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Review

Current Applications of Ultrasound in Fruit and Vegetables Osmotic Dehydration Processes

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Featured Application: The osmotic dehydration process is used on an industrial scale in the processing of fruits and vegetables. Fruits and vegetables processed by osmotic dehydration can be used for direct consumption as products with a short shelf life, but most often they are semi-finished products intended for the production of ice cream, confectionery and preserves (e.g., jams, jellies and marmalades). However, osmotic dehydration can also be applied to obtain products from meat and fish, when salt is used as an osmotic agent. Sonication can be applied before or during osmotic dehydration, giving important advantages in terms of the acceleration of mass transfer processes, as well as obtaining products often characterized by improved physical and chemical properties.

Abstract: Ultrasound (US) is a promising technology, which can be used to improve the efficacy of the processes in food technology and the quality of final product. US technique is used, e.g., to support mass and heat transfer processes, such as osmotic dehydration, drying and freezing, as well as extraction, crystallization, emulsification, filtration, etc. Osmotic dehydration (OD) is a well-known process applied in food processing; however, improvements are required due to the long duration of the process. Therefore, many recent studies focus on the development of OD combined with sonication as a pretreatment method and support during the OD process. The article describes the mechanism of the OD process as well as those of US and changes in microstructure caused by sonication. Furthermore, it focuses on current applications of US in fruits and vegetables OD processes, comparison of ultrasound-assisted osmotic dehydration to sonication treatment and synergic effect of US and other innovative technics/treatments in OD (such as innovative osmotic solutions, blanching, pulsed electric field, reduced pressure and edible coatings). Additionally, the physical and functional properties of tissue subjected to ultrasound pretreatment before OD as well as ultrasound-assisted osmotic dehydration are described.

Keywords: ultrasound mechanism; ultrasound assisted osmotic dehydration; physical properties; color; chemical properties; bioactive compounds; microbial growth; structure

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1. Introduction

Fruits and vegetables are an important part of the human diet because they contain a high amount of valuable compounds [1–3]. In accordance with the World Health Organization recommendations, at least 400 g of fruits and vegetables should be consumed on a daily basis, which is necessary to preserve a well-functioning of our organism [4]. A diversified and properly balanced diet not only prevents undernutrition but also helps protect the organism from developing various diseases [4,5]. Due to the profitability of production, fruits and vegetables are produced in large volumes on farms. However, it is well known that the seasonality of fruits and vegetables results in the formation of food surpluses. All crops collected in the same period cannot be consumed in fresh form. Thus, to avoid or reduce food losses, the use of different pretreatments and processes is required [3].

The technologies most frequently used to preserve food are freezing [6] and dewatering processes such as drying [7–10] or osmotic dehydration. The latter can be applied as a single process [11–13] or before drying process [14–17]. However, in recent years, there is a growing interest in new, non-thermal technologies which can be used as a pretreatment before mentioned processes [18–21] or in assistance to them [22–24].

US is one of the most promising treatment methods and supports for food production processes as proved by scientific and industrial research conducted currently on a large scale [25,26]. The research undertaken indicates that, depending on the type of raw material, its structure and anatomy, as well as properties of applied sound waves (length, frequency, intensity and, attenuation coefficient) and duration of application, one can obtain results of both shortening time [27] and extending mass exchange [28] in drying processes. It also impacts the heterogeneous physical and chemical properties [29,30] and the structure of final products [31,32]. Therefore, this review focuses on the latest applications of US in fruits and vegetables OD processes.

2. Osmotic Dehydration Process

Osmotic dehydration (OD) is a non-thermal process for a partial dehydration of plant tissue. It is also called a "dewatering impregnation soaking process", since along with the water removal there is a simultaneous impregnation of the tissue with the solutes present in the osmotic solution [33–36]. This process consists of soaking pieces of fruits and vegetables in hypertonic solution (Figure 1) and the mass transfer is allowed thanks to the differences in the water chemical potential between the product and the solution [20,37]. During OD, a multidirectional mass exchange occurs through the transfer of water from the material to the osmotic solution, and at the same time the penetration of the osmotic substance into the dehydrated tissue. Low-molecular substances such as vitamins, organic acids, saccharides or mineral salts are rinsed out from the tissue. During such a complex process of mass exchange, the water content decreases and the dry matter increases at the same time, which changes the chemical composition of dehydrated food [33,36].

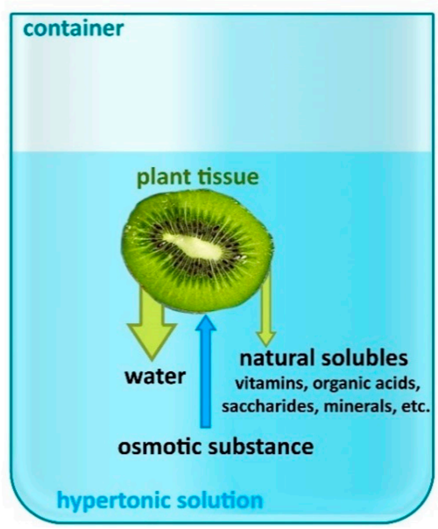

Figure 1. The mechanism of the osmotic dehydration process (e.g., kiwifruit tissue).

The effectiveness of the dewatering depends on many factors: the concentration, temperature and agitation of the osmotic solution; properties of the osmoactive substance; time and conditions of the process; the type, shape, size and chemical composition of raw material subjected to OD; the ratio of the solution to the raw material; etc. The most commonly used osmotic substance is a sucrose solution of high concentration [33,38,39], however other sugars as well as sodium chloride, sorbitol or other substances which produce high osmotic pressure and are acceptable for consumer can be used [33,38]. Recently, new trends are observed, such as replacing sugar solution with fruit syrups and juices enriched with various valuable ingredients in order to produce high value-added, functional products [39–41].

OD can be used as process for obtaining minimally processed food [42–44]; however, it is usually used as a pretreatment before the drying processes [14,16,45]. This process also plays an important role in increasing the overall availability of exotic fruits. For example, thanks to the pretreatment by OD followed by drying, it was possible to significantly minimize the loss of papaya during transport. Even 40% of the fruit was unmarketable after traveling from the plantation to the destination countries [46].

The osmotic dehydration process is long and often requires the acceleration of mass transfer using traditional and innovative methods. OD process allows obtaining semi-dried products with improved stability, thanks to the reduction of their water activity and freezable water content [34,47]. OD treatment can be applied at room temperature or at temperatures which are slightly higher in order to increase a mass transfer rate, however usually it does not exceed the temperature of 40–45 °C [34,39]. Traditionally, agitation and rotation are used for this purpose. However, OD, especially when applied at room temperature, is a time-requiring process, therefore recently the combination of OD with other traditional and innovative techniques has been studied. These combined treatments include the application of ultrasound, pulsed electric field, high hydrostatic pressure, vacuum, irradiation and centrifugal force [47,48], which are able to increase mass transfer in the treated products. All these techniques were extensively reviewed by Ahmed et al. [42].

