality with regard to the micro structure and texture hardness. Using low temperature and high US power will result in maximizing such effects (Figure 1) [20].

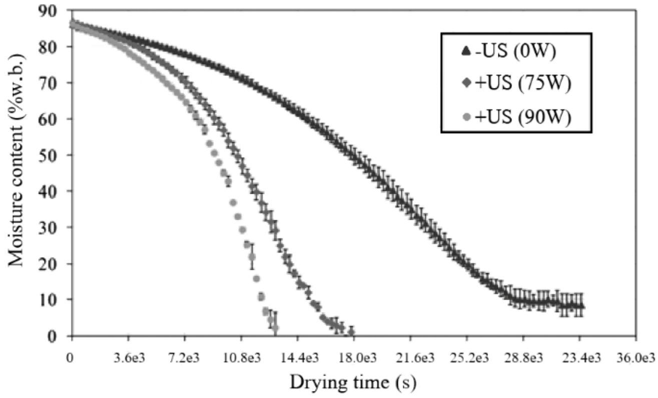

Figure 1. Effect of ultrasound on the drying kinetics of apple slices at different ultrasonic power levels (T=40ºC; RH=25%) [20].

Figure 2 demonstrates the effect of US on improvement of mass transfer and heat transfer in US assisted convective drying of biological materials. The curves show the moisture ratio decrease and temperature increase of the samples. Continuous curves (a) demonstrate the process without US while dotted curves (b) represent the US assisted drying. These curves show that moisture ratio decrease and temperature increase occurred faster in the US assisted drying which can be explained by US facilitation of heat and mass transfer [21].

Figures 1 and 2 demonstrate that US can significantly reduce the drying time by its effects (mechanical, heating, vibration, and synergistic effects) and by facilitating heat and mass transfer.

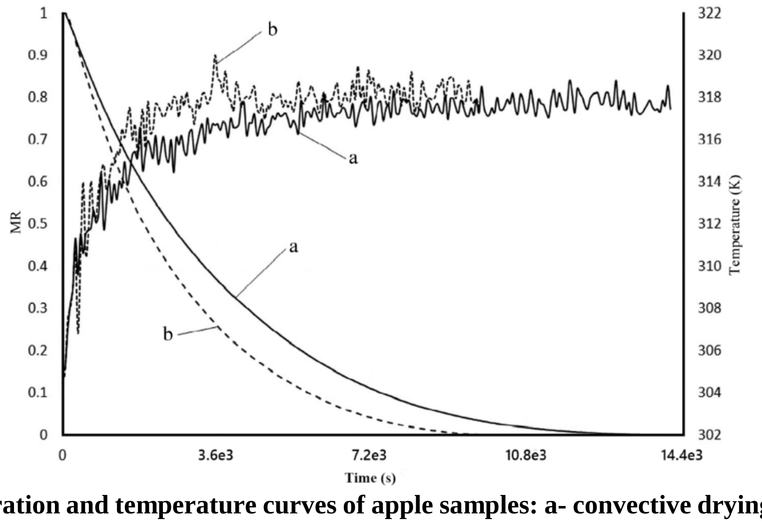

Figure 2. Moisture ration and temperature curves of apple samples: a- convective drying without US, b- US assisted convective drying [21].

3. Ultrasound assisted drying in food technology

3.1. Food drying process by direct contact power ultrasound

A pilot scale drying system based on the application of direct contact high intensity US at low temperatures equipped with forced-air, vacuum and static pressure, was designed at and tested by de la Fuente-Blanco et al., (2006). The US assisted dryer was based on a rectangular plate transducer, working with up to 100 W power and at a frequency of 20 kHz. The US transducer was mounted at the upper part of the drying chamber. A vacuum chamber was fixed parallel to the transducer plate to apply the suction while its upper porous surface acted as sample holder and also facilitated the elimination of the removed moisture. A pneumatic piston also allowed the application of pressure at the sample-transducer interface. A controlled temperature and flow-rate, forced-air fan also improved the elimination of the ejected internal moisture at the lateral surfaces of the samples. Using this dryer, carrot cylinder slices were dried at 30˚C and results (Figure 3) showed that the increase in US power, increased the drying speed and reduced the drying time significantly [8].

