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FOOD TECHNOLOGY

Novel technologies combined with osmotic dehydration for application in the conservation of fruits: an overview

Barbara de Sousa Pinto[1*] Ariane Carla Campos de Melo[2]
Esly Ferreira da Costa Junior[1] Andréa Oliveira Souza da Costa[1]

[1]Programa de Pós-graduação em Engenharia Química, Escola de Engenharia, Universidade Federal de Minas Gerais (UFMG), Belo Horizonte, 31910-810, MG, Brasil. E-mail: barbara.eq@hotmail.com. *Corresponding author.
[2]Departamento de Química, Universidade Federal de Minas Gerais (UFMG), Belo Horizonte, MG, Brasil.

ABSTRACT: Osmotic dehydration (OD) is a technique used for the partial removal of water from foodstuff, including fruit and vegetables, with the aim of producing a desiccated product. The process involves placing the material in a hypertonic solution for several hours and allowing water to move from the cell compartment into the solution by osmosis. OD is influenced by various factors such as the concentration and composition of the osmotic solution, the solution temperature, the type of agitation and the time of exposure, as well as the size, shape and compactness of the food material. The main advantages of OD over conventional drying processes are the superior quality of the dried products and the minimization of shrinkage. In recent years, research effort has focused on the combination of OD with other technologies, such as ultrasound, cryogenic freezing with liquid nitrogen, pulsed electric field, gamma radiation and high hydrostatic pressure. The application of these methods prior to or concomitant with OD accelerates mass transfer and reduces the drying rate of fruit and vegetables by increasing the permeability of cell membranes. In this manner, combined processes tend to be more efficient and economical in comparison with conventional OD because they reduce operating times and; consequently, energy consumption. In addition, the dried products generated by such coupled processes typically exhibit improved nutritional and physicochemical characteristics. This review summarizes the basic principles and applications of OD in combination with other methods, with particular emphasis on the production of dried fruits.
Key words: dehydration, fruit processing and conservation, osmosis, mass transfer, combined technologies.

Novas tecnologias combinadas com desidratação osmótica para aplicação na conservação de frutas: uma revisão

RESUMO: A desidratação osmótica (DO) é uma técnica utilizada para remover parcialmente a água dos alimentos, incluindo frutas e vegetais, com vistas a produção de alimentos secos. O processo consiste em colocar o material em uma solução hipertônica por várias horas e deixar a água passar do compartimento celular para a solução por osmose. A DO é influenciada por vários fatores como a concentração e composição da solução osmótica, a temperatura da solução, o tipo de agitação e o tempo de exposição, assim como o tamanho, forma e compactação do material alimentar. As principais vantagens da DO em relação aos processos de secagem convencionais são que ela dá origem a produtos secos de qualidade superior e minimiza o encolhimento. Nos últimos anos, tem-se investigado a combinação da DO com outras tecnologias, tais como ultrassom, congelamento criogênico com nitrogênio líquido, campo elétrico pulsado, radiação gama e alta pressão hidrostática. A aplicação desses métodos antes ou simultaneamente com a DO acelera a transferência de massa e reduz a taxa de secagem de frutas e vegetais através do aumento da permeabilidade das membranas celulares. Assim, os processos combinados tendem a ser mais eficientes e econômicos do que a DO convencional, pois reduzem o tempo de operação e, consequentemente, o consumo de energia. Adicionalmente, os produtos desidratados gerados através de processos associados geralmente apresentam melhores características nutricionais e físico-químicas. Esta revisão sumariza os princípios básicos e aplicações da DO em combinação com outros métodos, com ênfase especial dada à produção de frutas secas.
Palavras-chave: desidratação, processamento e conservação de frutas, osmose, transferência de massa, tecnologias combinadas.

INTRODUCTION

Osmotic dehydration (OD) enables the production of desiccated foods with high nutritional value and acceptable sensory properties whilst using lower temperatures and consuming less energy in comparison with traditional drying methods. However, OD techniques generally require long process times and, for this reason, generate some undesirable effects in the final product such as loss of color intensity, luminosity and texture strength (EROGLU & YILDIZ, 2010). In many cases, the texture may become hard and brittle, water-soluble vitamins and minerals may be lost and the risk of microbial deterioration may increase. In order to overcome such problems, extensive research effort aimed to increasing cell permeability, thereby reducing dehydration time.

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Various procedures have been employed prior to or concomitant with OD in attempts to accelerate drying time and to prevent deterioration and loss of quality of dry food products. Such methods include treatment with ultrasound, liquid nitrogen (cryogenic freezing), pulsed electric field, gamma radiation, high hydrostatic pressure and centrifugation (OLIVEIRA et al., 2011; PARNIAKOV, 2016). This review outlines the basic principles and applications of OD in combination with such methods, with particular emphasis on the production of dried fruits.