3. Sonication

3.1. Ultrasound Treatment

Ultrasound (US) is a form of energy generated by sound waves with a frequency higher than the hearing threshold of the human ear (18 kHz–100 MHz) [18,27,49,50]. Sound waves are characterized by particular frequency, length and amplitude. They can be divided into two basic groups, based on their intensity and frequency: ultrasound of low power—waves of low intensity (<1 W/cm^2)—and high frequency (>1 MHz) and ultrasound of high power (or power ultrasound)—waves of high intensity (>1 W/cm^2) and low frequency (18–100 kHz) [18,27,49,51–53].

The US waves of low intensity and high frequency are used for diagnostic purposes, mainly in medicine and industry, including food industry. These waves do not cause physical and chemical changes in the material they go through, which allows for their application in non-invasive analytical techniques [52]. High intensity US causes irreversible changes in the structure of the material and thus is used to accelerate the heat and mass transfer processes in the food industry as well as in cleaning machines [3,27,50,52,54–56]. High intensity US causes physical changes to the material, including its damage, as well as the initiation of various chemical reactions, including oxidation processes. It can also be successfully used to isolate intracellular proteins, for food preservation and to inactivate or activate enzymes [50,53,57–59]. Thus, this paper focuses only on the high intensity US.

Generally, US can be applied as a pretreatment or treatment during process (US-assisted process) by the means of various devices and methods (immersive, contact or airborne US) [50,60]. Immersive method is most commonly used to accelerate OD both before (US as a pretreatment) [11–13] and during OD, as well as for further drying [14–17].

3.2. Ultrasound Mechanism

The damage to the material's structure and activation of various chemical reactions as a result of US propagation is connected with its mechanism of action. Among the phenomena suggested in the literature, the following are predominantly reported [18,49,50]:

- "sponge effect";
- cavitation;
- absorption of acoustic energy; and
- effects accompanying cavitation (in particular at the solid/liquid border), such as microstreaming, microjetting or standing wave pattern.

Thermal, mechanical and physicochemical effects of sonication result from the absorption of the ultrasonic wave. The temperature increase is dependent on the US frequency, power or the kind of treatment (immersive, contact and airborne) [49,58]. Along with the propagation of high intensity ultrasound in a solid matter (such as plant tissue), due to its mechanical impact, a series of compression and decompression of the structure of the medium occurs, called "sponge effect", because the material then resembles a compressed and released sponge [49,50].

It is assumed that the major changes in the material are due to cavitation and the effects associated with cavitation. Cavitation takes place in liquids or solids (which contain moisture), after the application of high intensity ultrasound. The phenomenon consisting in formation of gas microbubbles (micro-bubbles of water vapor), which is caused by local drops in liquid pressure [49,59]. The cavitation causes thermal, physical (collapse pressure, turbulences and shear stresses) and chemical (free radical formation) effects [61]. Furthermore, the mechanical energy and pressure of sound waves cause a million bubbles to cyclically oscillate around their stable size in a very short time. With regard to plant tissue, disturbances intensify the flow of mass and heat. In the available literature, this phenomenon is called microstreaming. The bubbles that reached unstable size suddenly collapse [18,49,50]. The energy released during the collapse of one bubble is extremely small, but the simultaneous collapse of a million bubbles has a cumulative huge effect. This results in point (located in a small area) generation of very high pressures (up to 50–100 MPa) and temperature (up to 5500 °C) [18,50,62]. Considering cavitation regarding plant tissue immersed in solution (or inside the cells), it should be highlighted that bubbles near the solid surface collapse asymmetrically, releasing an irregular fluid beam (fountain of microbubbles) towards the solid surface, which microjet the tissue with a speed of 200 m/s. This in turn leads to erosion of the plant tissue. This effect is called microjetting [18,49].

The "sponge effect" and cavitation (especially asymmetric collapse) cause permanent damage to cell walls and cell membranes causing creation of microchannels in the material [27,32,50,63], which are discussed in the next section. The aforementioned, together with turbulences of solution reducing the laminar sublayer, shock waves and shear stresses in the fluid medium, facilitate the exchange of water with low-molecular substances and osmotic substance [49,59,64]. The ultrasound-assisted OD (UOD) is thus especially important in the case of heat-sensitive raw materials, as usually OD is accelerated by the increase of temperature of osmotic solution. However, the effectiveness of the impact of US depends primarily on the use of an appropriate frequency of US and the time of its application [64]. Moreover, the type of liquid medium in which the material is subjected to immersive US treatment is important. Fernandes and Rodrigues [65] found that treating bananas with US in water allows more water to be removed from the tissue during drying than when an osmotic solution was used. It is believed that one of the reasons for the observed behavior may be the sugar saturation of the microchannels formed by the action of US. The same results regarding the filling of microchannels with sugar molecules and limited moisture flow were obtained for osmodehydrated strawberry [66] and pineapple [31] using US.

3.3. Structure Changes of Material Subjected to Sonication and Osmotic Process

The US treatment in the plant tissue results in the structural changes of the tissue, due to several different effects undergoing through the sonication describe in previous paragraph. The plant material treated with US is characterized by multiple breakdowns of cells causing changes in tissue structure, as a consequence of the cavitation effect, the sponge effect and the accompanying effects [49]. Furthermore, the sonication causes changes in the structure of the material, dependent on the applied sonication parameters. Longer US pretreatment usually results in higher damage of the plant tissue.

The examples of changes in the structure are shown in Figure 2 for apple and potato tissue treated with US. Fresh samples and those after 30 min of US treatment (conducted in ultrasonic bath at 21 kHz for pear and 35 kHz for potato) were freeze-dried to preserve the structure of the material [28,67]. The photos (exanimated with a scanning electron microscope—Hitachi, model TM-3000, Tokyo, Japan) show alteration in a structure after the sonication. Sonicated apple tissue is characterized by distortions, and the coalescence of cells into larger clusters can also be observed (Figure 2a). In the case of potato tissue, the US caused breakdowns of the tissue and the exposition of the starch grains (Figure 2b). This effect was also observed by many researchers in apple [27,68,69], carrot [28], pineapple [31], melon [70], berries [71], basil [63], etc. For example, in the case of US-treated carrot [28], microchannels were formed, especially with shorter sonication time, i.e., 10 min. The image analysis revealed that the cross-section area of those samples and interspaces were smaller than in the material which was treated for a longer time of ultrasonic waves. The changes in structure of the carrot tissue were generated mainly by the direct US effect, i.e., the sponge effect, due to reduced cavitation with the used packaging. The US generated the formation of microchannels, especially at the beginning of the treatment, and then over time the sonication led to distortion of the structure, forming larger spaces in the tissue of apple [27] and carrot [28]. In addition, other researchers showed that the formation of microchannels occurred during sonication, and this phenomenon was observed in the structure of kiwifruit [32], apple [27,69], potato [72] and carrot tissue [28] after ultrasound's application.