3.2. Food drying process by airborne US

In another study, disk radiators were used to carry out the US drying experiments, and to provide resonant amplification of US vibrations (130-150 dB), a special drying chamber was designed and tested. Drying experiments on ginseng and other vegetables demonstrated that in comparison with pure convective drying, the airborne US application decreased power consumption by 20%. Furthermore, in a constant drying time, the final moisture content was 6% lower (Figure 4). The high level of drying intensification by US helped lowering the temperature of the drying agent (air) and improved the final color, texture and thermosensitive phytochemicals of the dried products [22].

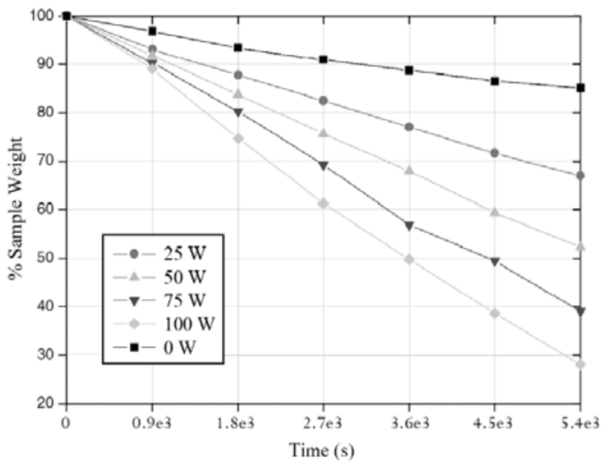

Figure 3. Effect of US power variation on dehydration process of carrot slices at 30˚C [8].

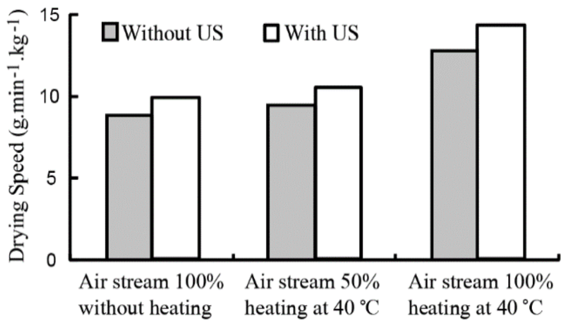

Figure 4. Effect of US application on drying speed [22].

A recent review article also mentioned possibility of the use of contact US in combination with different drying methods including convective drying, freeze-drying and solar flatbed drying [23].

Beck et al. (2014) evaluated an airborne US equipment to enhance the conventional hot air drying process. In order to eliminate the effect of tissue structure variations in different plant samples, they used a model food system consisted of water, cellulose, starch and fructose with similar physical and thermal properties of plant-based foods.

US application resulted in reduction of overall drying time and better product texture and thermophysical characteristics were retained. They stated that absence of a direct contact between the sample and the US horn will lead to a greater possibility of utilizing US on an industrial scale dryer. Optimal levels of US power, temperature, air humidity and air speed that significantly affected the drying process were found using the RSM method. Results showed that a certain level of relative air humidity was necessary for successful transmission of airborne ultrasound and above a certain US power level, stability of the acoustic field was decreased [24].

3.3. Intermittent US in food drying processes

In an experiment on drying apple, the net sonication time was successfully reduced by 50% by the use of intermittent US; while it caused only minor reductions in the US effects. So it was concluded that one of the ways to minimize the energy consumption of the US systems for the industry and an important indicator for process design is the successful application of intermittent US [25].

