Application of Power Ultrasound on the Convective Drying of Fruits and Vegetables: Effects on quality

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ABSTRACT

Drying allows the obtaining of products with a long shelf life by reducing the water activity to a level low enough for the growth of microorganisms, enzymatic reactions, and other deteriorative reactions to be inhibited. Despite the benefits of this operation, the quality of heat sensitive products is diminished when high temperatures are used. The use of low drying temperatures reduces the heat damage but being the drying time longer, oxidation reactions occur and a reduction of the quality is also observed. Thus, drying is a method that lends itself to being intensified. For this reason, alternative techniques are being studied. Power ultrasound is considered an emerging and promising technology in the food industry. The potential of this technology relies on its ability to accelerate the mass transfer processes in solid-liquid and solid-gas systems. The intensification of the drying process by means of power ultrasound can be performed by modifying the product behavior during drying, using pre-treatments like soaking in liquid medium assisted acoustically or during the drying process itself applying power ultrasound in the gaseous medium. The purpose of this review is to provide a summary of the effects caused by the power ultrasound application on the quality of different dried products, such as fruits and vegetables when the acoustic energy is intended to intensify the drying process, either if the application is performed before as pretreatment or during the drying process.

INTRODUCTION

Drying is a mass and heat transfer operation widely used to reduce the water activity of the material. Convective drying is a high demanding energy operation that usually uses hot air to increase the food temperature and evaporate the water from the product.

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Nevertheless, a high increment of the temperature promotes organoleptic and nutritional changes in food products that may cause quality degradation.[1] Therefore, low temperature drying has become an alternative to preserve the quality attributes. Moisture reduction can be achieved by evaporation if the drying temperature is above freezing point, or by sublimation if the temperature used is below freezing point. However, one of the main disadvantages in both cases is the low mass transfer rate of the process.[2]

During drying, water is transferred from inside the solid phase to the surface and then from the surface to the fluid phase. Considering negligible the resistance of the interphase, the global mass transfer can be considered as the result of two resistances:[3]

- Internal resistance: given by the characteristics of the material and the temperature.
- External resistance: because of the interaction between the surface of the solid and the fluid phase.

So, convective drying is prone to be intensified in terms of kinetics, however, the quality of the final food product should be considered.[4] In order to achieve an intensification of the drying process, several technologies have been tested such as microwave heating,[5, 6] high pressure,[7-9] electric pulses[10] and power ultrasound.[11-13]

Nowadays, power ultrasound (PU) is considered a promising and emerging technology in the food industry. The interest on this technique relies on its capacity to accelerate the mass transfer process due to its effect on both; the internal and the external resistances to mass transfer, and also on its versatility for being applied either on solid-liquid systems (as pre-treatment before drying) and on solid-gas systems (during drying).[14, 15] The effects of PU application on the quality of the food product vary according the structure and nature of the food product, the propagation medium (gas, liquid, solid), and the properties of the acoustic wave (frequency, power, attenuation, impedance).[16]

The aim of this paper is providing a critical review of the effects of the PU application on the quality of dried food products, either when it is applied before the drying process as pretreatment or during the drying process as a complementary technology. A summary of the research papers referred in this review is presented in Table 1 for those considering the PU application as pre-treatment and in Table 2 for those considering the use of PU during the convective drying. In both tables, it has been collected the most relevant aspects about product, conditions of the PU application and drying parameters, together with the quality attributes studied.

BASIC PRINCIPLES OF POWER ULTRASOUND

Acoustic waves are mechanical waves travelling through a conductive elastic medium producing mechanical oscillations. When the frequency of the acoustic waves is higher than the upper audible human limit (20 kHz) they are considered ultrasound.[17] In general terms, the generation system of ultrasonic waves is constituted by three main elements: a generator, a transducer and an emitter. The generator transforms the electrical signal into the selected frequency; the transducer, which is a vibrating body, converts the high frequency electrical signal into mechanical vibrations, and the emitter radiates the mechanical vibrations to the medium.[13]

Ultrasonic waves are characterized by different parameters, and their effects rely on the suitable selection and control of those parameters. The applied ultrasonic power (W) determines the effect of the acoustic energy on the material (food product). Thus, in diagnosis or monitoring applications, when the purpose is mainly the characterization of the food, high frequencies are considered (0.5-10 MHz), to increase the sensitive of the procedure, and low acoustic power is applied (less than 10 kW m^{-2}) to avoid some influence on the inspected product. On the contrary, when the purpose is to produce permanent changes in the propagation medium provoking disruptions or inducing physical, mechanical or chemical/biochemical changes, the power used is higher and constitute the area of high-intensity ultrasound or power ultrasound. Depending on the properties of the material, alterations are directly proportional to the ultrasonic power.[18] Moreover, because the losses of acoustic energy increase with the frequency, frequencies greater than 20-50 kHz are not usually used in these last applications.

Regarding the acoustic energy transferred by the system to the material, an important issue must be raised concerning to the units used for its expression. Different units have been used in literature and they include traditional power units (W),[19-21] acoustic density units referring to the volume (W m^{-3}),[4, 22, 23] where the acoustic energy is applied, or considering the irradiation area (W m^{-2}).[24-26] Authors of this review ponder thoroughly the necessity of making the expression of the real (not nominal) applied acoustic energy more homogeneous in order to facilitate on one hand, the replication of the study conditions, and on the other hand the comparison of the attained results.

The effects of ultrasound are highly dependent of two main parameters related with ultrasonic transmission, the attenuation coefficient and the acoustic impedance. They correlate with some physicochemical properties of the material where the acoustic energy is applied. Attenuation is the intensity loss of the wave when it travels through the medium due to the friction of molecules provoked by the compression and dilatation stress. The attenuation capacity is a characteristic of each material and can influence on the effectiveness of ultrasound application. Thus, in solid-liquid applications, the highly attenuant liquids can prevent that acoustic waves arrive to the solids with enough energy to produce significant effects.The acoustic impedance is related with the resistance of the medium to the propagation of the acoustic wave. At interfaces, the difference of impedance between media define the amount of acoustic energy is transferred or reflected. Thus, the great difference of impedance between solid or liquid and gas media[27] makes very difficult the transmission of acoustic waves and then, the effects produced by ultrasound.

ULTRASONIC PRETREATMENTS IN FOOD PRODUCTS

When applied in a liquid medium, the acoustic waves produce cavitation. Bubbles or voids are formed, grown and collapsed due to the pressure fluctuation provoking sudden and localized increments in both temperature and pressure.[19, 27] The magnitude of the cavitation depends on the parameters of the acoustic wave (frequency, intensity) and the properties of the medium (viscosity, surface tension, vapor pressure, temperature, presence of dissolved gases). The implosion of cavitation bubbles close to the solid-liquid interface may cause the generation of a microjet into the bubble, which moves through and leave it striking the solid surface. This microjet raises the mass and heat transfers between the liquid and the solid by breaking the respective diffusion boundary layers.[12, 21]

Acoustic energy during the interaction with the medium is converted into thermal energy, therefore heating is observed during the PU application.[24, 28] When the acoustic wave interacts with the solid causes turbulences in the solid-liquid interphase affecting mainly the diffusion boundary layer and modifying the structure of the solid.[29] Once the wave reaches the solid, alternative compressions and expansions are produced resulting in a sponge effect in the solid, which helps the liquid to flow out of the solid in an interchange with the entry of fluid from outside. This mechanical stress also can create microscopic channels that may ease the mas transport.[12, 19, 25]

DEVICES

Mostly two types of devices are used in the PU application in liquid medium: ultrasonic baths and ultrasonic probes and they differed in its effectiveness, efficiency and capability.

Commercial ultrasonic baths are available in different tank capacities, ultrasonic powers or frequencies. Adjustable wave amplitude and the control of temperature made them suitable for laboratory or industrial applications. The acoustic field produced by ultrasonic baths is very irregular due to the reflections of acoustic waves with bath walls and liquid-gas interface. Moreover, cavitation occurs heterogeneously through the tank and induces wave reflections, so the sonication effect it is unequally distributed. One of the main drawback of using ultrasonic baths is the low ultrasonic intensity capacity. The indirect application makes the wave not only has to travel through the liquid in the tank but also must cross the sample container, therefore the acoustic intensity that arrives to the sample is lower than expected; besides, the reflection of the acoustic waves in the ultrasonic bath makes the repeatability and scalability of the process very difficult.[30, 31] Ultrasonic baths have been used in the pretreatment of banana,[12, 32] pineapple,[33] guava,[19] carrot,[20, 21] apple,[34, 35] blueberry,[36] cherry,[37] malay apple,[38] melon,[26] mushrooms,[39] papaya,[40] and strawberry[38]. A direct application of PU on liquid media can be achieved by using ultrasonic probes. The different geometries of probes can permit to transmit (cylindrical) or concentrate (conical, stepped) the ultrasonic energy.[2] The sonication time depends on the specific treatment but usually ranges between 0.5 and 5 min. During the performance, the probe is immersed in the liquid medium and acoustic energy is directly given. An intense sonication zone (ca. 100 times higher than the average ultrasonic bath) can be identified directly beneath the probe and the ultrasonic irradiation distance is limited to a certain area of the probe's tip, therefore small volumes are recommended to keep dead zones to minimum.[16]. Ultrasonic probes have been used in the pretreatment of apple,[24, 41] guava,[19] mushrooms, brussels and cauliflower,[25] carrot,[42] blackberry,[22] mulberry[43] and parsley leaves.[44] Table 1 collects the description of the pretreatment conditions, drying conditions and quality parameters considered when PU was applied as pretreatment by using ultrasonic bath or probe.