It is well known that during the OD process the fruits lose water and gain the osmotic substance [70]. With longer immersion time in osmotic solution, greater changes in the texture occur and this impacts the structure. After 1 h of OD process, a gradual disconnection and breakdown of the tissue, a loss of shape of cellular walls and loss of turgor pressure are noticed [11]. As aforementioned, the use of sonication causes the formation of microchannels and the alteration of the tissue structure. Furthermore, the increased bidirectional exchange during OD causes greater alteration to the microstructure when compared with the dehydrated material, but not pretreated with US [24,32]. After the application of US, the maximum cross-section area of cells increased in kiwifruits, especially at longer sonication time (30 min) (Figure 3a). The analysis allowed expressing in numbers the changes in size of cells and intracellular spaces, leading to better understanding of the alterations in microstructure of the plant tissue [28]. Allahdad et al. [24] observed greater changes in microstructure in arils tissue when combination of sonication and OD was applied. The cell wall between two cells of arils tissue, after 30 min of OD, was partially broken and some cells were merged together, while for combined OD and US treatments the cells were characterized by larger cell interspace and microchannels. However, in the case of pumpkin subjected to 10 min sonication and 12 h of OD, the changes were small and comparable with US treatment applied for 20 and 30 min before OD. In addition, the use of coating with sodium alginate on pumpkin resulted in decrease of porosity of cell structure, when coating with higher percentage (3%) was applied [73].

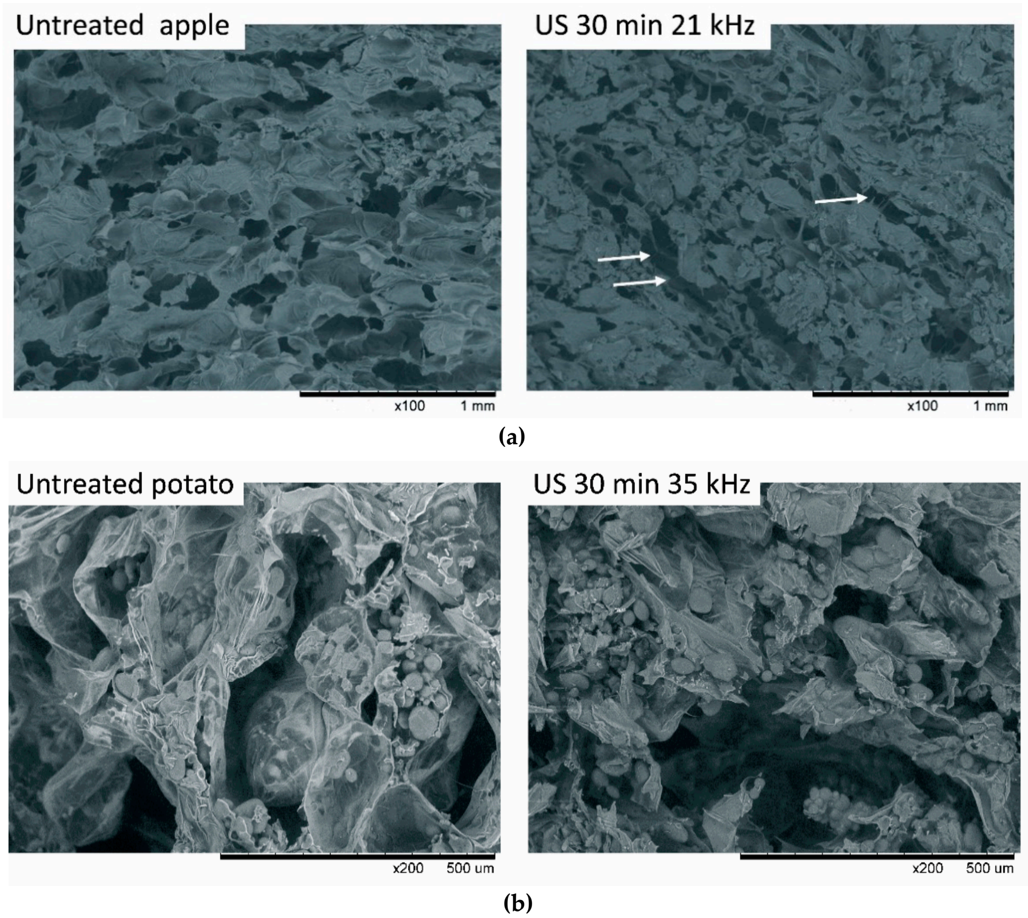

Figure 2. The influence of ultrasound treatment on the structure of: apple (**a**); and potato (**b**). The magnification is 100× and 200×, respectively. Own unpublished data. The white arrows indicate microchannels.

The entity of changes in the plant tissue structure following the treatments by US, OD or UOD depends on many factors (processing time, US frequency, type and concentration of the solution, etc.). With short time of OD, better preservation of the kiwifruit structure subjected to the novel method of osmotic-dehydrofreezing with US enhancement was observed. For kiwifruits subjected to 120 min of either OD or UOD significant differences were observed in their structure as compared to fresh samples. However, for longer OD with US assistance (180–300 min), cells of kiwifruit tissue became distorted and formed large intercellular spaces [74]. A similar effect was observed in cranberry samples treated by a combination of cutting or blanching with US assisted OD process, even if the UOD treatment was set up to 30 (Figure 3b) and 60 min. Moreover, these treatments promoted a merging of the neighboring cells and creation of microchannels. Furthermore, with the thermal treatment (blanching), the tissue was characterized by more porous structure [75]. The sonication applied during OD caused also changes in microstructure in coconut tissue [76], pineapple [31] and cherries [77].

In addition, the frequency of US used during OD process impacts on microstructural alterations. OD assisted by US with high frequency (130 kHz) caused serious ruptures and damages in cranberries tissue microstructure, while at lower frequency (35 kHz) only few microchannels were observed. The significant changes in structure resulted in texture ruptures, which could not preserve the puffiness formed by steam pressure caused by microwave treatment [78].