COMBINATORIAL APPROACHES TO OSMOTIC DEHYDRATION

Ultrasound-assisted OD

Ultrasound instruments operate at frequencies ranging from 20 kHz to 10 MHz (CHENG et al., 2014; MOSES et al., 2014; FEI et al., 2018) with both low- and high-frequency waves being used in food processing and allied industries (SU et al., 2014). Low energy, high-frequency (MHz range) ultrasound is used mainly in monitoring food quality, while high-energy, low-frequency (kHz range) ultrasound is employed predominantly in food processing in order to modify the structure of raw materials (MASON & CORDMAS, 1996; MOTHIBE et al., 2011; SIUCIŃSKA & KONOPACKA, 2014; SU et al., 2014; CAMPUS et al., 2018). Since ultrasound is simple, relatively inexpensive and eco-friendly, the technique is of increasing importance as an alternative process with potential application in many areas of food production (SU et al., 2014).

Ultrasound treatment of porous food in aqueous medium induces deformation of the solid material and the creation of micro-channels on the surface (FERNANDES & RODRIGUES, 2008; MOSES et al., 2014; FEI et al., 2018). In fruits, the micro-channels created by ultrasound result from acoustic cavitation (MOTHIBE et al., 2011; FEI et al., 2018) in which gas bubbles that are formed within the liquid collapse explosively, generating sufficient localized pressure to help remove moisture that may be tightly adhered to the tissue (ALLAHDAD et al., 2018). However, the formation of micro-channels can limit the diffusion of sucrose, ascorbic acid and soluble proteins by virtue of their high molecular weight compared with that of water (FERNANDES & RODRIGUES, 2008; FEI et al., 2018).

Novel approaches to drying that incorporate ultrasound-assistance can increase the efficiency of the process by reducing the consumption of energy while preserving the quality of the final product (MOSES et al., 2014). In the case of hard fruit such as banana, apple, pineapple and papaya, advanced techniques involving the application of ultrasound prior to drying have attracted considerable research interest. Pre-treatment with ultrasound can be performed using an ultrasonic water bath or probe that transmits ultrasound waves directly into the liquid medium. The equipment typically comprises three basic parts, namely a generator, a single/multiple piezoelectric transducer and a coupler (MOTHIBE et al., 2011), while the rate of drying is influenced by the frequency and power of the ultrasound and the time of application (SUN et al., 2019).

Although, ultrasound has varying effects on different fruits, application of the technique has been shown to increase drying rates significantly, thereby reducing the overall processing time. For example, when low-calorie dried fruits are required, ultrasound treatment in distilled water as the medium is worthwhile prior to hot air drying because it significantly increases the effective diffusivity of water leading to a reduction in drying time and in processing costs (MOTHIBE et al., 2011).

Ultrasound-assisted OD involves the application of ultrasonic waves through an osmotic solution in order to facilitate the hydrodynamic mechanism of mass transport (water removal and sugar gain) during the drying process (GARCÍA-PÉREZ et al., 2009; AWAD et al., 2012; MOTHIBE et al., 2011; CHENG et al., 2014; SIUCIŃSKA & KONOPACKA, 2014; ZHANG & JIANG, 2014; SUN et al., 2019). It is important to note that an increase in mass transfer is essential to improve the drying rate of fruit (SIMAL et al., 1998; MOTHIBE et al., 2011). However, ultrasound-assisted OD is not a viable drying process when a large amount of water has to be removed from the fruit and/or when the final moisture content of the product has to be very low. The reason for these two exceptions is that the process induces high solid gain by the fruit and the sugar concentrates predominantly on the surface of the sample making it difficult to remove the water. Moreover, soluble nutrients may be lost in the ultrasound liquid medium during pretreatment (MOTHIBE et al., 2011). According to AWAD et al. (2012), it can also be quite challenging to interpret the results of the combined approach because there is an indirect relationship between the parameters associated with food quality and those of the drying process**.** While this difficulty may restrict the wide application of ultrasound-assisted OD, appropriate statistical treatment of the data obtained should be sufficient to overcome the problem (SU et al., 2014).