PROPAGATION MEDIUM

The selection of the liquid medium used in the ultrasonically assisted pretreatment depends on of the desired outcome. Thus, the pH or solute concentration can induce a great influence in the effect of the acoustic energy on the food product and the interaction between the solid and the surrounding medium. One of the most common solution for osmotic pretreatments of fruits is sucrose dissolved in distilled water.[26, 32] Thus, the osmotic dehydration of banana,[12] pineapple,[14] guava,[19] blueberry,[36] cherry,[37] melon,[26, 45] papaya,[40] malay apple,[38] apple,[46] strawberry,[47] carrot,[48] have been carried out using sugar solutions ranging from 30 to 70 °Brix. In these studies, the acoustic assistance was done mainly by using ultrasonic baths and the applied ultrasonic power varied from 60 to 2500 W operated at 25 or 40 kHz. Garcia-Noguera *et al.*[47] reported that PU application using an ultrasonic bath (25 – 40 kHz) on strawberry halves immersed in 25 and 50 °Brix solutions promoted a steep increase in water loss, which may be related to the formation of microscopic channels and breakdown of tissue cells. Kek *et al.*[19] observed that increasing osmotic solution concentration from 35 to 70 °Brix resulted in a significant increase in water loss of guavas due to the increase in the concentration gradient between the soluble solids in the fruit and in the osmotic solution. According to these authors, the PU application (1.0 – 2.5 kW) promoted a gain of solid content (sugar) of 0.05 g d.m g^{-1} d.m when a 35 °Brix solution was used and of 0.09 g d.m g^{-1} d.m when a 70 °Brix solution was used. Regarding the water loss, both the use of ultrasonic bath or probe promoted a similar trend where water loss increased slightly when ultrasound input was increased. When ultrasonic bath was used, the water loss ranged from 0.11 to 0.11 g water g^{-1} d.m while when ultrasonic probe was used it ranged from 0.07 to 0.11 g water g^{-1} d.m. In all cases, the ultrasonic assistance increased the efficiency of the total osmotic dehydration process. Carcel *et al.*[46] reported that the higher the ultrasonic power applied the higher the solid gain and the water loss. Thus, working with apple slices during 45 min of treatment in a 30 °Brix sucrose solution at 30 °C, these authors found a solid gain and water loss of 0.4 g water g^{-1} d.m and 0.9 g d.m g^{-1} d.m respectively at 3.6 W cm^{-2}, and 0.6 g water g^{-1} d.m and 1.4 g d.m g^{-1} d.m, respectively at 11.5 W cm^{-2}. A different result was observed by Siucinska *et al.*[37] in the acoustically assisted (0.4 W cm^{-2}) osmotic dehydration of cherry using a 60 °Brix solution at 40 °C during 30 to 120 min. These authors did not observe significant differences among samples treated under different condition, however, the average solid gain and water loss were of 0.3 g d.m g^{-1} d.m and 3.0 g water g^{-1} d.m, respectively in treated cherries.

Generally, when distilled water is used, the food product exhibits a gain of water content and a reduction of solid matter due to the mass transfer exchange promoted by the solute gradient between the food product and the surrounding media.[38, 49] These mass transport is enhanced by the PU application. As an example, Fernandes *et al*.[12, 14, 26] used distilled water (as control) in the study osmotic dehydration of banana, pineapple and melon, respectively. In all these cases, the PU application (4780 W m^2) up to 30 min promoted on one hand, a reduction of the solid content (0.11 – 0.21 g d.m g^{-1} d.m in banana, 0.44 – 0.52 g d.m g^{-1} d.m in melon and 0.22 – 0.23 g d.m g^{-1} d.m in pineapple); and on the other hand, a gain of moisture content (0.04 – 0.11 g water g^{-1} d.m in banana, 0.08 – 0.0 9 g water g^{-1} d.m in melon and 0.02 – 0.03 g water g^{-1} d.m in pineapple).

The use of the self–juice of the fruit has been recently used in few researches with the purpose of evaluating the effect of the PU application when the liquid medium and the food product are of the same nature, consequently no water nor solid gradients were present in the system. Rodriguez *et al*.[24] used apple juice (pH = 3.3; °Brix = 11.6) in the pretreatment of apple parallelepipeds by using an ultrasonic probe (2.1 and 12.9 W cm^{-2}). These authors did not observe any significant change in the moisture content of the samples after 5 min treatment. Besides, during drying (50 °C, 1 m s^{-1}) a similar kinetic was observed among samples immersed in juice being the average, however apples treated with juice and PU (12.9 W cm^{-2}) exhibited a reduction of the drying time of 33.1% compared with the untreated sample. Pineapple juice (pH = 3.4; °Brix = 12.2) was used by Rodriguez *et al*.[33] as medium during the acoustic pretreatment (5.1 W L^{-1}) of pineapple cubes. Compared to the untreated sample, after 30 min of treatment, the increment of the moisture content was of 6% and 10% in samples treated without and with acoustic assistance, respectively. Regarding the drying kinetics, compared to the untreated sample, samples immersed in pineapple juice and sonicated using an ultrasonic bath exhibited a drying time reduction (50 °C, 0.5 m s^{-1}) of 4.6 and 9.0% for 20 and 30 min of pretreatment. It is worth pointing out that the increase in the initial moisture content of treated samples is indicative of the water intake during the treatment, being higher due to the ultrasonic waves, but this water might have a free character inside the fruit tissue, leading to a weak interaction with the solutes in the sample and an easier removal during the convective drying process under these conditions.

ULTRASONIC ASSISTED DRYING

Power ultrasound can be also directly applied to intensify the convective drying. In this case the effects of ultrasound are mainly mechanical and no significant overheating of the material being dried take place.[50] The acoustic vibration produced by ultrasound generates a successive compression and expansion of the material, leading to an stress of the structure (''sponge effect''). This mechanical force can create microscopic channels that allow an easier inner water movement.[2, 32, 51] Moreover, PU application can produce cavitation which takes place in the liquid phase inside the moist solid. The asymmetric implosions of cavitation bubbles near to the solid surface, can lead to the partial release of some water bounded to the solid structure. All these mechanical effects results in a reduction of the internal resistance to mass transport.[52] Regarding the external resistance, the acoustic waves reduce the boundary layer thickness due to different effects such as pressure variations, oscillating velocities and micro-stirring on the solid-gas interface. The reduction of the boundary layer allows an improvement of the vapor transfer rate from the solid surface to the drying air. [28, 53]

Two main handicaps must be overcome to achieve an efficient application of PU on gas media. On the one hand, the mismatch between gases and solids or liquids due to the acoustic impedance differences makes the transfer of the acoustic energy generated into the air to the solid very difficult. On the other hand, gases media are very attenuating media that significantly reduces the acoustic energy applied to the materials being dried.[20, 54] Currently different systems have been developed to efficiently transmit the acoustic energy from the emitter to the solid during the convective drying in any of its most conventional procedures: hot-air drying and low temperature drying and two different configurations have been used: contact and contactless systems.[16, 53, 55]

A first attempts to apply power ultrasound in drying processes was carried out by direct contact between transducer and samples. Thus, ultrasonic vibrations are directly transmitted to the sample. Stepped plate transducers constitute a good option as a contact system due to their high radiating surface. Some average characteristics of these kind of transducers are a beam width (at 3 dB) of 1.5 degrees, power capacities up to 2 kW, and intensity levels reached in air as high as 175 dB. Its efficiency ranges about 80%.[53, 55, 56] The good acoustic impedance matching between the stepped plate transducer and the food material favors the deep penetration of acoustic energy. These systems showed a very intense effect which can be increased if low static pressure is applied on the sample. This system has been used in the drying of apple[53] and carrot.[57] Nevertheless, the scaling up of these option to an industrial level is quite difficult.[13]

Another ultrasonic system used consisted of a ring sonotrode driven by an ultrasound processor which works at a frequency of 24 kHz. Although the system was initially created for ultrasonic sieving, it was equipped with a laboratory drying screen where the sample could be placed and the acoustic energy transmitted.[58] The whole system is placed inside the drying oven and the drying air passes perpendicularly to the sample. This system has been used in the drying of potato,[59] apple[60] and bell pepper.[61] When drying at 70 °C, compared to non-sonicated samples, the use of the ring sonotrode promoted savings in the drying time of 10, 27 and 23% in potato, apple and red bell pepper, respectively.

The development of specific ultrasonic transducers with higher power capacities have partially solved the problems observed in the contact systems application. [62] One of the most popular contactless system is the aluminum vibrating cylinder (AVC) driven by a piezoelectric composite transducer (21.8 kHz) capable of converting the electric energy in vibration movement generating a high-intensity ultrasonic field inside the cylinder (75 W, 154.3 dB) with a relative low energy consumption. [63-66] Thus, cylinder is used as a vibrating drying chamber. This system has been used in the drying of several fruits and vegetables like apple,[1, 23, 64, 65] cassava[4], tomato,[67] strawberry,[51] orange peel,[68] potato,[66] carrot,[69] eggplant,[70] grape skin,[71] passion fruit peel.[72] Different process conditions like air temperature and velocity, mass load, and applied ultrasonic power have been tested using this system.

Other kind of transducers for air borne ultrasonic application are the plate (stepped or not) transducers. With one of this, a laboratory hybrid chamber dryer equipped with an ultrasonic airborne system (26 kHz, 200 W) and microwave generator (100 W) was developed.[58, 73, 74] Thus, the apparatus allows the drying process with the use of thermal (hot air), acoustic and microwave energy separately or simultaneously. Kowalski *et al*.[52] used this set-up in the acoustically assisted drying (100 W, 45 °C) of apple slices and reported a reduction of 32% in the drying time when applying PU. The effect of the microwave energy (100 W) during the acoustic assisted drying (100 – 200 W, 55 °C) of raspberry,[58] being the reduction in the drying time of 79% with the microwave assistance and 59% without it. The effect of the microwave energy used only in the first stage on the acoustically assisted drying process was studied by Szadzińska *et al*. in strawberry[73] (first 30 min) and green pepper[74] (first 10 min). These authors concluded that dosing the microwave radiation improved the drying kinetics without risking the quality of the dried product which can be affected by the vibration and heating effect. In both studies, the energy consumption was significantly reduced in 50 and 20%, respectively.

Table 2 collects the description of the drying conditions and quality parameters considered when PU was applied to intensify the drying process.

ON THE QUALITY OF THE DRIED PRODUCT

During drying, food products undergo physical, structural, chemical, organoleptic and nutritional alterations that cause quality changes. The extent of the changes depends on the characteristics of the food matrix, and the process conditions. These process conditions includes the combination of pretreatment (if any) and drying and the assistance of power ultrasound on the pretreatment or during drying. Therefore, the process variables and the PU parameters should be selected properly to limit the irreversible changes in the food quality that risks its commercial acceptance in the market.