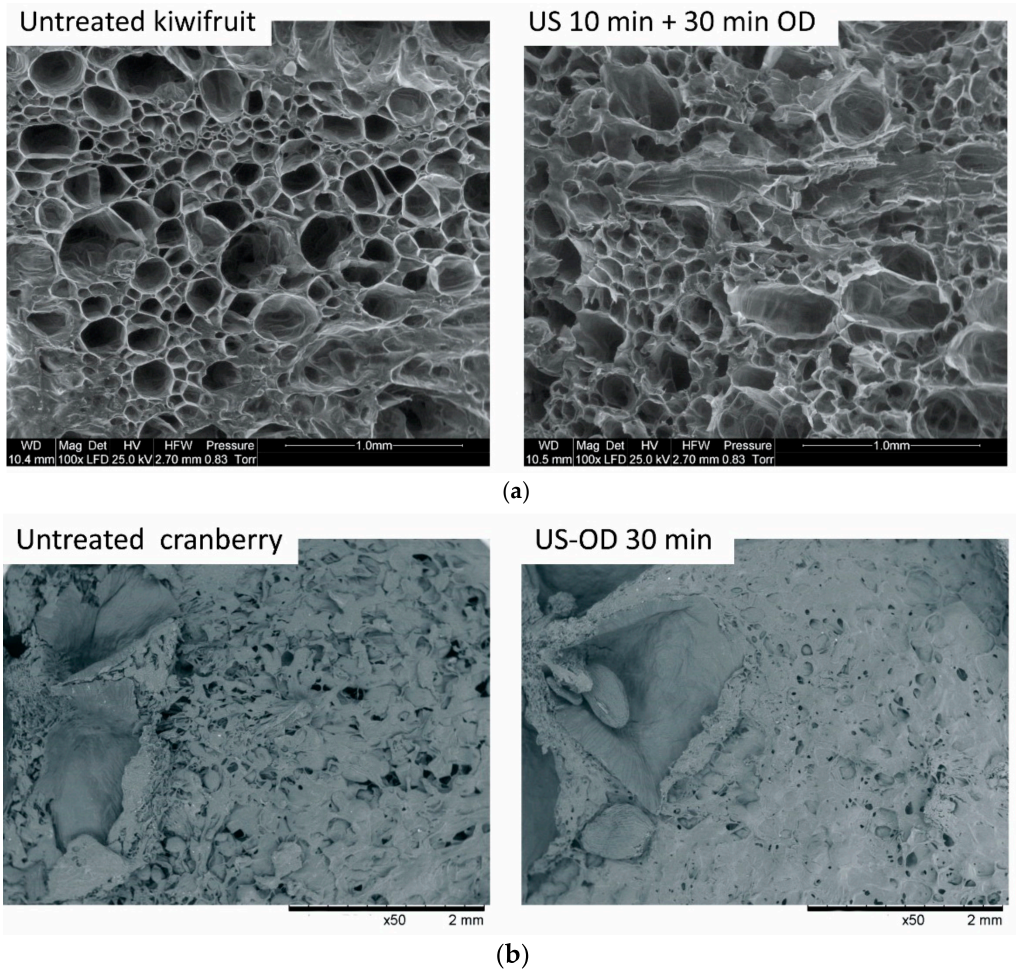

Figure 3. Structural changes of: (**a**) kiwifruits subjected to ultrasound treatment (10 min) and osmotic dehydration (30 min); and (**b**) cranberries treated with ultrasound-assisted osmotic dehydration (30 min). Own unpublished data.

The concentration of osmotic solution and method of OD conduction is also of great importance. Karizaki et al. [79] observed less damages of the potato tissue, while a lower concentration of osmotic solutions was applied. In comparison to OD process, UOD with 15% salt or 50% sugar solution resulted in mechanically damaged and broken cells. Furthermore, the black jamun subjected to OD process in atmospheric conditions and under vacuum with (UVOD) and without (VOD) simultaneous application of US was characterized by different microstructure, depending on the process applied. The samples subjected to OD had oval pores, while those treated by VOD had small and irregular intercellular spaces and UVOD treated samples presented a shrinkage of the cellular structure [80].

3.4. Effect of Sonication and Osmotic Dehydration Process on Microbial Growth

The use of the sufficient power of US positively affects the microbial aspects. The US can be applied individually or in combination with different sanitizers [81,82] or with elevated temperature [83]. Ugarte-Romero et al. [84] studied the effect of acoustic energy on the microbial safety of apple cider. Results showed that sonication increased *E. coli* K12 cell destruction and with the use of higher temperature from 40 to 60 °C caused bacteria reduction by 0.1–5.3-log cycles. Similarly, Zenker et al. [83] mentioned that ultrasound-assisted thermal treatment of *E. coli* is better than when the sonication is applied separately. On the other hand, Duckhouse et al. [82] stated that the use of sonication as a pretreatment at higher frequency (850 kHz) immediately followed by hypochlorite addition is as good as, or even better than, using a short period with chlorination simultaneous (1–5 min) at 20 kHz to kill microorganism. Zinoviadou et al. [83] explained that the reduction of microorganisms under the influence of ultrasound results from the mechanism related to localized heating even to 5500 °C and high pressure to even 500 MPa and formation of free radicals, which cause the sonolysis of water. Furthermore, the collapsing of the cavitation bubble may cause the destruction of the cell surface. However, Ananta et al. [85] stated that US induced cell death is not be related to membrane damage.

According to the mechanism of the OD process, the reduced amount of freezable water content and water activity and therefore the inferior availability of water for the degradative reactions and growth of microorganisms can guarantee a higher microbial stability [34,86–88] For example, pumpkin subjected to OD process in different osmotic solutions, after 90 days of storage was characterized by low values up to 3–4 log CFU, while the initial microbial counts of total aerobic bacteria, yeast and molds after OD process were at undetectable levels (<10 CFU/g) [89]. Moreover, Nowacka et al. [39] studied the growth of mesophilic aerobic bacteria and yeast in cranberries subjected to the UOD process with different osmotic solutions and stored for eight weeks at the temperature of 10 °C. They noticed that the sucrose solution enabled for longer shelf-life in comparison to other two solutions used (trehalose solution or reduced concentration of sucrose with the addition of steviol glycosides), due to the lower water activity achieved in the final products. However, any significant differences in microbial growth were noticed between the samples pretreated with or without US assistance [39].

Sakooei-Vayghan et al. [90], instead, observed a positive effect on the microbial load reduction in UOD-pretreated and coated dried apricots compared to the OD pretreated ones. The decrease of 0.29–0.52 log cycles of total mesophilic aerobic was noticed in the UOD-pretreated and coated dried samples compared to the control ones, showing the lowest values (35–45 CFU/g), when UOD at 35 kHz and temperature of 30 and 40 °C was used in combination with coating (pectin + ascorbic or citric acid). Similar results were observed as concern the total yeast and mold count [90].

3.5. Use of Sonication in Food Technology

Ultrasound-enhanced processes are good alternative to conventional processing due to reduction of costs and often better quality of products, depending on the processing. Studies carried out over the past decades resulted in wide industrial applications of sonication in various food processing [91]. Among them, US is applied in the industry in the following processes: surface cleaning, extraction, degassing, foam removal, homogenization, crystallization, emulsification, extraction, filtration, sterilization, cutting, enzyme inactivation and desensitization [91,92].

Nonetheless, in recent years, research efforts are focused on exploitation of US in other heat and mass transfer processes, e.g. drying [50,93], freezing [94], disinfection, cooking [95] or osmotic dehydration [3,42,96]. The use of US in OD causes a faster removal of water from the raw material, than when it is carried out in a traditional way due to turbulences of medium and structures changes [97]. US supports not only the removal of water from the material but also increases the dry matter content [31,70]. The selection of appropriate conditions for the technological process contributes to the preservation of a better aroma, color and taste of the product as well as retention of valuable nutrients.

4. Ultrasound-Assisted Osmotic Dehydration

The application of ultrasound in the OD process is of great interest for researchers and food industries, since it offers the possibility to be used both prior the OD (as a pretreatment) and during the OD process (ultrasound-assisted osmotic dehydration (UOD)). Due to the cavitation phenomenon and continuous compression and decompression of the tissue, US leads to the creation of microchannels, which facilitate the mass transfer between the product and osmotic solution [32,70,75,98].