Continuous US application with direct contact at 6.7 µm amplitude in a freeze dryer caused an instant increase in the sample temperature and freeze-drying conditions were lost. By applying intermittent US treatment, sonication time was reduced to 10%; amplitude was also decreased to 4.9 µm which increased the sublimation rate while the sample temperature was not increased. The required drying time to achieve a final moisture content of 10% (dry base) was reduced by 11.5% by the intermittent US treatment. Moreover, the US treatment did not affect the quality of the product in terms of color, vitamin C content, bulk density, and rehydration [26].

3.4. US as pre-treatment for drying of fruits and vegetables

Ultrasound can also be used as pre-treatment on fruits and vegetables prior to the drying process. Studies have shown that such pre-treatment can result in a faster drying process, reduction in energy consumption of the drying process and better product quality.

A study on the application of US as a pretreatment before drying of mushrooms, cauliflower and brussels sprouts showed that US pretreatment can reduce the drying time while the US treated samples had higher rehydration properties [27]. Another study showed that after US pretreatment on banana prior to drying, water diffusivity was increased that caused 11% reduction in overall drying time which lead to increased energy efficiency [28]. Likewise US pretreatment on pineapple before air drying, increased water diffusivity so the drying time was reduced over 1 hr. (8% reduction in total drying time) [29].

Many studies have been conducted on the effects of US pre-treatment on drying process; Table 1 have summarized some of the recent studies and their results in this area.

4. Combination of ultrasound with novel drying technologies

4.1. Ultrasonic assisted fluidized bed drying

In another study where the dryer chamber was a vibrating aluminum cylinder, which was able to create a high intensity US field in the air flow inside it. A power US transducer with 21.8 kHz frequency was mounted to the chamber's center. Carrot cubes and lemon peel cylinders were dried with and without US at 40 ºC and different air speeds. The effect of US on drying rate was affected by US power, air speed and mass loading (Figure 5). The acoustic field inside the chamber was disturbed at high air speeds which weakened its effect on drying kinetics [39]. The effects of power US on drying of lemon peel cylinders were observed in all of 0–37 kW/m3 power range, whereas for carrots, it was necessary to apply a threshold acoustic power density in the range of 8–12 kW/m3 or higher to be able to achieve the effects. The effect of acoustic energy on lemon peel drying was more powerful than carrots which may be due to the fact that lemon peel is a more porous than carrot [40]. This conclusion about the effect of texture and porosity was later confirmed in a study on dehydration of grape seeds which was carried out with and without US application at 1.0 and 1.5 m/s air velocity. Results showed that the dehydration kinetics of grape seeds was not influenced by US application. This showed that the physical characteristics (low porosity and hardness) of the grape seeds may influence the absorption and reflection of the acoustic waves reaching inside and affecting the product [41].

4.2. US assisted low temperature drying

A research on low temperature drying of clipfish showed that by using US with 25 Wkg-1 intensity and at 20 ºC, drying time can be decreased by 43%. US was more effective on the drying rate during the primary stage of the process, while the effects was weakened toward the end of drying process. However, despite the quicker dehydration, the energy consumptions for US drying increased multiple times. It was concluded that in order to achieve a feasible and energy efficient US assisted low temperature drying process, US intensities in the convective drying of clipfish should not go above 2 Wkg-1, while the drying time should be decreased by at least 50% [42].

In another study, diced apples were dried at low temperatures (-10, -5, 0, 5 and 10 ºC) with and without US application. At every tested temperature, the application of power US hastened the drying kinetics, resulting in decrease of the drying time up to 77%, which was occurred due to ultrasonic improvement in convective mass transport and diffusion. Chemical analysis showed that US application caused a larger degradation of flavonoid and polyphenol contents and a reduction in the antioxidant capacity, which was associated to the cell disruption promoted by the mechanical stress of US vibrations [10].