STRUCTURE

As it was mentioned before, ultrasonic waves induce structural changes that can make easy the mass transport. Those structural changes have been analyzed by means of techniques like scanning electron microscopy (SEM),[37, 64, 72, 75] cryo-SEM [4, 68, 70] or light microscopy.[26, 38, 41, 47, 49] The extent of these changes mainly depends on the ultrasonic intensity and the porosity (ε) of the food product. Thus, the sponge effect is more important in high-porosity products (like eggplant or orange peel) due to the large intercellular spaces, therefore a lower ultrasonic intensity level is needed to promote the water removal.[54]

In the pretreatment of melon (ε=0.133)[76] using osmotic solutions (25 – 70 °Brix) without acoustic assistance, the cell wall weakened due to solubilizing of pectin together with the high osmotic pressure, therefore water transport became easier and effective water diffusivity increased.[26] However, when PU was applied on a middle porosity product like strawberry (ε=0.471)[76] using an ultrasonic bath (25, 40 kHz, 4870 W m^{-2}), smaller and needle shaped cells were observed proving the formation and appearance of microchannels formed by the elongation and flattening of cells in some regions of the sample.[47] In apple (ε=0.233)[4, 76], the PU application by means of an ultrasonic probe (2.1, 19.9 W cm^{-2}) using distilled water as medium promoted a relative increase in cell separation and cellular collapse probably associated with extensive damage to the cell walls and membranes produced by the acoustic waves. This damage was more evident when low-pH media like apple juice or 1% citric acid solution were used.[24]

The effect of the PU application during the convective drying on the structure of the product has been also studied. As an example, when PU was applied during hot air convective drying of eggplant (ε=0.423)[77] at 40 ºC (1 m s^{-1}), the alternating expansions and contractions promoted the degradation of the endocarp cells, the effect was more intense at a lower acoustic power of 18.5 W L^{-1} (3.5 h) than when the acoustic power was of 37.0 W L^{-1} (1.8 h). [70] However, these authors observed that eggplant samples dried without ultrasonic assistance exhibited a more noticeable degradation of the endocarp cells, which was related to the longer extension of the drying process (7 h). In orange peel (ε=0.330)[4] drying (40 °C, 1 m s^{-1}), the albedo was disrupted by the drying air and the cell tubular shape disappeared while the water is released. The PU application (21.7 kHz; 45, 90 W) promoted a higher collapse of the cell structure due to a more intense disruption of the albedo cells. Also, the spread of waxy compounds (flavedo) in the coticule was more evident when PU was applied.[68]

When applying PU on low-porosity products like cassava[4] or potato[59] changes in the microstructure were observed but in a lower degree. Probably, the dense structure of these products makes difficult the transmission of ultrasonic energy at the interface with the drying air and this fact did not allow the creation of microchannels for the removal of moisture from the inner cell layers. Cassava (ε=0.029), with a hard and compact structure composed by tightly-joined cells along the cell walls did not exhibited a severe structure change after the PU application (6 – 31 kW m^{-3}) during drying at 40 °C; however, compared with the not acoustically assisted sample, an increment in the D_e figure from 7 to 56% was observed. [4] Cell injury was measured in potato (ε=0.060) cylinders during drying (70 °C) assisted by PU application (42 W) using a ring sonotrode.[59] It was observed that the extent of the cell injury was directly related to the acoustic energy applied instead of the water removal achieved, it was also observed that the injury was strongly reduced in the inner layers of the sample being more noticeable in the surface of the samples.

The combined effect of ultrasound application and drying temperature can significant influence the structure of the product. In this sense, ultrasonically assisted drying with acoustic densities of 18.5 and 30.8 kW m^{-3} at high temperature air drying of apple (ε=0.233)[4] showed that the disruption of the cell structure and enlargement of the porous, being more evident at 30 °C than at 50 °C (shorter drying time); however at 70 °C, the tissue was clearly devastated, and cells collapse, holes and disruptions were observed.[64] Wen drying took place at low temperature with an applied acoustic density was of 20.5 kW m^{-3}, the structure of apple dried at -10 °C was more porous than the one dried at 10 °C, probably as consequence of the growth of crystals during the sample's freezing. Nevertheless, the PU application induced a greater degradation of the sample structure at both temperatures which was reflected in the appearance of more pores with higher diameters.[23]

REHYDRATION CAPACITY

Rehydration takes place in three different stages: the imbibition of water into the dried material, the swelling, and the leaching of soluble solids, and its rate is linked to the cellular damage and the structural disruption suffered by the sample during the drying process.[34, 78] As a general rule, the application of PU before or during the drying process promoted an increment of rehydration capacity (RC) of dried samples compared to samples dried without PU application. Moreover, in some cases, the lower acoustic intensity applied, the higher RC observed. For instance, the RC of dried mushroom, Brussel sprout and cauliflower was studied at 80 °C in samples acoustically treated before drying using either an ultrasonic bath (0.5 W cm^{-2}) or an ultrasonic probe (39 – 43 W cm^{-}

^{2}).[25] In this study, the highest RC was achieved in samples pretreated at the lowest acoustic intensity (ultrasonic bath) during the shortest time under studied (3 min), while the samples dried without pretreatment showed the lower RC. The application of a higher acoustic intensity during pretreatment provoked the loss of turgor and the deterioration of the cell wall, therefore the loss of the rehydration capacity of these dried vegetables.

Fijalkowska *et al.*[34] acoustically pretreated (3 – 4 W cm^{-2}) apple slices for 30 min, and then dried them at 70 °C, 2 m s^{-1}. These authors reported that after 3h of rehydration at 20 °C no significant differences were observed among pretreated and untreated samples. However, Mothibe *et al.*[41] observed that PU application by using an ultrasonic probe (25 kHz, 200W) during 5 – 15 min of apple slices before drying at 70 °C promoted an increase between 19.6 – 22.1 % of the RC compared with the untreated sample when they were immersed in boiling water for 2 min. The RC at 25 °C of acoustically pretreated (41 W L^{-1}) carrot slices dried at 40 and 60 °C was studied by Ricce *et al.*[20] RC of samples subjected to ultrasonic pretreatment at both 30 and 60 min was greater compared to untreated samples, which can be attributed to the higher porosity and micro-channels formation during the pretreatment. Gamboa-Santos *et al.*[21] studied the effect of acoustic pretreatments (20 kHz, 400W) during 10 min, 60 °C (minced carrot) and 15 min, 70 °C (sliced carrot) before drying at 46 °C of temperature and 4.9 m s^{-1} of air velocity on the RC. These authors found that the RC of acoustic pretreated samples was higher than the one of samples minced or sliced blanched with boiling water or steam at 98 °C for 1 or 2 min, respectively.

Santacatalina *et al.*[79] studied the RC (30 °C) of eggplant dried at -10 °C and 10 °C with the application of PU (50 W). Although PU application caused a faster water intake, it did not lead to greater final water absorption after rehydration at 30 °C compared with the sample dried without acoustic assitance.[79] Similarly, the PU application (76 – 110 W) during freeze drying (-30 °C) of red bell pepper did not promote a significant change of the RC (using boiling water) compared with sample dried without acoustic assistance.[61]

WATER MOBILITY

The modification of the structure of the sample (cell walls deformation, lysis of membranes, tissue shrinkage) plays an important role in the mobility of water and solids during processing.[24] Time domain nuclear magnetic resonance can be used to obtain information about cellular modifications of biological tissues during pretreatment and/or drying, considering that different subcellular compartments are characterized by specific water–solutes ratio ranges, leading to different transverse relaxation time (T_2) values.[41]

The water mobility after pretreatment by immersion in assisted by PU application was studied by Rodriguez *et al*.[24] in Granny Smith apple after the pretreatment and by Mothibe *et al*.[41] in Red Fuji apple before and during drying process (70 °C). In the first case, compared with the raw sample, treaded ones exhibited longer T_2 figures in all the compartments under study: cell wall, cytoplasm and vacuole. During the pretreatment, a water movement from the vacuole to the cytoplasm was observed because of the structural changes. This effect was more noticeable when PU (2.1 and 12. 9 kW cm^{-2}) was applied during soaking, besides significant both water intake and solute transfer to the soaking medium. The authors concluded that these increments in mass transfer were due to the modification of the original cellular organization and subcellular structures of the vegetal tissue promoted by ultrasound. In the second case, after 5 – 15 min of acoustically treatment (200 W) the water intake and its free character inside the tissue led to longer T_2 figures. During drying, the T_2 figures in all cellular compartments decreased, specially the one corresponding to the vacuole compartment, which suggests that most of the water loss was removed from this compartment which is related to the volume shrinkage of the whole cell.

COLOR

The color change in a food product may affect the overall acceptability of the product by the consumers, therefore it should be considered when designing a drying process.[18, 80] In the CIELab uniform color space, L^* indicates lightness, a^* is the chromaticity on a green (−) and red (+) axis and b^* is the chromaticity on a blue (−) and yellow (+) axis. These three parameters are included in the estimation of the color difference ΔE to the raw sample. ΔE figures higher than 2.0 might lead to noticeable differences in the visual perception of consumers.[81]

Different trends were observed regarding the effect of PU on the color of food products when applied as pretreatment. Kek *et al.*[19] reported that sonicated (20 kHz, 400 W) guavas immersed in either 35 or 70 °Brix solutions at 30 °C were darker and greener than the raw ones (whitish green) and ΔE figures of 3.0 and 6.0 were observed. Fijalkowska *et al.*[34]

reported that ultrasonic pretreatment modified the color of the apple tissue (var. Idared). In this study, using ultrasonic baths, at an ultrasound frequency of 21 kHz (3 W cm^{-2}), the L^*, a^*, and b^* figures increased; however, at a frequency of 35 kHz (4 W cm^{-2}) the opposite outcome was observed. The *ΔE* figure of the non-sonicated samples was of 3.7, while for sonicated apples it was of 6.0 (3 W cm^{-2}) and 3.6 (4 W cm^{-2}). Similar findings were reported by Rawson *et al.*[42] in carrots. In this study, after 3 – 10 min treatment using distilled water at 25 °C and acoustic assistance by means of an ultrasonic probe (78 – 190 W), samples dried at 60 °C exhibited a *ΔE* figure between 9.5 and 10.0, while blanched samples without acoustic assistance exhibited a *ΔE* figure lower than 7.5.

The PU application (35 kHz, 480 W) during the pretreatment of mushrooms using distilled water (30 min, 30 °C) was studied by Çakmak *et al.*[39] The *ΔE* figure of dried samples (50 °C) decreased from 22.1 (no sonicated) to 3.36 (sonicated). Mothibe *et al.*[41] reported that after drying at 70 °C, L figures in ultrasonically treated apples, tended to decrease with increasing exposure time to ultrasonic waves (25 kHz, 200 W). This might be because ultrasound destruction of cells might have released enzymes responsible for browning to the surface leading to dark color. In convective drying of melon at 60 ºC, acoustically pretreated (25 kHz, 4780 W m^{-2}) samples using distilled water led to brighter (lower L^* figures) samples than those dried without pretreatment; however, regarding the *ΔE* figure no significate differences were observed between them.[45] Stojanovic *et al.*[36] studied the effect of the sonication (850 kHz, 100 W) on the color change in blueberry using a 55 °Brix solution at 21 °C during 3 h, followed by a convective drying at 70 °C during 10 h. They reported *ΔE* figures lower than 2.0 before drying and around 6.0 after drying. However, no significant effect of the PU application was observed.