Despite these limitations, ultrasound-assisted OD is recognized as an effective method for preserving the nutritional value and the natural color and flavor of foods during air-drying at room temperature (FEI et al., 2018). For example, ALLAHDAD et al. (2018) evaluated the efficiency of the OD of pomegranate arils when ultrasound was applied for different lengths of time, and reported that ultrasonic waves at 25 and 40 kHz facilitated the detachment of moisture from cell walls and increased water loss by 2-fold and 2.7-fold, respectively. The combined process also enhanced solid gain and improved color quality, although these effects were accompanied by a reduction in total anthocyanins and an increase in hardness in comparison with fruit subjected to OD alone. In an earlier study, CHENG et al. (2014) investigated the ultrasound-assisted OD of strawberries in which fruits were immersed in 25 and 50° Brix sucrose solutions at 40 °C for 3 h in a ultrasonic bath (40 kHz, 150 W and 0.167 W cm^{-2}). The loss of water in fruits that had been exposed to ultrasound for 2 h was 10 to 43% higher than in those subjected to OD under normal mechanical agitation, especially when the higher concentration of sucrose was employed. In addition, the solid gain after 3 h of ultrasound was 5.46% in comparison with the gain of 4.55% achieved by OD under mechanical agitation; although, the ultrasound-treated fruits showed the lowest firmness values. Other studies involving ultrasound-assisted OD of fruits are presented in table 1.

Multifrequency ultrasound-assisted OD

The efficiency of ultrasound-assisted OD can be enhanced by increasing the intensity of cavitation and this can be achieved by applying multifrequency ultrasound and conducting the process at elevated external pressure (LEE et al., 2018). Furthermore, pre-treatment with multifrequency ultrasound is more energy efficient than that using a single frequency mode. Despite the potential advantages, there is only one study in the literature describing the impact of the multifrequency process (FENG et al., 2018). These researchers compared the effects of vacuum pre-treatment coupled to ultrasound-assisted OD (VUOD) with traditional OD, vacuum pre-treatment OD and multifrequency

Table 1 - Studies involving ultrasound-assisted osmotic dehydration.

Reference	Treatment conditions	Observed alterations
CICHOWSKA et al. (2019)	Apple tissues were treated with ultrasound (21 kHz; 40°C) for 30–180 min in various osmotic solutions containing 30% erythritol, xylitol, maltitol or dihydroxyacetone.	Pre-treatment with ultrasound resulted in significant reduction of water activity in the fruit tissue under all tested solutions.
NOWACKA et al. (2014)	Kiwi slices (10 mm thick) treated with ultrasound (35 kHz) for 10, 20 and 30 min, followed by osmotic dehydration.	Pre-treatment with ultrasound resulted in improved water loss and solid gain. The formation of micro-channels was observed during the ultrasound process, and this facilitated moisture removal and water diffusion.
LABORDE et al. (2018)	Grapes were immersed in distilled water at room temperature using a fruit/solvent ratio of 1:4 by weight for 10, 20 and 30 min (osmosis) and simultaneously treated with ultrasound (40 kHz).	The use of ultrasound during osmotic dehydration resulted in significantly greater removal of soluble solids from the samples compared with treatments without ultrasound at all times tested.
BOZKIR et al. (2019)	Ultrasound-assisted osmotic dehydration (30 °C, 45 °Brix) was performed at 35 kHz for 10, 20, and 30 min in persimmon fruit.	The ultrasound-assisted osmotic dehydration affected the rehydration rate, total phenolic content and drying time significantly.
FERNANDES et al. (2008)	Pineapple samples were subjected to ultrasound (25 kHz and 4870 W m^{-2}) and immersed in sucrose osmotic solution (30 °C, 35 and 70 ºBrix).	Water diffusivity and sugar incorporation increased after application of ultrasound and that the overall drying time was reduced.
SILVA et al. (2016)	Ultrasound or combinations of ultrasound/vacuum were used as pretreatments for the osmotic dehydration of melon. Samples were subsequently immersed in a liquid medium (distilled water or sucrose solution).	Both ultrasound and ultrasound/vacuum combinations resulted in faster drying rates. Melon pretreated prior to OD presented higher carotenoid content, softer texture and color similar to the untreated dried fruit.

ultrasound-assisted OD on the water loss of garlic slices, and found that water loss after VUOD was significantly higher than those achieved using the other pre-treatments (21.12, 10.67, 14.18 and 11.20 to 13.56%, respectively). Interestingly, the quality of the VUOD-treated garlic slices, as measured by surface color change, firmness and the content of allicin (the main pharmacologically active component of garlic), were predominantly better than those of samples that had been subjected to the other drying processes. It is noteworthy that, to date, multi-frequency ultrasound has not been described for the pretreatment of fruits.