4.1. Comparison of Ultrasound Assisted Osmotic Dehydration to Sonication Treatment—Kinetics Aspects

The influence of the application of US before or during OD treatment has been widely studied. The first studies concerning the utilization of US treatment (sonication) combined with (OD) assumed the application of US as a pretreatment before further OD. When US is applied as a pretreatment for the OD process, the plant tissue is usually immersed in distilled water and then subjected to the OD process in the osmotic solution. Fernandes et al. [31,70] studied the changes in the structure and diffusivity of melon [70] and pineapple [31] subjected to US treatment for 10, 20 and 30 min and then to osmotic solution (0, 35 and 70 °Brix). The changes in the structures were significant with breakdown of cells, which resulted also in a higher water loss and a higher sugar gain. Further, Fernandes at al. [98] analyzed the influence of time of US treatment (10, 20, 30, 45 and 90 min) applied in water and in osmotic solution on water loss, sugar loss and water diffusivity during drying of papaya. They stated that sonication positively influences the effective diffusivity of water, resulting in a drying time reduction of approximately 16%. Furthermore, the results show that after 30 min of sonication papayas lost around 13.8% sugars, which can be used in production of dried fruit with a lower sugar content. Finally, the same research group investigated also the effect of the different solution concentrations (0%, 25% and 50% sucrose), times (10, 20, 30 and 45 min) and frequencies (25 and 40 kHz) of sonication applied before or during OD of strawberries, subjected further to a drying process [66]. The drying time was reduced up to 30% in comparison to untreated dried material [66]. In addition, Nowacka et al. [32] observed that US pretreatment performed at the frequency of 25 kHz for 20 and 30 min had a positive effect on the mass exchange in the kiwifruit subjected to the OD process for a period of 30 min. Similarly, Prithani and Dash [99] observed that pretreatment of kiwifruit with US (25 kHz, 20 min) in distilled water increased the effective moisture and solute diffusivity in samples OD treated by 300 min in 60 °Brix sucrose solution.

As the use of US accelerated the dehydration process and improved some properties of the dehydrated products (described in Sections 5.1 and 5.2), the researchers started to pay more attention on the integrated process such as ultrasound-assisted OD. Goula et al. [72] treated the potato cubes with static OD, OD with agitation, OD with US pretreatment and UOD. The sonication applied as a pretreatment as well as with ultrasound-assisted OD process increased water loss and solids gain. Higher water diffusivity of about 5.5–260% was observed in samples UOD treated with 30% NaCl, depending on the treatment time. However, for osmotic solution with a concentration of 70% NaCl and US pretreatment in water, diffusivity increased up to 130%. In addition, Bchir et al. [100] noticed higher mass transfer rate for UOD of pomegranate seeds in comparison to OD process. On the basis of surface methodology response, the optimum conditions for a higher mass transfer rate were established at 240 min, 60 °Brix and 41 °C for UOD and 240 min, 29 °Brix and 50 °C for OD process. The highest mass transfer during US-assisted OD was noted for organic cranberries, even though the assistance of US was only 30 min [39].

Due to the fact that OD process often precedes the drying process, several studies consider obtaining products subjected to US, OD and then drying. Usually, the sonication positively impacts on shortening the drying process applied after OD. For example, Corrêa et al. [101] noticed that the application of US with and without OD process resulted in significantly accelerated drying time of pineapple.

4.2. Synergic Effect of US and Other Innovative Technics/Treatments in Osmotic Dehydration

Recently, the synergic effect of the combination of US with other technics/treatments (innovative osmotic solutions, blanching, PEF, reduced pressure and edible coatings) has gained a particular attention in the food research.

Taking into consideration that high sugar products are not desirable in the human diet [3,16,102], there is a necessity to develop a method to improve the taste of products and make them acceptable for consumers, without affecting too much their final sugar content. In fact, different combinations of UOD with solutions containing sweeteners or sweetness enhancer have been proposed as an alternative to the use of sucrose. The most popular substances from these groups are xylitol, erythritol, maltitol and dihydroxyacetone (DHA) [40], steviol glycoside [3,16,29] and trehalose [39] applied in order to reduce sugar content in the product, and therefore decrease the calories.

Cichowska et al. [40] observed that the application of erythritol, xylitol and DHA solutions in OD process showed a similar efficiency to sucrose and good water removal properties, however the application of US during OD did not promote any advantages on mass transfer in apple tissue if compared to just OD treatment. The application of sonication by the continuous method rather than those with 30-min intervals allowed for a significant reduction in water activity in apple tissue in all four tested solutions. Nowacka et al. [39] studied the influence of UOD treatment with sucrose (SA) (61.5%), 30% sucrose + 0.1% of steviol glycoside (SA + STV) and 40% trehalose (T) on the mass transfer parameters and on quality characteristics during storage of cranberries. They observed that the UOD significantly increased the weight loss and water loss in cranberry samples dehydrated in all tested solutions, showing the highest values for samples dehydrated in SA, followed by SA+STV, and finally for samples treated by T. Solid gain instead was influenced by the application of UOD when SA+STV was used as osmotic agent. During storage, US pretreatment led to a lower weight reduction and higher lightness in cranberry samples treated with any type of solution in comparison to those without US pretreatment. The influence of the replacement of sucrose with 0.1% STV during UOD treatment (21 kHz, 400 W) combined with blanching and PEF treatment on the quality of hot air-dried cranberries was also studied by Wiktor et al. [16]. The samples treated with this innovative combination of the pretreatments were compared to blanched (BL) and control (cut) samples. Drying time of cranberries subjected to BL alone was reduced by 48–50% compared to the control samples, while the combined method (BL+PEF+UOD) reduced the drying time up to 55%. However, no significant differences were observed concerning the type of osmotic solution used. Both pretreatments also resulted in a higher amount of anthocyanins and flavonoids and less sucrose than in control (cut) samples. The authors suggested that, even if there was no improvement of the quality of dried fruits treated with the combined method compared to only blanched samples, the reduction of drying time could be of benefit for the incorporation of PEF and US techniques in the industries considering especially a low energy consumption of these processes. In addition, the researchers from the same working group [3] studied the influence of combined pretreatment methods (blanching, US and vacuum) on the kinetics of OD and selected quality properties of cranberries. It was observed that the application of US in combined pretreatments lowered the water loss and solid gain if compared to the cranberry samples pretreated with BL and triplicate lowering of the pressure, independently of the solution (SA or SA+STV) used for OD. Contrarily, Feng et al. [103] observed a significant increase in water loss in combined vacuum (100 mbar)-US pretreated garlic samples (21.12%) dehydrated in 25% NaCl solution, in comparison to the untreated (10.67%), vacuum treated (14.18%) and US-treated in multi-frequency mode (11.20–13.56%) samples. Moreover, Alolga et al. [48] observed that vacuum-assisted osmosonication (UVOD) of garlic resulted in the shortest drying time (280 min) and lower energy consumption in comparison to the untreated samples (570 min) or those treated with US (330 min) or UOD (300 min). Therefore, the reduction of the drying time of the pretreated samples with respect to the control samples was 57.90%, 52.63% and 49.12% for UVOD, UOD and US, respectively. Alizehi et al. [96] studied the effect of different pretreatments, such as OD (50% sucrose and 10% (*w*/*v*) NaCl solution), vacuum-assisted OD (VOD) (200 mbar, 15 min), UOD (35 kHz, 130 W, 15 min) and UVOD on drying time and physicochemical characteristics of dried carrots. The results demonstrate that the application of US and vacuum alone, as well in combination, could reduce the drying time of carrots in comparison to the OD treated samples (470 min). The lowest drying time was exhibited in the UOD-treated samples (355 min), followed by UVOD- (422 min) and VOD-treated samples (441 min).