The change of color has been related to the degradation of biocompounds during processing. For instance, osmotic dehydration (40 and 60% fructose for 2 h at 25 °C) of carrot promoted a very negative effect in the color of the dried product (30 min of heating at 70 °C, 5 min of cooling at 21 °C) being the ΔE figure of 14.4; however, when the osmotic dehydration was ultrasonically assisted (38 kHz, 320 W) the *ΔE* figure was lower (9.0). This situation was related to a higher preservation of carotenoid compounds.[48]

Kowalski *et al.*[82] reported that the dying (60 °C) of cherries led to a degradation of anthocyanins revealed as a color change (red color) by a decrease of L^* and a^* parameters.

In this study, cherries were osmotically dehydrated (60 °Brix solution, 25 °C, 30 min) without and with acoustic assistance (25 kHz, 700 W). The *ΔE* figure of dried cherries was of 16.0, 12.0 and 10.0 for those dried without pretreatment, osmotically treated without and with acoustic assistance, respectively. According to Sledz *et al.*[44] the green color (negative figures of a^*) in parsley leaves is an expression of both the chlorophyll *a* and *b* contents. The parameter a^* in fresh samples was of -13.7, and it increased to -12.8 and -9.6 in dried leaves without and with ultrasonic assisted pretreatment by immersion in distilled water at 22 °C during 20 min in an ultrasonic bath (21 kHz, 300W) and convectively dried at 20 – 40 C with microwave assistance (100 – 300 W) which means a less green product. However, the *ΔE* figure did not exceed the values of 2.0 when PU was applied and the convective drying was assisted by microwave (100W) at 20 and 30 °C.

In freeze drying red bell pepper at -30 °C, no differences between dried samples with and without ultrasonic assistance (76 – 110 W) were reported by Schössler *et al*.[61] However, Szadzinska *et al*. in drying of strawberry[73] and green pepper[74] at 54 and 52 °C, respectively, without and with acoustic assistance (100 – 200 W) found that convective drying assisted by PU promoted lower *ΔE* figures. Conventionally dried strawberry and green pepper samples exhibited a *ΔE* figure of 22.0 and 15.1, respectively; while those dried with acoustic assistance exhibited *ΔE* figures of 12.0 and 11.5, respectively. Similar findings were observed in the drying of raspberries carried out at 70 °C. The PU application reduced the *ΔE* figure from 16.5 (not assisted) to 14.5 and 12.5 when an ultrasonic intensity of 100 W and 200 W were used.[58] This improvement was justified with the intensification of the drying process, and therefore the shorter exposition to the thermal treatment.

ANTIOXIDANT ACTIVITY

The compounds with multiple biological effects presented in fruit, vegetables and plant extract corresponded mainly to vitamins C and E, polyphenols, carotenoids and compounds of the Maillard reaction. The major property of them is their radical-scavenging capacity, which is involved in their antioxidant properties.[83] The knowledge of the antioxidant activity of food products and the effects of processing conditions on it allows to determine the protection against oxidation and the deterioration of the food that diminishes its quality and nutritional value. The effect of sonication as pretreatment on the antioxidant activity (AA) depends on the product considered. Romero *et al*.[22] reported that the sonication (24 kHz, 38 – 76 W cm^{-3}) applied on blackberry using distilled water at 15 °C during 10 – 30 min promoted a significant reduction of the AA (FRAP assay). Without sonication, samples exhibited a reduction of 5% during the treatment while the application of acoustic energy promoted a reduction up to 90% (30 min, 76 W cm^{-3}). In this study, the increase of the acoustic intensity applied was more harmful than the sonication time. Stojankovic *et al.*[36] reported that the osmodehydration (3 and 12h, 55 °Brix) of blueberry samples promoted a reduction of 50 % in the AA (DPPH assay) compared with the fresh sample (30 %), however no effect of the PU assistance was observed. After drying (10 h, 70 °C) the reduction of the AA was higher than 50 %.

A positive effect of sonication carried out at 75, 226 and 373 W cm^{-2} on the AA of cashew bagasse was found by Fonteles *et al*.[75] According to these authors, the acoustic treatment during 2 – 10 min promoted a raise of the AA from 275 (untreated) to 500 – 650 µmol Trolox g^{-1} before the drying process, this could be related to the cell disruption and the release of the intracellular content. During the convective drying at 60 °C, the AA of treated sample increased with the drying time up to 600 – 700 µmol Trolox g^{-1}. However, the AA of the untreated sample decreased below 200 µmol Trolox g^{-1}. The authors attributed this result to the formation of new compounds with higher antioxidant activity due to, for example, the Maillard reaction, which creates several products with markedly higher antioxidant activity.

The sonication of mulberry leaves, using an ultrasonic probe (63.0 W L^{-1}) during 10 min before convective drying at 60 °C promoted a slight increment of 6.9% of the AA measured by FRAP assay compared to the untreated dried sample; nevertheless, no significant differences were observed regarding the AA measured by ABTS assay among untreated, treated without and with sonication samples.[43] According to these authors, although the acoustic pretreatment led to a solid loss, the reduction in drying time promoted could alleviate the damage caused by thermal energy, therefore, conserving of the AA in the dried product.

Rodriguez *et al*.[33] studied the effect of sonication (25 kHz, 5.1 W L^{-1}) in pineapple using distilled water at 30 °C during 10 – 30 min. Compared with the fresh sample, the AA of sonicated samples measured by DPPH assay was between 20 and 30% higher, while non-sonicated ones exhibited a slight reduction near to 10%. The AA measured by FRAP assay was lower in all treated samples. In this case, the longer acoustic application the higher AA loss, up to 50 % after 30 min of sonication. After drying at 60 °C, only sonicated samples exhibited an increase between 37 and 57% of the AA measured by DPPH assay. Regarding the AA measured by FRAP assay, drying promoted a loss of the AA; nevertheless, all dried samples exhibited a higher AA figure than the one observed in the untreated dried sample.

The effect of PU application during convective drying of Granny smith apple has been studied by Rodriguez *et al.*[64] and Santacalina *et al.*[65] In the first study, using hot air (30 – 70 °C) the higher the acoustic intensity applied (30.8 kW m^{-3}), the better retention of the AA (ABTS, FRAP assays) at a drying temperature of 30 °C, however when a drying temperature of 70 °C was used the PU application promoted a higher degradation of the AA. In the second study, when low drying temperatures were used (-10 – 10 °C) the PU application (20.5 kW m^{-3}) involved a greater degradation of the AA (CUPRAC; ABTS; FRAP; DPPH assays) which was linked to the cell disruption under acoustic stress. The effect of the acoustic intensity applied (25, 50 and 75 W) on the AA was studied by Santacatalina *et al.*[23] during the low temperature drying (10 and -10°C) of Granny Smith apple. According to the authors, regardless the acoustic intensity used, the AA (FRAP assay) degradation ranged between 46 and 76%. At intermediate acoustic intensities (25 and 50 W) the AA loss was higher at -10 °C than at 10 °C, however, at 0 and 75 W the differences were not significant.

In drying grape skin at different temperatures (40, 50, 60 and 70 °C) the acoustic assistance of 45 W, promoted a decrease in the AA (FRAP assay) of dried samples regardless the drying temperature.[71] This degradation could not be related to any heating effect from the acoustic energy; however, ultrasound could provoke severe structural modifications, degrading cell wall components and making the enzyme release and so the phenolic oxidation easier. [68] do Nascimento *et al.*[72] studied the effect of the PU application (30.8 kW m^{-3}) on the AA (FRAP assay) during the drying of passion fruit peel at 40, 50, 60 and 70 °C. In this study, the influence of the acoustic assistance was different at each temperature. Thus, at 40 and 50 °C, the AA was similar to the fresh sample (15.2 μmol Trolox/g d.m.), but at 60 and 70 °C, the average AA was 40 % lower than the fresh sample. The application of PU, on one hand, reduced the drying time and then limited the oxidation reactions which maintain the AA when is applied at lower temperatures. On the other hand, it affected negatively the AA when applied at higher temperatures due to a negative synergy effect of thermal and acoustic energy.

BIOACTIVE COMPOUNDS

The PU applied as pretreatment or during convective drying may shorten the drying time, thus favoring the bioactive compound retention which is highly beneficial for the final quality of the dried product.[37]

Plants produce an extraordinary diversity of phenolic compounds which are excellent oxygen radical scavengers. [84] In general, studies carried out in blueberry,[36] cherry,[37] mushroom,[39] and carrot[85] reported that the PU application as pretreatment before drying produced a reduction of the total phenolic content (TPC) of treated samples, mostly attributed to the leakage of phenolic compounds through the vegetal tissue during the pretreatment. Similar results were reported by Rodriguez *et al*.[33] in the acoustically assisted pretreatment (25 kHz, 5.1 W L^{-1}) of pineapples using distilled water at 30 °C during 10 – 30 min. A reduction of 40 – 60% of TPC was observed in sonicated samples. However, after drying (60 °C) the TPC increased, so the final loss was only between 10 and 25%. This increment can possibly be explained by the release of more bound phenolic compounds from the breakdown of cellular constituents during the drying that did not migrate during the pretreatment.

When convective drying was acoustically assisted, the PU application (18.5 and 30.8 kW m^{-3}) allowed a better preservation of phenolic compounds in apple[64] and passion fruit peel[72] when lower temperatures were used (30 and 40 °C), but when higher temperatures were used (50 and 70 °C) the ultrasonic assistance promoted a higher degradation of these compounds. Cruz *et al*.[71] reported that TPC were more sensitive to ultrasound application (45 W), since acoustically assisted dried samples exhibited a TPC 18.4% and 31.0% lower than the non-assisted samples. A negative effect of PU (20.5 kW m^{-3}) application was also observed during the freeze drying (-10 – 10 °C) of apple.[65] The average loss of was significantly higher (41%) in samples acoustically assisted than the one found in non-ultrasonically assisted samples (31%) at every temperature tested. This fact could be linked to the structural damage of cells brought about by ultrasound

Carotenoids determine the color and the nutritional quality of many dried fruits and vegetables. They are very stable in the fresh tissue but unstable by the action of heat, light and oxygen, The carotenoid content has been measured in papaya,[40] carrot[42] and melon[45] when PU was applied during pretreatment. Azoubel *et al.*[40] pretreated papaya slices using a distilled water or a sucrose solution (56 °Brix) at 34 °C during 10 – 30 min. The ultrasound frequency was 25 kHz, and the intensity was 4870 W m^{-2}. After drying (70 °C) the carotenoid loss in untreated samples was of 76%; however, in acoustically treated samples immersed in water the loss ranged between 60 and 69% and still, the loss was lower and ranged between 35 and 54 % in samples immersed in sucrose solution. According to the authors, a sugar barrier layer can be located at the sample's surface when using osmotic solutions that limited the contact between the fruit and the oxygen during drying, reducing carotenoid oxidation. Similarly, Dias da Silva *et al.*[45] applied PU (4870 W m^{-2}) on melon slices using distilled water or sucrose solution (50 °Brix) during 10 – 30 min at 30 °C. After drying (60 °C), untreated sample lost up to 95% of the carotenoid content, and a similar loss was observed in acoustically treated sample, being the loss of 96 and 94 when samples were immersed in distilled water and osmotic solution, respectively. Rawson *et al.*[42] applied PU (78 – 190 W) on carrot disks immersed in distilled water at 25 °C. After drying (60 °C) the carotenoid retention in samples acoustically treated during 3 min ranged between 65 and 83%, and between 65 and 75% after 10 min of acoustic treatment, while the untreated sample exhibited a 73% retention. After freeze drying (0 °C), the carotenoid retention in samples acoustically treated during 3 min ranged between 95 and 100%, and between 98 and 106% after 10 min of acoustic treatment, while the untreated conserved the integral carotenoid content.