Santacatalina et al., studied the drying process of desalted cod slices without and with US application (20.5 kW/m3) at different low temperatures (-10, 0 and 10 ºC). The drying rate was increased by the application of US at each tested temperature, drying time was also decreased by 16% at 0 ºC and up to 60% at -10 ºC. The US assisted dried samples rehydration rate was slightly lower than that of conventionally dried samples, but the US assisted dried samples were whiter and harder, which was closer to the qualities preferred by consumers [43].

Recently a study on the combination of US with low temperature drying at -10 ºC and 10 ºC to dry diced apple, also showed that US can be considered as a non-thermal method with minor impact on the texture, rehydration characteristics, antioxidants and phenolic content of the product to facilitate the low temperature drying of fruits [44].

Table 1. Recent studies on the effects of US pre-treatment on drying of food material.

Product	Drying Method	Results	Reference
Parsley leaves	Microwave-convective drying	Significant reduction of the drying time and energy consumption and maintaining quality	[30]
Pineapple	Convective drying	US accelerated the drying process	[31]
Cashew apple bagasse puree	Hot air drying	US reduced the quality loss and improving the quality (antioxidant activity)	[32]
Mulberry (Morus alba L.) leaves	Convective drying	US enhanced the drying kinetics and reduced energy consumption without damaging the quality	[33]
Melon	Fixed bed dryer	Faster drying rates, higher carotenoids content, softer texture and color difference similar to the untreated sample	[34]
Pineapple	Hot air drying	Drying process was accelerated and final vitamins content was higher than untreated sample.	[35]
Apple	US assisted convective drying	Enhancement of osmotic dehydration and accelerated the convective drying process resulting lower water activity and better color	[36]
Tomato Slices	Hot air-microwave hybrid oven	Reduced drying time and better rehydration	[37]
Button mushroom slices	Hot air drying and far infrared drying	Drying time reduction and improvement of mass transfer coefficient and effective moisture diffusivity	[38]

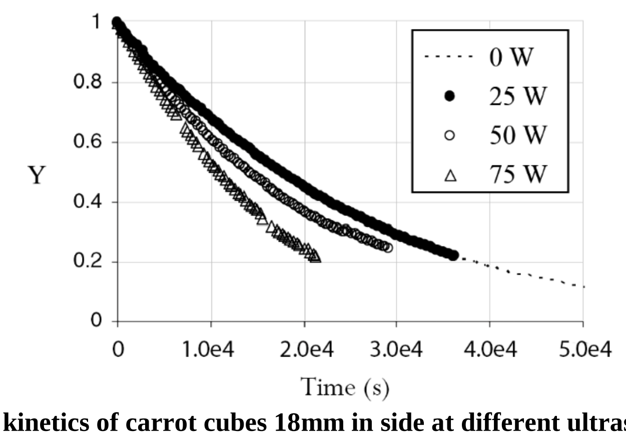

Figure 5. Drying kinetics of carrot cubes 18mm in side at different ultrasonic powers [39].

4.3. US assisted vacuum drying

A laboratory scale ultrasonically assisted and vacuum drying (USV) system was developed to reduce the dehydration time of chicken meat and beef (Figure 6). The drying time for the USV, oven and vacuum drying techniques at 75 °C was measured to be 330, 780 and 570 min for chicken and 300, 750 and 480 min for beef, respectively and USV technique resulted the lowest energy consumption rate. It was observed that by an increase in the temperature, the difference between the USV, vacuum or oven drying time was increased. Consequently, faster dehydration using USV, and vacuum drying instead of oven drying caused less damage to the meat fats. In addition, decreasing the drying time is beneficial for drying the products which contain heat-sensitive biomolecules [12].

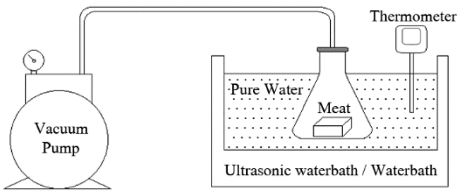

Figure 6. Ultrasonic assisted vacuum drying system [12].