Recently, the synergic effect of the US application along with the edible coating has been studied, with the aim of increasing mass transfer rate and to modify some properties of plant tissue by US while decreasing the solid uptake due to the application of coating film. Jansrimanee and Lertworasirikul [73] observed that the combined application of US (40 kHz, 150 W, 10 min) and 3% sodium alginate (SA) coating to the pumpkin resulted in a high WL/SG (5.18), better structure preservation and decreased time of the OD process (from 12 to 9 h) compared to the samples pretreated with the SA alone.

Usually, the dried products show moderate or low rehydration capacity because, during the drying process, there is cellular and structural rapture of the tissue, therefore a combination of US with firming agents was proposed by Prosapio and Norton [104]. They studied the combined effect of application of UOD in solution containing firming agents (calcium chloride and calcium lactate) on strawberry physical parameters and rehydration of freeze-dried samples. They showed that freeze-dried samples pretreated with UOD with firming agents presented an enhanced rehydration capacity, better color retention, improved texture and better preserved microstructure.

5. Properties of the Product Treated with US before or during OD

5.1. Physical Properties of the Product Treated with US before or during OD

As described above, the US propagation before or during the OD causes irreversible changes in the structure of the material. Plant tissue, which was partially damaged during the pretreatment or further drying, is unable to absorb the same water content during rehydration [105]. On the other hand, porosity and material shrinkage changes during the treatments also contributed to changes in rehydration ability or texture. Furthermore, the leakage of the cellular content and activation or inactivation of various enzymes results in alteration of color of plant tissue [96,106].

Table 1 summarizes the impact of US applied as a pretreatment or during OD on the physical properties of fruits and vegetables tissue. The effect of US on the physical properties is generally related to type of material, treatment type and parameters. Spinei and Oroian [106] studied the effect of US treatment (20%, 60% and 100% amplitude) in 61.5% sucrose solution at 30, 40 and 50 °C for 20, 40 and 60 min. The results show that the optimal conditions were obtained at 30 °C for 40 min at a 100% amplitude for obtaining good physico-chemical characteristics (mass transfer parameters, moisture content and functional properties). Moreover, sonication resulted in color changes causing a higher lightness (L*) and a lower water activity in OD samples. In addition, an increase of lightness was observed in the case of US enhanced OD of cranberries [30] and blueberries [106]. In turn, a better or unchanged color of UOD samples in comparison to OD was noted for bananas [107], kiwifruits [108] and pomegranate arils [24]. However, when the UOD material was dried, the changes were more visible [109–111]. For instance, Rahaman et al. [110] reported a significant decrease of lightness, a*, b* and chroma parameters of UOD plum, which were explained by increased Maillard reactions.

Alizehi et al. [96] subjected carrot to OD, UOD, VOD and UVOD, and they reported a better rehydration ability (RR), lower shrinkage and hardness and higher lightness (L* value) of dried UOD samples. The authors explained that microchannel formation and higher porosity of carrot due to sonication were probably the reasons of such behavior. The applied vacuum mainly increased hardness and decreased the lightness but in combination with US (UVOD) the total color change was the lowest. Similar texture alteration was reported by Nowacka et al. [112], who treated whole, cut and blanched cranberries with US for 30 and 60 min in osmotic solution. After the treatment the changes in the texture were observed. For all of the samples, a slight, but statistically significant, reduction in peak force was observed, whereas the work required to deform the fruit was the lowest among all the investigated samples. It was associated with the US impact on modification the plant tissue, resulting in lower cell turgor [69]. The greatest changes in mechanical properties of cranberries were observed when the combined methods were applied, including cutting or blanching prior to sonication in the osmotic solution (C+US_30, C+US_60, BL+US_30, BL+US_60). Both the use of US and the penetration of osmotic solution inside the tissue influenced the mechanical properties of cranberries. Due to sonication, the OD was more intense, hence the loss of turgor pressure and shrinkage of the protoplast along with its separation from the cell wall [113] probably resulted in a decrease in the maximum compression force and an increase of work required to deform the sample. On the contrary, the hardness was not significantly changed in UOD pomegranate arils [24] and pomegranate seeds [100] when compared with OD. The studies carried out on kiwifruits [108] revealed that US pretreatment significantly enhanced the firmness after 120 min of OD, resulting in similar value for samples treated by 20 and 30 min of US+OD than for fresh kiwifruit. However, no significant effect was observed directly after the treatment compared to immersed in water samples.

Table 1. The physical properties of products osmo-dehydrated with the assistance of US.

Product [References]	Treatment Applied	Physical Properties after OD	Physical Properties after Drying
Blueberries [106]	UOD (25 kHz, 400 W, 30–50 °C, 20–60 min and amplitude of 20, 60 and 100%)	US results in a higher lightness (L*) and decreased water activity.	-
Cranberries [112]	CUT or BL (90 °C for 5 min) + UOD (21 kHz, 30 or 60 min in two osmotic solution SA and SAG)	US reduced the maximum force necessary for conduction 90% of material deformation, whereas the work for cut and blanched fruits after UOD increased.	-
[30]	UOD (21 kHz, 180 W, 30 and 60 min) BL (90 °C for 5 min) + UOD (21 kHz, 180 W, 30 and 60 min)	After UOD of whole fruits water activity and volume did not change, while cut and blanched was unchanged or lower. Combined treatment (CUT/BL+UOD) led to increase the lightness and decrease a*.	-
Carrots [96]	OD (40 °C, 2 h) UOD (35 kHz, 130 W, 15 min) VOD (200 mbar, 15 min) UVOD (35 kHz, 130 W, 200 mbar, 15 min)	-	Better RR, lower shrinkage and hardness and higher lightness of UOD samples were observed. UVOD caused the smallest changes in color.
Garlic [48]	US (40 kHz, 600 W, 40 min, water) UOD (40 kHz, 600 W, 40 min, 30% $CaCl_2$) UVOD (100 mbar, 40 kHz, 600 W, 40 min, 30% $CaCl_2$)	-	All pretreatments increased the rehydration ability in the following trend: UVOD > UOD > US.
Apples [115]	OD (30 °C, 30 min); US (20 kHz, 300 W/L) UOD (20 kHz, 300 W/L, 30 °C, 30 min)	-	L*, b* and chroma values of color of UOD apple were higher compared to US, OD and control sample.
Banana [107]	OD (40, 45, 50, 55 and 60% sucrose, 15, 30, 60, 90, 120 and 180 min) Indirect UOD (40 kHz, 130 kW/m^2, 5, 10, 15 and 20 min) Direct UOD (20 kHz, 200 W, intermittent mode 5 s on/5 s off, total time: 1, 3, 5, 7, 10 and 15 min)	UOD resulted in a lower total color change than in the case of mechanical agitation (OD). Indirect UOD caused lower changes than direct UOD.	-