In the convective drying of carrots at 20, 40 and 60 °C, Frias *et al.*[57] reported that the PU application (100 W) promoted a slight reduction (<3%) of the β-carotene content compared to the fresh sample and no differences were observed among the three temperatures used. (No data of the sample dried without acoustic assistance). Fernandes *et al.*[67] reported that, in general, when PU was applied (21 kHz, 75 W) during the drying (45 and 60 °C; 1 – 3 m s^{-1}) of cherry tomato it was observed an increment in the lycopene and carotenoid content of 2 and 12%, respectively when drying was carried out at 45 °C and 1 m s^{-1}; in contrast with the non-ultrasonically assisted dried sample which exhibited losses of 44 and 31% of both biocompounds under the same drying conditions. In general, for the others drying experiments, samples exhibited losses of both biocompounds, however the loss was lower in the acoustically assisted dried one.

Berries and cherries are well known by their anthocyanin content and its strong antioxidant and anti-inflammatory activities.[82] Stojanovic *et al*.[36] reported a negative effect of the PU application (850 kHz, 100 W) in osmotic conditions in berry. After treatment, the loss of anthocyanin content was of 50% and after drying it reached 82%, while the untreated sample exhibited a loss of 68% after drying. Similarly, in drying cherry, Siucinska *et al*.[37] found that the PU application in osmotic conditions promoted a reduction of 30 – 48% before drying, and it increased to 50 – 67% after drying. The highest retention was observed when cherries were osmodehydrated up to 60 min, longer pretreatment times promoted a higher degradation.

The chlorophyll content of parsley and mulberry leaves has been considered as quality parameter by Sledz *et al*.[44] and Tao *et al*.[43] In the first case, the pretreatment of parsley leaves was carried out with an ultrasonic power of 300 W using distilled water at 22 °C during 20 min. Convective drying was carried out at 20, 30 and 40 °C without and with microwave assistance (100 and 300 W). According to these authors, acoustically treated samples exhibited a higher chlorophyll retention (60 and 80 %) than non-treated one (58 and 65%) when the drying was carried out at 20 °C and assisted with 100 and 300 W. In the second case, mulberry leaves were treated with 25.2, 63.0 and 117.6 W L^{-1} using distilled water during 5 – 15 min. After drying (60 °C), the chlorophyll content of untreated sample was of 2.4 g g^{-1}, and the treatment promoted a slight increment of 9% in both treated samples.

VITAMINS CONTENT

Regarding vitamin C, Kek *et al*.[19] reported that after drying, the acoustically treated guavas under osmotic conditions exhibited the lowest vitamin content and it was 4-17% lower than the untreated sample, however with a 70 °Brix solution, the reduction was less which might be related to a lesser cavitation effect produced in viscous liquids. The sonication induced an increment in the vitamin C content of cashew apple bagasse, and it was justified due to the cell disruption and the release of the intracellular content. After drying, a reduction of the vitamin C content was observed, however, sonicated samples exhibited a higher final content (6 times) than untreated ones.[75] In pineapple, the sonication promoted a reduction of this vitamin ranged between 15 – 40%, possibly related to the leakage of solids into the soaking medium; however, after drying, the final vitamin C content of treated samples was higher (250 – 275%) than the untreated one. The reduction of the drying time and thus, the time exposed to high temperature is one of the main factors towards reducing the loss of vitamin C.[33] Frías *et al*.[57] reported retention figures of 82-92% when blanched carrot were acoustically dried (100 W) while a retention lower than 50% was observed in not acoustically dried samples.[51] Szadzinska *et al*.[74] reported retention figures of 62 – 69% in acoustically treated (100 – 200 W) samples and 42% in not assisted ones. In strawberry, compared to the not assisted sample, the vitamin C retention (~65%) was lower in samples acoustically (30, 60 W) dried at higher temperature (50 – 70 °C). In this case, the combination of thermal and acoustic energy was negative possibly because the PU application could facilitate the air penetration in the sample which eases the oxidation of the ascorbic acid.

Thiamin (B_1), riboflavin (B_2), niacin (B_3), pantothenic acid (B_5), pyridoxine (B_6) belong to the water-soluble B vitamins and the effect of the PU application on them has been studied by Rodriguez *et al*.[33] in pineapple and Fernanes *et al*.[1, 67] in apple and cherry tomato. In the first case, when PU was applied as pretreatment (25 kHz, 5.1 W L^{-1}), the acoustic energy promoted a noticeable increment in all B vitamins between 250 and 600% before drying, as consequence of the disruption of the chemical bounding between vitamins and their coenzymes. However, the drying process (50 °C) promoted a dramatic reduction of these vitamins due to their thermolability, and the final amount was like the one of the untreated dried sample. In drying apple and cherry tomato, the influence of the PU application was more noticeable at low air velocities and drying temperatures. The application of ultrasound could help increasing the availability of the free form of vitamins B_1+B_2, B_3, and B_6, releasing the vitamin from its bound to membrane, protein, or apoenzyme. Degradation of vitamin B_5 was observed (only in apple) possibly because it was presented in its free form.

The degradation of lipid-soluble vitamins during drying have been studied in apple (vitamins A and E)[1] and in cherry tomato (vitamin E).[67] In apple, PU application (21 kHz, 75 W) promoted and increment of the vitamin A when air velocities of 2 (50%), 3 (100%) were used at 60 °C, but losses were observed when air velocities of 1 (20%) and 2 m s^{-1} (25%) were used at 45 °C. The drying process promoted a reduction of the vitamin E ranged between 25 and 75% regardless the drying temperature or air velocity. Nevertheless, samples dried at 60 °C with acoustic assistance exhibited higher figures of vitamin E. Vitamin A is usually found associated with cell membrane and lipoproteins and its degradation may be linked to the reduction of vitamin E, which plays a protective role. The radical scavenging behavior of vitamin E may play a role in its consumption during drying. Since the UP application induces the production of small quantity of free radicals, in the fruit matrix, that will be attacked by vitamin E. In cherry tomato, the acoustic assistance (21 kHz, 75 W) promoted an increment of the vitamin E content only at 45 °C and 1 (141%) and 2 m s^{-1} (102%), in the other conditions under study, the retention of the vitamin E ranged between 63 and 97% while the not assisted sample exhibited figures between 66 and 104%. Compared with apple, the higher retention if vitamin E in cherry tomato might be related to the lycopene content in tomato, which is more prone to degradation by free radicals and hydrogen peroxide than vitamin E.

ENZYMATIC ACTIVITY

In cashew apple bagasse, Fonteles *et al*.[75] studied the effect of the PU application as pretreatment on ascorbate peroxidase (APX), peroxidase (POD) and polyphenol oxidase (PPO). The sonication promoted only a significant inactivation (75%) of the POD activity; that remain stable during the drying. Regarding the APX and PPO activities, sonicated samples exhibited a reduction of 12 – 20% and 20 – 30% respectively. Not sonicated sample exhibited higher enzymatic activities at the end of the drying process. Rodriguez *et al*.[24] measured the PPO activity in apple after sonication. A reduction of 13 – 58% of the PPO enzyme activity was observed, being the best inhibitory results those obtained when citric acid was used as the soaking medium and the highest acoustic intensity was applied (12.9 W cm^{-2}). In both cases, authors related the inhibitory effect with the intense pressures and shear forces generated by ultrasonic waves that denature the protein.

CONCLUSIONS

This review meant to give a general outline of the research works covering the application of power ultrasound in the intensification of the drying of fruits and vegetables. All included papers covered the study of the effect of power ultrasound application on the different quality parameters of the food product, either when the application has been carried out as pretreatment before drying, or during the drying process itself. From the results obtained by various authors, the effects of ultrasound application on the product quality differed according to the system where it was applied: as pretreatment (liquid) or during drying (gas), the acoustic intensity applied, and mainly due to the nature of the food matrix.

According to the authors cited in this review, the application of power ultrasound as pretreatment by means of either ultrasonic baths or ultrasonic probes and using as liquid medium distilled water increase the reduction of the solid content together with the increment of the moisture content from. When osmotic solutions were used, the effect of the power ultrasound application was observed as the enhancement of the mass transport, increments in the solid content and reductions of the moisture content were observed in the treated products.

The transport of solids and water between sample and medium under the acoustic waves, promoted also the leakage of important biocompounds which affect mainly the appearance (color) and the nutritional quality of the treated and dried product. The sponge effect which affects the internal structure of the sample, promoting the movement of solids outside of the sample can be one of the main effects of ultrasound responsible of this. However, the acoustic energy applied during the pretreatment allowed the bond breakage between the cellular matrix and the strongly attached fraction of these biocompounds, so the leakage can be compensated by the release of this fraction. As a result, a higher bioavailability of these biocompounds was achieved. However, despite the higher bioavailability, the thermolabile character of these biocompounds together with the thermal energy given to the system during drying promoted a reduction of their content in the dried product. It is worthy of pointing out that in almost all cases the content of these biocompounds in dried acoustically treated products was higher than the one in non-treated dried products.

The use of osmotic solutions during pretreatments was reported in few papers. The high viscosity of these solutions, diminished the cavitation effect produced by acoustic waves and then reduces the effects of ultrasound. On the contrary, after treatment a sugar barrier on the surface of the product could reduce contact between the product and the oxygen during drying, therefore less oxidation.

The application of power ultrasound during the convective drying affected in different levels the quality of the dried product and similarly to the application as pretreatment, that is, the effects varied according to the nature of the sample and the type of drying carried out. The application of PU, on one hand, promoted an intensification of the drying process and then limited the oxidation reactions which maintain most of the biocompounds intact when it was applied at lower temperatures. On the other hand, it affected negatively the biocompounds when it was applied at higher temperatures due to the synergy of thermal and acoustic energy.