5. Summary of recent US assisted drying studies

Some of the recent studies published on the use of ultrasound in combination with conventional and novel drying technologies and its effects on drying time, energy consumption and quality parameters of the dehydrated food materials are summarized in Table 2.

Table 2. Recent studies published on US assisted drying of food materials.

Product	Method	Results	Reference
Passion fruit peel	Hot air drying with ultrasound assistance	Significantly reduced the drying time, increased the mass transfer coefficient and effective diffusivity; the antioxidant activity was maintained and phenolic content loss was reduced.	[45]
Raspberries	Microwave and ultrasound enhancement of convective drying	Significantly improved the drying kinetics, energy utilization and product quality	[46]
Purple-Fleshed Sweet Potato	Hot air drying with contact ultrasound assistance	Significant acceleration of internal mass transfer and faster drying rate.	[47]
Desalted codfish	Ultrasonically assisted low-temperature drying	Increased drying rate and shortened drying time (16-60%)	[43]
Strawberries	Microwave and ultrasound enhancement of convective drying	Significant improvement of the efficiency of heat and mass transfer	[48]
Apple	Ultrasonically assisted low-temperature drying	Shortening of the drying time up to 80.3% with minor quality loss	[44]
Green pepper	Airborne ultrasound and microwaves on convective drying	Drying time and energy consumption was reduced and quality factors was positively affected.	[49]
Eggplant	Ultrasound-assisted atmospheric freeze-drying	Reducing the drying time while maintaining antioxidant content	[50]
Pea seeds	Ultrasound-assisted heat pump drying	Improved drying rate and better germination performance seeds.	[51]

6. Effects of US assisted drying on phytochemicals and vitamins

The influence of power US assisted drying on the kinetics of apple dehydration and its microstructural and antioxidant properties was investigated by Rodríguez et al. [52] Results showed that at the acoustic power density of 30.8 W/m^3 the decrease in temperature causes a decrease in degradation of polyphenols, flavonoids and the antioxidant activity. This indicated that US assisted drying is suitable for preserving antioxidant activity and phenolic compounds because it helps to reduce the drying temperatures. Although cell collapse and disruption occur during the drying process specially at higher temperatures, the effect of the US on the cell tissue was more detected at 30 ºC than at 70 ºC [52].

Fernandes et al. investigated US assisted air drying of apple and their results showed that US application at 45 °C and 60 °C, increased the effective diffusivity of water up to 79 % which caused a reduction in the total drying time by 35 % in comparison with unsonicated air-drying. The availability of vitamins B1, B2, B3, and B6 in dried products was increased by the application of US while the availability of vitamins B5 and E was decreased in the products of all tested drying conditions [53].

Overall many other articles, including the ones mentioned in Table 2, confirm this conclusion that US assisted drying can help to preserve phytochemicals and vitamins in the dried products.

7. Conclusions

In this review, different applications of ultrasound in food drying process were discussed including combination of US with different conventional and novel drying technologies and also ultrasonic pretreatment. Numerous studies have shown that ultrasonic waves can intensify heat and mass transfer during the drying process thus reducing the drying time, preserving product quality and increasing energy efficiency. It should be noted that some types of food material are not suitable for ultrasonic drying (e.g. low porosity, hard texture).

Ultrasound vibrations can be applied to the material to be dehydrated via direct contact or in air borne form. It can also be used continuously or intermittently and in combination with different drying technologies like convective drying, fluidized bed drying, low temperature drying and vacuum dying.

The overall quality of ultrasonic dried products is usually higher than conventionally dried products whereas the effect of ultrasonic drying on the texture and nutritional value of the products and combining US with other novel drying technologies and investigating the effects of ultrasound on the texture and nutritional value of the products should be further investigated. Operational limitations to generate the needed scale of airborne US, and relatively high cost and its energy consumption of such industrial scale US equipment can hinder its application in food drying industry. Therefore, optimization of ultrasound assisted drying in terms of energy consumption and process design is another area that deserves more research.

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