Table 1. *Cont.*

Product [References]	Treatment Applied	Physical Properties after OD	Physical Properties after Drying
Pomegranate arils [24]	OD (10-80 min, 50% sucrose) UOD (25 or 40 kHz, 10–80 min, 100 W, 50% sucrose)	UOD especially at 40 kHz greater decreased the water activity than OD. UOD did not change significantly the hardness and color compared with OD.	-
Pomegranate seeds [100]	OD (sucrose 0, 30, 60%) UOD (20 kHz, 30, 40, 50 °C for 20, 130, 240 min, respectively)	Hardness of OD and UOD seeds were significantly higher than for fresh seeds, while toughness values were lower. Between OD and UOD the texture factors were almost the same.	The application of UOD reduces the rehydration ratio. UOD and OD did not have a significant influence on the color of dried pomegranate seeds.
Strawberry [114]	UOD (40 kHz, 21 min, 20–31 °C; 47.5 °Brix)	-	A higher shrinkage and RR of UOD strawberries than dried without pretreatment was noted. The UOD caused only minor changes in color.
Pumpkin [111]	UOD (53 kHz, 40 and 60% sucrose, 40, 80 and 120 min	Dry matter increased with increasing both treatment time and sugar concentration. Increased treatment time caused increase of a* and b* color parameters but hue angle was not altered.	RR of dried pumpkin was dependent on drying method, treatment time and sugar concentration. For air and vacuum dried samples there was no apparent effect but for freeze-dried samples with increasing time the RR decreased. In comparison to untreated sample, UOD caused a decrease of L* and increase of a* color parameters.
Kiwifruits [108]	US (35 kHz, 10–30 min) and/or OD (61.5 °Brix, 120 min, 25 °C)	US pretreatment significantly enhanced the firmness after 120 min of OD, resulting in similar value for 20 and 30 min of US+OD than for fresh kiwifruit. US contributed to less changed color after OD than in the case of OD alone.	-
[109]	OD (50 °Brix, erythritol, sorbitol and sucrose, 120 min) UOD (25 kHz, 50 °Brix, erythritol, sorbitol and sucrose, 120 min)	-	The total color change of OD and UOD kiwifruit was dependent on the type of solution and method of drying. US caused both decrease and increase of color changes values. There were no significant changes in water activity due to a different treatment.
Plum [110]	UOD (25 kHz, 30 and 60 min, 50 °Brix glucose or sucrose, 30 °C)	-	In comparison to dried untreated plum, the UOD caused a higher and a lower hardness when sucrose and glucose were used, respectively. Color was significantly changed due to UOD—a lower lightness, a*, b* and chroma parameters were'noted.

BL, blanching; US, ultrasound; OD, osmotic dehydration; V, vacuum; VOD, vacuum assisted osmotic dehydration; UOD, ultrasound assisted osmotic dehydration; UVOD, ultrasound, vacuum assisted osmotic dehydration; RR, rehydration ratio; L*—color lightness; a* and b*—chroma parameters indicating color from green (-a*) to red (a*) and from blue (-b*) to yellow (b*).

A good rehydration ability is very important in the case of further use of dehydrated fruits and vegetables. The sonically-enhanced OD usually resulted in a better rehydration ratio, as was proved in the case of dried: carrots [96], garlic [48] and strawberry [114], probably due to a microchannel formation and higher porosity. It should however be highlighted that the shrinkage was not lower in every case. Amami et al. [114] observed a higher shrinkage and rehydration ratio of UOD strawberries than dried without pretreatment. On the other hand, sometimes the UOD caused such damage to the structure that did not allow absorbing the same water content as in the case of dried sample without treatment [100].

5.2. Functional Properties of the Product Treated with US before or during OD

Fruits and vegetables are a good source of micronutrients and non-nutrient functional compounds, such as polyphenols, carotenoids, vitamins, minerals as potassium, calcium and magnesium and dietary fiber, which are known to have a benefit effect on the human health [116]. However, the application of US in combination with OD and/or drying could have an influence on functional compounds retention. Table 2 summarizes some of the recent findings regarding the effect of US on vitamin C, polyphenol content and other bioactive compounds, as well as antioxidant activity of different fruit and vegetables subjected to OD and/or drying process.

Table 2. The functional properties of products osmo-dehydrated with the assistance of US.

Product [References]	Treatment Applied	Functional Properties after OD	Functional Properties after Drying
Cranberries [29,30]	UOD (21 kHz, 180 W, 30 and 60 min) BL (90 °C for 5 min) + UOD (21 kHz, 180 W, 30 and 60 min)	Both pretreatments promoted a decrease in vitamin C, which was higher in BL+UOD samples. Anthocyanins, TPC and antioxidant activity were strongly influenced by the applied treatment type and duration.	-
[19]	BL (90 °C for 5 min) + US (21 kHz, 10 or 20 min) + V (40 kPa, 10 or 20 min) + OD (72 h, 40 °C)	Combined treatment resulted in a better preservation of anthocyanins and similar retention of TPC, TF and vitamin C if compared to untreated samples.	-
[16]	BL (90 °C for 5 min) + US (21 kHz, 30 min) + PEF (5.5 kV/cm, 2.0 kJ/kg) + OD (72 h, 40 °C)	-	Combined treatment caused a decrease in total polyphenols, flavonoids and anthocyanins content if compared to untreated samples.
Carrots [96]	OD (40 °C, 2 h) UOD (35 kHz, 130 W, 15 min) VOD (200 mbar, 15 min) UVOD (35 kHz, 130 W, 200 mbar, 15 min)	-	Better preservation of total carotenoids was observed in UOD treated samples and dried at low temperature (55 °C).
Garlic [48]	US (40 kHz, 600 W, 40 min, water) UOD (40 kHz, 600 W, 40 min, 30% $CaCl_2$) UVOD (100 mbar, 40 kHz, 600 W, 40 min, 30% $CaCl_2$)	-	All pretreatments increased the TPC, TFC, antioxidant activity and allicin content, following the trend: UVOD > UOD > US