Increments in the vitamins B_1, B_2, B_3, and B_6, availability after acoustically assisted drying were observed in few cases, but they corresponded to specific drying settings (air velocity and temperature, ultrasonic intensity), not being this positive effect observed under other different drying conditions. The increments were linked to higher detachment of these vitamins from its bound to the apoenzyme which was induced by the ultrasound application. The degradation of vitamins vitamin C, E and B_5 was related to their free character in the food matrix, which made them more susceptible to thermal and acoustic energy.

Regarding enzyme activity, acoustic assistance as pretreatment or during drying promoted a significant reduction of it due to denaturation of the enzyme protein.

The application of power ultrasound to intensify drying has been deeply studied by food technologist and it is still avid of more research focus on the optimization of the use of this technology in terms of the quality of the dried product. Effects are widely diverse among products under study, so major effort must be done to cover a widely variety of product and to take this technology from laboratory scale to industrial level.

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REFERENCES

1. Fernandes FAN., Rodrigues S, Cárcel JA and García-Pérez JV, Ultrasound-assisted air-drying of apple (Malus domestica L.) and its effects on the vitamin of the dried product. *Food Bioprocess Tech* **8**: 1503-1511(2015).
2. Cárcel JA, García-Pérez JV; Riera E, Rosselló C and Mulet A, Drying Assisted by Power Ultrasound. In *Modern Drying Technology*, ed. Wiley-VCH Verlag GmbH & Co. KGaA, pp. 237-278 (2014).
3. Bird B, Stewart W and Lightfoot E, *Transport Phenomena.* John Wiley & Sons, Inc. (2006).
4. Ozuna C, Álvarez-Arenas TG, Riera E, Cárcel JA and Garcia-Perez JV, Influence of material structure on air-borne ultrasonic application in drying. *Ultrason Sonochem* **21**: 1235-1243. (2014).
5. Venkatesh MS and Raghavan GSV, An overview of microwave processing and dielectric properties of agri-food materials. *Biosyst Eng* **88:** 1-18 (2004).
6. Feng H, Yin Y and Tang J, Microwave drying of food and agricultural materials: basics and heat and mass transfer modeling. *Food Eng Rev* **4:** 89-106 (2012).
7. Oey I, Lille M, Van Loey A and Hendrickx M, Effect of high-pressure processing on colour, texture and flavour of fruit- and vegetable-based food products: a review. *Trends Food Sci Tech* **19:** 320-328 (2008).
8. Chen D, Xi H, Guo X, Qin Z, Pang X, Hu X, Liao X and Wu J, Comparative study of quality of cloudy pomegranate juice treated by high hydrostatic pressure and high temperature short time. *Innov Food Sci Emerg* **19:** 85-94 (2013).
9. Landl A, Abadias M, Sárraga C, Viñas I and Picouet PA, Effect of high pressure processing on the quality of acidified Granny Smith apple purée product *Innov Food Sci Emerg* **11:** 557-564 (2010).
10. Ade-Omowaye BIO, Angersbach A, Taiwo KA and Knorr D, Use of pulsed electric field pre-treatment to improve dehydration characteristics of plant based foods. *Trends Food Sci Tech* **12**: 285-295 (2001).
11. Chemat F, Zill EH and Khan MK, Applications of ultrasound in food technology: Processing, preservation and extraction. *Ultrason Sonochem* **18:** 813-835 (2011).
12. Fernandes FAN and Rodrigues S, Ultrasound as pre-treatment for drying of fruits: Dehydration of banana. *J Food Eng* **82:** 261-267 (2007).
13. Cárcel JA, García-Pérez JV, Benedito J and Mulet A, Food process innovation through new technologies: Use of ultrasound. *J Food Eng* **110:** 200-207 (2012).
14. Fernandes FAN, Linhares Jr. FE and Rodrigues S, Ultrasound as pre-treatment for drying of pineapple. *Ultrason Sonochem* **15:** 1049-1054 (2008).
15. García-Pérez JV, Cárcel JA, Benedito J and Mulet A, Power ultrasound mass transfer enhancement on food drying. *Food Bioprod Process* **85:** 247-254 (2007).
16. Mason TJ, Riera E, Vercet A and Lopez-Buesa P, Application of Ultrasound, in *Emerging Technologies for Food Processing*, Sun, D.-W., Ed. Academic Press: London, pp. 323-351 (2005).

17. Soria AC and Villamiel M, Effect of ultrasound on the technological properties and bioactivity of food: a review. *Trends Food Sci Tech* **21:** 323-331 (2010).

18. Pingret D, Fabiano-Tixier A-S and Chemat F, Degradation during application of ultrasound in food processing: A review. *Food Control* **31:** 593-606 (2013).

19. Kek SP, Chin NL and Yusof YA, Direct and indirect power ultrasound assisted pre-osmotic treatments in convective drying of guava slices. *Food Bioprod Process* **91:** 495-506 (2013).

20. Ricce C, Rojas ML, Miano AC, Siche R and Augusto, PED, Ultrasound pre-treatment enhances the carrot drying and rehydration. *Food Res Int* **89:** 701-708 (2016).

21. Gamboa-Santos J, Montilla A, Soria AC and Villamiel M, Effects of conventional and ultrasound blanching on enzyme inactivation and carbohydrate content of carrots. *Eur Food Res Technol* **234:** 1071-1079 (2012).

22. Romero JCA and Yépez VBD, Ultrasound as pretreatment to convective drying of Andean blackberry (Rubus glaucus Benth). *Ultrason Sonochem* **22:** 205-210 (2015).

23. Santacatalina JV, Contreras M, Simal S, Cárcel JA and Garcia-Perez JV, Impact of applied ultrasonic power on the low temperature drying of apple. *Ultrason Sonochem* **28:** 100-109 (2016).

24. Rodríguez Ó, Llabrés P, Simal S, Femenia, A and Rosselló C, Intensification of predrying treatments by means of ultrasonic assistance: effects on water mobility, PPO activity, microstructure, and drying kinetics of apple. *Food Bioprocess Tech* **8:** 503-515 (2015).

25. Jambrak AR, Mason TJ, Paniwnyk L and Lelas V., Accelerated drying of button mushrooms, Brussels sprouts and cauliflower by applying power ultrasound and its rehydration properties. *J Food Eng* **81:** 88-97 (2007).

26. Fernandes FAN, Gallão MI and Rodrigues S., Effect of osmotic dehydration and ultrasound pre-treatment on cell structure: Melon dehydration. *LWT-Food Sci Tech* **41:** 604-610 (2008).

27. Beck SM, Sabarez H, Gaukel V and Knoerzer K, Enhancement of convective drying by application of airborne ultrasound – A response surface approach. *Ultrason Sonochem* **21:** 2144-2150 (2014).

28. Yao Y, Enhancement of mass transfer by ultrasound: Application to adsorbent regeneration and food drying/dehydration. *Ultrason Sonochem* **31:** 512-531 (2016).

29. Oladejo AO and Ma H, Optimisation of ultrasound-assisted osmotic dehydration of sweet potato (Ipomea batatas) using response surface methodology. *J Sci Food Agr* **96:** 3688-3693 (2016).

30. Santos HM, Lodeiro C, Capelo-Martínez J-L, The Power of Ultrasound, in *Ultrasound in Chemistry*, Wiley-VCH Verlag GmbH & Co. KGaA, pp. 1-16 (2009).

31. Fernandes FAN and Rodrigues S, Osmotic Dehydration and Blanching, in *Ultrasound in Food Processing*, John Wiley & Sons, Ltd, pp. 311-328 (2017).

32. Azoubel PM, Baima MdAM, Amorim MdR and Oliveira SSB, Effect of ultrasound on banana cv Pacovan drying kinetics. *J Food Eng* **97:** 194-198 (2010).

33. Rodríguez Ó, Gomes W, Rodrigues S and Fernandes FAN, Effect of acoustically assisted treatments on vitamins, antioxidant activity, organic acids and drying kinetics of pineapple. *Ultrason Sonochem* **35:** 92-102 (2017).

34. Fijalkowska A, Nowacka M, Wiktor A, Sledz M and Witrowa-Rajchert D, Ultrasound as a pretreatment method to improve drying kinetics and sensory properties of dried apple. *J Food Process Eng* **39:** 256-265 (2016).

35. Nowacka M, Wiktor A, Śledź M, Jurek N and Witrowa-Rajchert D, Drying of ultrasound pretreated apple and its selected physical properties. *J Food Eng* **113:** 427-433 (2012).

36. Stojanovic J and Silva JL, Influence of osmotic concentration, continuous high frequency ultrasound and dehydration on antioxidants, colour and chemical properties of rabbiteye blueberries. *Food Chem* **101:** 898-906 (2007).

37. Siucińska K, Mieszczakowska-Frąc M, Połubok A and Konopacka D, Effects of Ultrasound Assistance on Dehydration Processes and Bioactive Component Retention of Osmo-Dried Sour Cherries. *J Food Sci* **81:** 1654-1661 (2016).

38. Oliveira FIP, Gallão MI, Rodrigues S and Fernandes FAN, Dehydration of malay apple (Syzygium malaccense l.) using ultrasound as pre-treatment. *Food Bioprocess Tech* **4:** 610-615 (2011).

39. Çakmak RŞ, Tekeoğlu O, Bozkır H, Ergün AR and Baysal T, Effects of electrical and sonication pretreatments on the drying rate and quality of mushrooms. *LWT-Food Sci Tech* **69:** 197-202 (2016).

40. Azoubel PM, da Rocha Amorim M, Oliveira, SSB, Maciel MIS and Rodrigues JD, Improvement of water transport and carotenoid retention during drying of papaya by applying ultrasonic osmotic pretreatment. *Food Eng Rev* **7:** 185 -192 (2015).

41. Mothibe KJ, Zhang M, Mujumdar AS, Wang YC and Cheng X, Effects of ultrasound and microwave pretreatments of apple before spouted bed drying on rate of dehydration and physical properties. *Dry Technol* **32:** 1848-1856 (2014).

42. Rawson A, Tiwari BK, Tuohy MG, O'Donnell CP and Brunton N, Effect of ultrasound and blanching pretreatments on polyacetylene and carotenoid content of hot air and freeze dried carrot discs. *Ultrason Sonochem* **18:** 1172-1179 (2011).

43. Tao Y, Wang P, Wang Y, Kadam SU, Han Y, Wang J and Zhou J, Power ultrasound as a pretreatment to convective drying of mulberry (Morus alba L.) leaves: Impact on drying kinetics and selected quality properties. *Ultrason Sonochem* **31:** 310-318 (2016).

44. Sledz M, Wiktor A, Rybak K, Nowacka M and Witrowa-Rajchert D, The impact of ultrasound and steam blanching pre-treatments on the drying kinetics, energy consumption and selected properties of parsley leaves. *Appl Acous* **103:** 148-156 (2016).

45. Dias da Silva G, Barros ZMP, de Medeiros RAB, de Carvalho CBO, Rupert Brandão SC and Azoubel PM, Pretreatments for melon drying implementing ultrasound and vacuum. *LWT-Food Sci Tech* **74:** 114-119 (2016).

46. Cárcel JA, Benedito J, Rosselló C and Mulet A, Influence of ultrasound intensity on mass transfer in apple immersed in a sucrose solution. *J Food Eng* **78:** 472-479 (2007).

47. Garcia-Noguera J, Oliveira FIP, Gallão MI, Weller CL; Rodrigues S and Fernandes FAN, Ultrasound-assisted osmotic dehydration of strawberries: effect of pretreatment time and ultrasonic frequency. *Dry Techol* **28:** 294-303 (2010).

48. Kowalski SJ, Szadzińska J and Pawłowski A, Ultrasonic-assisted osmotic dehydration of carrot followed by convective drying with continuous and intermittent heating. *Dry Techol* **33:** 1570-1580 (2015).

49. Fernandes FAN, Gallão MI and Rodrigues S, Effect of osmosis and ultrasound on pineapple cell tissue structure during dehydration. *J Food Eng* **90** 186-190 (2009).

50. Cárcel JA. García-Pérez JV, Riera E, Rosselló C and Mulet A, Ultrasonically Assisted Drying, in *Ultrasound in Food Processing*, John Wiley & Sons, Ltd, pp. 371-391 (2017).

51. Gamboa-Santos J, Montilla A, Cárcel JA, Villamiel M and Garcia-Perez JV, Air-borne ultrasound application in the convective drying of strawberry. *J Food Eng* **128:** 132-139 (2014).

52. Kowalski SJ and Pawłowski A, Intensification of apple drying due to ultrasound enhancement. *J Food Eng* **156:** 1-9 (2015).

53. Sabarez HT, Gallego-Juarez JA and Riera E, Ultrasonic-assisted convective drying of apple slices. *Dry Technol* **30:** 989-997 (2012).

54. Cárcel JA, García-Pérez JV, Riera E and Mulet A, Improvement of convective drying of carrot by applying power ultrasound-influence of mass load density. *Dry Technol* **29:** 174-182 (2011).

55. Gallego-Juarez JA, High-power ultrasonic processing: Recent developments and prospective advances. *Physcs Proc* **3:** 35-47 (2010).

56. Gallego-Juárez JA, Riera E, de la Fuente Blanco S, Rodríguez-Corral G, Acosta-Aparicio VM and Blanco A, Application of high-power ultrasound for dehydration of vegetables: Processes and devices. *Dry Technol* **25:** 1893-1901 (2007).

57. Frias J, Peñas E, Ullate M and Vidal-Valverde C, Influence of drying by convective air dryer or power ultrasound on the vitamin c and β-carotene content of carrots. *J Agr Food Chem* **58:** 10539-10544 (2010).

58. Kowalski SJ, Pawłowski A, Szadzińska J, Łechtańska J and Stasia M, High power airborne ultrasound assist in combined drying of raspberries. *Innov Food Sci Emerg* **34:** 225-233 (2016).

59. Schössler K, Thomas T and Knorr D, Modification of cell structure and mass transfer in potato tissue by contact ultrasound. *Food Res Int* **49:** 425-431 (2012).

60. Schössler K, Jäger H and Knorr D, Effect of continuous and intermittent ultrasound on drying time and effective diffusivity during convective drying of apple and red bell pepper. *J Food Eng* **108:** 103-110 (2012).

61. Schössler K, Jäger H and Knorr D, Novel contact ultrasound system for the accelerated freeze-drying of vegetables. *Innov Food Sci Emerg* **16:** 113-120 (2012).

62. García-Pérez JV, Carcel JA, Mulet A, Riera E and Gallego-Juarez JA, Ultrasonic drying for food preservation. In *Power Ultrasonics*, Woodhead Publishing: Oxford, pp 875-910 (2015).

63. Garcia-Perez JV, Carcel JA, Riera E, Rosselló C and Mulet A, Intensification of low-temperature drying by using ultrasound. *Dry Technol* **30:** 1199-1208 (2012).

64. Rodríguez Ó, Santacatalina JV, Simal S, Garcia-Perez JV, Femenia A and Rosselló C, Influence of power ultrasound application on drying kinetics of apple and its antioxidant and microstructural properties. *J Food Eng* **129:** 21-29 (2014).

65. Santacatalina JV, Rodríguez O, Simal S, Cárcel JA, Mulet A and García-Pérez JV, Ultrasonically enhanced low-temperature drying of apple: Influence on drying kinetics and antioxidant potential. *J Food Eng* **138:** 35-44 (2014).

66. Ozuna C, Cárcel JA, García-Pérez JV and Mulet A, Improvement of water transport mechanisms during potato drying by applying ultrasound. *J Sci Food Agr* **94:** 2511-2517 (2011).

67. Fernandes FAN, Rodrigues S, García-Pérez JV and Cárcel JA, Effects of ultrasound-assisted air drying on vitamins and carotenoids of cherry tomatoes. *Dry Technol* DOI: 10.1080/07373937.2015.1090445 (2015).

68. García-Pérez JV, Ortuño C, Puig A, Carcel JA and Perez-Munuera I, Enhancement of water transport and microstructural changes induced by high-intensity ultrasound application on orange peel drying. *Food Bioprocess Tech* **5:** 2256-2265 (2012).

69. García-Pérez JV, Cárcel JA, Benedito J, Riera E and Mulet A, Drying of a low porosity product (carrot) as affected by power ultrasound. *Defect Diffus Forum* **273-276:** 764-769 (2008).

70. Puig A, Perez-Munuera I, Carcel JA, Hernando I and Garcia-Perez JV, Moisture loss kinetics and microstructural changes in eggplant (Solanum melongena L.) during

conventional and ultrasonically assisted convective drying. *Food Bioprod Process* **90:** 624-632 (2012).

71. Cruz L, Clemente G, Mulet A, Ahmad-Qasem MH, Barrajón-Catalán E and García-Pérez JV, Air-borne ultrasonic application in the drying of grape skin: Kinetic and quality considerations. *J Food Eng* **168:** 251-258 (2016).

72. do Nascimento EMGC, Mulet A, Ascheri JLR, de Carvalho CWP and Cárcel JA, Effects of high-intensity ultrasound on drying kinetics and antioxidant properties of passion fruit peel. *J Food Eng* **170:** 108-118 (2016).

73. Szadzińska J, Kowalski SJ and Stasiak M, Microwave and ultrasound enhancement of convective drying of strawberries: Experimental and modeling efficiency. *Int J Heat Mass Tran* **103:** 1065-1074 (2016).

74. Szadzińska J, Łechtańska J, Kowalski SJ and Stasiak M, The effect of high power airborne ultrasound and microwaves on convective drying effectiveness and quality of green pepper. *Ultrason Sonochem* **34:** 531-539 (2017).

75. Fonteles TV, Leite AKF, Silva ARA, Carneiro APG, Miguel EdC, Cavada BS; Fernandes FAN and Rodrigues S, Ultrasound processing to enhance drying of cashew apple bagasse puree: Influence on antioxidant properties and in vitro bioaccessibility of bioactive compounds. *Ultrason Sonochem* **31:** 237-249 (2016).

76. Boukouvalas CJ, Krokida MK, Maroulis ZB and Marinos-Kouris D, Density and porosity: literature data compilation for foodstuffs. *Int J Food Prop* **9:** 715-746 (2006).

77. Ozuna C, Cárcel JA, Walde PM and Garcia-Perez JV, Low-temperature drying of salted cod (Gadus morhua) assisted by high power ultrasound: Kinetics and physical properties. *Innov Food Sci Emerg* **23:** 146-155 (2014).

78. Chen Z-G, Guo X-Y and Wu T, A novel dehydration technique for carrot slices implementing ultrasound and vacuum drying methods. *Ultrason Sonochem* **30:** 28-34 (2016).

79. Santacatalina JV, Soriano JR, Cárcel JA and Garcia-Perez JV, Influence of air velocity and temperature on ultrasonically assisted low temperature drying of eggplant. *Food Bioprod Process* **100:** 282-291 (2016).

80. Musielak G, Mierzwa D and Kroehnke J, Food drying enhancement by ultrasound – A review. *Trends Food Sci Tech* **56:** 126-141 (2016).

81. Francis FJ and Clydesdale FM, Food Colorimetry: Theory And Applications, ed.The Avi Publishing Company, Inc., pp. 90-91(1977).

82. Kowalski SJ and Szadzińska J, Convective-intermittent drying of cherries preceded by ultrasonic assisted osmotic dehydration. *Chem Eng Process* **82**, 65-70 (2014).

83. Pérez-Jiménez J, Díaz-Rubio ME and Saura-Calixto F, Non-extractable polyphenols in plant foods: nature, isolation, and analysis, in *Polyphenols in Plants*, ed. Academic Press, San Diego, pp. 203-218 (2014).

84. Ainsworth EA and Gillespie KM, Estimation of total phenolic content and other oxidation substrates in plant tissues using Folin-Ciocalteu reagent. *Nat Protoc* **2:** 875-877 (2007).

85. Gamboa-Santos J, Soria AC, Villamiel M and Montilla A, Quality parameters in convective dehydrated carrots blanched by ultrasound and conventional treatment. *Food Chem* **141:** 616-624 (2013).

86. Kadam SU, Tiwari BK and O'Donnell CP, Effect of ultrasound pre-treatment on the drying kinetics of brown seaweed Ascophyllum nodosum. *Ultrason Sonochem* **23:** 302-307 (2015).

87. Santacatalina JV, Cárcel JA, Simal S, Garcia-Perez JV and Mulet A, Atmospheric freeze drying assisted by power ultrasound. *IOP Conf Ser-Mat Sci* **42:** 012021 (2012).

Table 1. Application of power ultrasound as pretreatment before drying. Ultrasonic devices, pretreatment and drying conditions, and quality parameters under study.