Table 2. *Cont.*

Product [References]	Treatment Applied	Functional Properties after OD	Functional Properties after Drying
Apricot [119]	OD (55 °C, 30 and 45 min) + edible coating (P, P+CA, P+AA) UOD (25 and 35 kHz, 30 and 45 min) + edible coating (P, P+CA, P+AA)	Decrease in TPC and vitamin C content was observed in both OD and UOD samples if compared to untreated ones; higher decrease in UOD samples with 35 kHz and longer duration.	The highest retention of TPC and vitamin C was noticed in OD samples coated by P+AA followed by UOD and P+AA samples. Both treatments led to a higher antioxidant activity. UOD and P+CA coating preserved better the β-carotene content.
Blueberries [106]	UOD (25 kHz, amplitude of—20, 60 and 100%; 61.5% sucrose solution at 30, 40 and 50 ◦C for 20, 40 and 60 min)	The optimal conditions for the highest antioxidant activity and total content of anthocyanins, flavonoids and polyphenols were obtained by using 30 °C for 40 min at a 100% amplitude.	-
Sour cherries [120]	UOD (25 kHz, 60% sucrose solution for 0–120 min, shaking 30 rpm for 0–120 min, 40 °C)	Total anthocyanins and TPC decreased in all samples, however retention of these compounds was observed when US and shaking were applied for 60 min.	After drying, a further decrease of each compound was observed, confirming the trend observed in OD samples.
Sweet potatoes [118]	OD (10–20% glucose, 10–45 min US (20 kHz, 10–45 min) UOD (20 kHz, 10–20% glucose, 10–45 min)	-	Better preservation of TPC and TF was observed in OD samples, while antioxidant activities were improved by US alone or in combination with OD. The vitamin C was retained better in UOD samples.
[117]	UOD (28 kHz, 300 W, 20–60 min)	>70% of vitamin C retention, however higher loss of carotenoids was noticed in UOD samples in comparison to OD ones.	-
Apples [115]	OD (30 °C, 30 min); US (20 kHz, 300 W/L) UOD (20 kHz, 300 W/L, 30 °C, 30 min)	-	Higher retention in vitamin C content was reported in UOD samples (46.05%), than in US (31.28%) and OD ones (25.95%).
Strawberry [114]	UOD (40 kHz, 21 min, 20–31 °C; 47.5 °Brix)	-	TPC content decreased in the dried samples in the similar range for samples with UOD pretreatment and those just dried.
Kiwifruits [108]	US (35 kHz, 10–30 min) and/or OD (61.5 °Brix, 120 min, 25 °C)	US pretreatment for 20 and 30 min significantly enhanced the chlorophyll content in kiwifruit if compared to OD samples.	-
[109]	OD (50 °Brix, erythritol, sorbitol and sucrose, 120 min) UOD (25 kHz, 50 °Brix, erythritol, sorbitol and sucrose, 120 min)	-	UOD promoted a decrease in polyphenols and carotenoids if compared to OD samples; better retention of these compounds was achieved when hybrid conventional +US drying was applied.

Table 2. *Cont.*

Product [References]	Treatment Applied	Functional Properties after OD	Functional Properties after Drying
Physalis [121]	US (20 kHz, 30 min) + OD (55 °C, 55 °Brix, 10 h)	No influence on carotenoids content was reported.	-
Plum [110]	UOD (25 kHz, 30 and 60 min, 50 °Brix glucose or sucrose, 30 °C)	-	Higher TPC and antioxidant activity when UOD was applied for 30 min in glucose solution.

BL, blanching; US, ultrasound; OD, osmotic dehydration; V, vacuum; VOD, vacuum assisted osmotic dehydration; UOD, ultrasound assisted osmotic dehydration; UVOD, ultrasound, vacuum assisted osmotic dehydration; P, pectin; CA, citric acid; AA, ascorbic acid.

Concerning the vitamin C, its content and behavior upon the application of different treatments strongly depended on the type of product and combination of different pretreatments. In sweet potato, US application allowed better retention of vitamin C in the final osmo-dehydrated product [117] and hot air-dried product [118]. Similarly, in dried apple samples, Amanor-Atiemoh et al. [115] observed a higher retention of vitamin C when apples were subjected to a pretreatment with UOD rather than to US and OD alone. In apricot, UOD-treated samples [119], instead, a higher decrease of vitamin C was observed if compared to the untreated samples or those treated just with OD. This decrease was proportional to the increase in the frequency and treatment duration. A similar relation was observed also after the hot-air drying of apricot cubes [119]. Nowacka et al. [29] observed that the combination of blanching with US in the OD process caused a decrease in vitamin C content of semi-moist cranberries, while the same treatment with an addition of reduced pressure led to a similar retention of vitamin C as in the untreated dried cranberries [3].

Considering the phenolic compounds and antioxidant activity, Siucińska et al. [120] observed that prolonged application of US (longer than 90 min) during OD process caused a loss of about 10% of TPC and anthocyanin in osmo-dried sour cherries. Similarly, UOD caused a decrease of TPC in semi-dried and dried apricot [90] and dried kiwifruit [109], while a higher retention of TPC and antioxidant activity was noticed in dried plum [110] and dried garlic [48]. Finally, no effect on the retention of TPC in dried strawberries was observed [114].

Nowacka et al. [29,30], studying the influence of different pretreatments on osmodehydrated cranberries, noticed that anthocyanins, TPC and antioxidant activity were strongly influenced by the applied treatment type and duration. The same research group observed a decrease of bioactive compound in BL + US + PEF treated osmodehydrated cranberries [16], while a better preservation of anthocyanins and similar retention of TPC and TF was achieved when the combination of BL + US + Vacuum was used as a pretreatment before drying of cranberries.

Ultrasound-assisted OD caused a higher loss of carotenoids in sweet potato samples in comparison to the conventional OD [122], while no effect was observed in physalis [121]. However, for blueberries, the selection of appropriate conditions of UOD results in obtaining the highest antioxidant activity and total content of anthocyanins, flavonoids and polyphenols [106]. Nowacka et al. [108] observed enhanced chlorophyll content in semi-dried kiwifruit subjected to the US pretreatment. When fruits and vegetables were subjected to the further drying, different behaviors in pigments were observed depending on both pretreatment and drying process parameters. For kiwifruits, Kroehnke et al. [109] observed a decrease of carotenoid as well as TPC in UOD samples compared to OD ones, while a better retention of these compounds was achieved when hybrid US-assisted conventional drying was applied. Better preservation of total carotenoids in UOD treated samples was observed in died at low temperature carrot samples [96] and in dried apricot subjected combined UOD and pectin + citric acid coating [119].

6. Conclusions

The ultrasound treatment of the plant tissue generates several effects, including cavitation, the sponge effect and the accompanying effects, which lead to destruction of the structure. Due to the abovementioned phenomena, microchannels are formed, especially at the beginning of the sonication. The longer sonication time resulted in greater damage to the tissue and forming empty areas. As a consequence of changes in the cellular structure, the processes based on mass exchange such as osmotic dehydration are intensified. Furthermore, the application of ultrasounds prior to osmotic dehydration or during dehydration process influences the physical and chemical, including bioactive component contents, properties of the plant tissue. Thus, the ultrasound application offers possibility to design products, e.g., fruit snacks characterized with different, often better, properties than the ones obtained thanks to the traditional methods.

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