	Acoustically assisted pretreatment					
Product	**Ultrasonic Device**	**Pretreatment Conditions**	**Medium**	**Drying conditions**	**Quality parameters**	**Reference**
Apple *Malus domestica var Red Fuji*	Probe	25 kHz; 200 W 5 – 15 min	Distilled water	70 °C 75 W/g*	Color; Texture; Rehydration; Water distribution	41
Apple *Malus domestica var. Granny Smith*	Probe	0 – 12.9 W cm^{-2} 25 °C; 5 min	Distilled water 1% citric acid Juice	50 °C 1 m s^{-1}	Microstructure; Enzymatic activity; Water distribution	24
Apple *Maus domestica Var. Idared*	Bath	35 kHz 25 °C, 10 – 30 min	Distilled water	70 °C 1.5 m s^{-1}	Microstructure; Rehydration, Shrinkage, Apparent density, Porosity,	35
Apple *Maus domestica Var. Idared*	Bath	21, 35 kHz; 3, 4 W cm^{-2} 30 min	Distilled water	70 °C 2 m s^{-1}	Color; Rehydration	34
Blackberry *Rubus glaucus Benth var. Andean*	Probe	24 kHz;85 W cm^{-3} 15 °C, 10 – 30 min	Distilled water	40 – 60 °C 3 m s^{-1}	Antioxidant activity,	22
Blueberry *Vaccinium ashei Reade*	Probe	850 kHz, 100 W 21 °C; 3 h	55 °Brix	70 °C	Color; Total polyphenol and anthocyanin contents, antioxidant activity	36
Brown seaweed	Probe	7 – 76 W cm^{-2} 10 min	Distilled water	50 °C 0.3 m s^{-1}	Color	88

Ascophyllum nodosum						
Brussels sprout *Brassica oleracea var. gemmifera*	Bath/Probe	20 – 24 kHz; 0.5 – 43 W cm^{-2}/ 18 °C; 3 – 10 min	Distilled water	60 °C 0.3 m s^{-1}	Rehydration	25
Carrot *Daucus carota L.*	Bath	38 kHz; 320 W 25 C; 120 min	40, 60 °Brix	70 °C 1.1 m s^{-1}	Color	48
Carrot *Daucus carota L. var. Nantesa*	Probe	20 kHz; 400 W 60 – 70 °C; 10 – 15 min	Distilled water	46 °C; 4.9 m s^{-1}	Microstructure; Rehydration Protein profile; Total polyphenol content Soluble carbohydrates; 2-FM-AA content	87
Carrot *Daucus carota L var. Flakee*	Bath	25 kHz, 700 W 23 °C; 30 – 60 min	Distilled water	40 – 60 °C; 2 m s^{-1}	Rehydration	20
Carrot Daucus carota L var. Nerac	Probe	20 kHz; 0.4–1.0 W mL^{-1} 25 °C; 3, 10 min	Distilled water	60 °C 0.3 m s^{-1}	Color, Polyacetylene and total carotenoid contents	42
Cashew apple baggase *Anacardium occidentale L.*	Probe	20 kHz; 75 – 373 W cm^{-2} 20 °C; 2 – 10 min	Distilled water	60 °C 1 m s^{-1}	Microstructure, Color, Antioxidant activity, Vitamin C content, Enzymatic activity	77
Cauliflower *Brassica oleracea var. botrytis*	Bath/Probe	20 – 24 kHz; 0.5 – 43 W cm^{-2}/ 18 °C; 3 – 10 min	Distilled water	60 °C 0.3 m s^{-1}	Rehydration	25
Cherries *P. cerasus L.*	Bath	25 kHz; 700 W	60 °Brix	60 °C	Color	84

		25 °C; 30 min				
Cherries *P. cerasus L.*	Bath	25 kHz; 0.4 W cm^{-2} 40 °C; 0 – 120 min	60 °Brix	60 °C 2.5 m s^{-1}	Microstructure, Total phenolic and anthocyanin contents,	37
Guava *Psidium guajava*	Bath	25 kHz; 0 – 2.5 kW 30 °C; 20 – 60 min	0 – 70 °Brix	70 °C 0.06 m s^{-1}	Color; Texture; Vitamin C content	19
Guava *Psidium guajava*	Probe	20 kHz; 400 W 6 – 20 min	0 – 70 °Brix	70 °C 0.06 m s^{-1}	Color; Texture; Vitamin C content	19
Malay apple *Syzygium malaccense L.*	Bath	25 kHz; 60 W 25 °C; 10 – 60 min	25 – 50 °Brix;	60 °C	Microstructure	38
Melon	Bath	25 kHz, 4.9 kW/m^{-2} 30 °C; 20 – 30 min	Distilled water	60 °C	Microstructure	26
Melon *Cucumis melo L. Var. cantalupensis Naud*	Bath	25 kHz; 4.9 kW m^{-2} 30 °C; 10 – 30 min 0.02 – 0.03 MPa	Distilled water	60 °C 2.0 m s^{-1}	Color; Texture, Total carotenoid content; Sensory analysis	45
Mulberry leaves *Morus alba L.*	Probe	25.2–117.6 W L^{-1} 20 °C; 5–15 min	Distilled water	60 °C 2.5 m s^{-1}	Color, Phenolic and flavonoid contents, Antioxidant activity, Chlorophylls, 1-deoxynojirimycin and γ-aminobutyric acid contents	43
Mushroom *Agaricus biosporus*	Bath	35 kHz; 480 W 30 °C; 10 – 30 min	Distilled water	50 °C 1.5 m s^{-1}	Rehydration, Total polyphenol content	39
Mushroom *Agaricus biosporus*	Bath/Probe	20 – 24 kHz;	Distilled water	60 °C 0.3 m s^{-1}	Rehydration	25

		0.5 – 43 W cm^{-2}/ 18 °C; 3 – 10 min				
Parsley leaves *Petroselinum crispum*	Bath	21 kHz; 300 W 22 °C; 20 min	Distilled water	20 – 40 °C 0.7 m s^{-1} 100 – 400 W*	Color; Chlorophyll content; Lutein content	44
Papaya *Carica papaya var. Formosa*	Bath	25 kHz; 4.9 kW m^{-2} 30 °C; 10 – 30 min	0 – 56 Brix;	70 °C 2.0 m s^{-1}	Total carotenoid content	40
Pineapple *Ananas comosus var. Perola*	Bath	25 kHz; 5.1 W L^{-1} 30 °C; 10 – 30 min	Distilled water Juice	50 °C 0.5 m s^{-1}	Vitamins C, B_1, B_2, B_3, B_5, organic acids; Total polyphenol and flavonoid contents; Antioxidant activity	33
Strawberry *Fragaria ananassa var. Camarasa*	Bath	0 – 40 kHz 30 °C; 10 – 45 min	25, 50 °Brix	60 °C 0.5 m s^{-1}	Microstructure	47

*Microwave power

Table 2. Application of power ultrasound during convective drying. Conditions and quality parameters under study.

Acoustically assisted drying					
Product	**Ultrasonic Device**	**Ultrasonic parameter**	**Drying conditions**	**Quality parameters**	**Reference**
Apple *Malus domestica var. Granny Smith*	Flexural vibrating plate	20 kHz 20 – 90 W	40 – 60 °C 1 m s^{-1}	Microstructure, Texture	53
Apple *Malus domestica var. Granny Smith*	Aluminum vibrating cylinder	21.8 kHz 0 – 31 kW m^{-3}	40 °C 1 m s^{-1}	Microstructure, Porosity, Texture	4
Apple *Malus domestica*	Aluminum vibrating cylinder	25 -75 W	-10 – 10 °C 2 m^{-1}	Rehydration, Hardness, Texture,	23

var. Granny Smith				Antioxidant activity	
Apple *Malus domestica var. Granny Smith*	Aluminum vibrating cylinder	21.8 kHz 18.5 – 30.8 kW m^{-3}	30 – 70 °C 1 m s^{-1}	Microstructure; Total polyphenol and flavonoid contents, Antioxidant activity	66
Apple *Malus domestica var. Granny Smith*	Aluminum vibrating cylinder	20.5 kW m^{-3}	-10 – 10 °C 2 m s^{-1}	Polyphenol and flavonoid contents, antioxidant activity	67
Apple *Malus domestica L.*	Aluminum vibrating cylinder	21.7 kHz 75 W	45, 60 C 1 – 5 m s^{-1}	Vitamins A, B_1, B_2, B_3, B_5, B_6 and E	1
Carrot *Daucus carota L. var. Nantesa*	Aluminum vibrating cylinder	20 kHz 100 W cm^{-2}	20 – 60 °C 1, 2 m s^{-1}	Vitamin C and β-carotene contents	59
Carrot *Daucus carota L. var. Nantesa*	Aluminum vibrating cylinder	0 – 2.5 kW m^{-3}	-10 °C 2 m s^{-1}	Rehydration, Texture	89
Cassava *Manihot esculenta*	Aluminum vibrating cylinder	21.8 kHz 0 – 31 kW m^{-3}	40 °C 1 m s^{-1}	Microstructure, Porosity, Texture	4
Red pepper *Capsicum annuum L*	Ring sonotrode	76 – 110 W	-30 °C 46 Pa	Bulk density, Rehydration, Color, Ascorbic acid content	63
Cherry tomato *Solanum lycopersicum var. Cerasiforme*	Aluminum vibrating cylinder	21.7 kHz 75 W	45, 60 °C 1 – 3 m s^{-1}	Vitamins B_1, B_2, B_3, B_5, B_6 and E, Lycopene and β-carotene contents,	69
Eggplant *Solanum melongena L.*	Aluminum vibrating cylinder	21.7 kHz 18.5 – 37.0 W L^{-1}	40 °C 1 m s^{-1}	Microstructure	72
Eggplant *Solanum melongena L.*	Aluminum vibrating cylinder	21.9 kHz 90 W	-10 – 10 °C 1 m s^{-1}	Hardness, rehydration, oil intake	81
Grape skin *Vitis vinifera L. var Bobal*	Aluminum vibrating cylinder	45 W	40 – 70 °C 1 m s^{-1}	Antioxidant activity, polyphenolic compounds	73

Green pepper *Capsicum annuum L*	Ring sonotrode	100 – 200 W 46 Pa	54 °C 2.5 m s^{-1}	Color, vitamin C content	76
Orange peel *Citrus sinensis var. Navelina*	Aluminum vibrating cylinder	21.8 kHz 45, 90 W	40 °C 1 m s^{-1}	Microstructure	70
Passion fruit peel	Aluminum vibrating cylinder	21.7 kHz 30.8 kW m^{-3}	40 – 70 °C 1 m s^{-1}	Microstructure, Antioxidant capacity, total polyphenol content	74
Potato	Ring sonotrode	24 kHz	70 °C	Microstructure	61
Raspberry *Rubus idaeus L.*	Airborne system	100 – 200 W	55 °C 0.4 m s^{-1}	Color	60
Strawberry *Fragaria ananassa*	Ring sonotrode	100 – 200 W	52 °C 2 m s^{-1}	Color, Water activity	75
Strawberry *Fragaria x ananassa var. Duch.*	Aluminum vibrating cylinder	21.8 kHz 30-60 W	40 – 60 °C 2 m s^{-1}	Vitamin C content, 2-furoylmethyl amino acids, Microbiological quality,	51