Treatment with liquid nitrogen prior to OD

Immersion of fruit samples in liquid nitrogen prior to OD is a novel approach which aim to accelerating water loss and increasing sugar gain; although, reports concerning the efficiency of the methodology are scarce. ARAYA-FARIAS et al. (2014) compared various pre-treatments applied in the OD of whole sea-buckthorn berries and reported that water losses and sugar gains through the waxy-skinned fruit were, respectively, 36.26 and 19.96% with liquid nitrogen, and 39.14 and 18.76% with steam blanching. Despite the similarity of these two pre-treatments, immersion in liquid nitrogen was a better option since steam blanching induced macroscopic rupture of the fruit skin during OD. Pre-treatment with liquid nitrogen comprised three immersion cycles, each involving 2 min in the cryogenic fluid followed by 2 min at room temperature, and the subsequent OD was performed over a 6 h period in a water bath filled with sucrose solution (60° Brix) and subjected to mild agitation. Sugar intake during OD improved the organoleptic properties of sea-buckthorn berries, given that the fresh fruit is not appreciated by consumers because of its acidity and peculiar flavor. Following OD, the water content of the berries could be reduced by subsequent vacuum drying and, to an even greater degree, by hot air drying. However, the concentrations of the bioactive components of the berries, namely carotenoids, phenolics and vitamin C, decreased by 22, 12 and 78%, respectively, during the hot air or vacuum drying processes.

KETATA et al. (2013) investigated the impact of liquid nitrogen (-196 ºC) pretreatments on the kinetics of OD of two blueberry species and on the physicochemical characteristics of the dehydrated fruit. The number of immersions was reportedly a decisive factor in accelerating water loss, with reductions in OD times in the range 45 to 65% in comparison with untreated blueberries. Microscopic observations of blueberry skin after liquid nitrogen pre-treatment revealed a reduction in cuticle thickness and the presence of micro-fissures that facilitated moisture and sugar transfer during OD. Dewaxing of the blueberry skin caused by immersion in liquid nitrogen was confirmed by quantification of the wax before and after cryogenic pretreatments. Berries that had been subjected to OD after pretreatment with liquid nitrogen presented mildly reduced concentrations of phenolics and anthocyanins compared with the fresh fruit.

In a more recent study, ALFARO et al. (2018) re-evaluated the effects of cryogenic pretreatment on the OD of blueberries. Fruit that had been immersed in liquid nitrogen for 10 s and subsequently thawed showed increased skin permeability in comparison with fresh fruit. Moreover, when pretreated blueberries were subjected to OD in sucrose solution (60° Brix) at 40°C for 8 h, they exhibited greater water loss and solid gain in comparison with the non-pretreated controls. Nonetheless, the concentrations of anthocyanins and total phenolics in the dried pre-treated and control fruits were similar.

Treatment with a pulsed electric field (PEF) prior to OD

Utilization of a moderate intensity PEF is considered an alternative pre-treatment for OD since it produces non-thermal damage to cell membranes and accelerates mass transfer during the drying process (AMAMI et al., 2006; PARNIAKOV et al., 2016). The treatment involves the application of an external electric field to the food material with the purpose of inducing a critical electric potential across cell membranes (AMAMI et al., 2005) leading to electroporation or electroplasmolysis (AREVALO et al., 2004). According to PARNIAKOV et al. (2016), PEF pretreatment is an effective tool for improving dehydration of different tissues of fruits and vegetables. Moreover, PEF-assisted OD affords greater rehydration capacity, which is defined as the maximum amount of water that a product is able to absorb by immersion, better retention of solids and dried products with firmer texture (TAIWO et al., 2003; AMAMI et al., 2006).

Many studies of the effects of PEF pretreatment on the drying process have been carried out using apple tissues (TAIWO et al., 2003; AREVALO et al., 2004; LEBOVKA et al., 2004; AMAMI et al., 2005, 2006; WIKTOR et al., 2013, 2014; PARNIAKOV et al., 2016). For example, PARNIAKOV et al. (2016) described the influence of PEF pre-treatment on the vacuum freeze-drying of apple discs. PEF was applied using a Hazemeyer generator with electric field strength of 800 V cm^{-1} and a series of monopolar pulses with duration ranging from μs to ms. PEF pre-treatment affected the evolution of temperature inside the sample as well as the sample weight during freeze-drying. The pre-treatment also accelerated the cooling-drying process, preserved the shape of the dried samples, prevented shrinking and increased pore size, thereby facilitating the permeability of small molecules and even macromolecules. These factors taken together resulted in a high rehydration capacity.

With regard to the combination of PEF and OD, AMAMI et al. (2005) submitted apple discs to PEF pre-treatment followed by OD in a sucrose solution (44.5° Brix) at 25°C. Compared with untreated control discs, the application of PEF resulted in a reduction in sugar concentration in the osmotic solution and higher solid content in the apple samples. The optimum PEF parameters were 0.90 kV cm^{-1} electric field strength and 750 pulses of 100 μs duration, corresponding to an energy input of 13.5 kJ kg^{-1}. In subsequent experiments, AMAMI et al. (2006) investigated a range of sucrose concentrations (44.5–65° Brix), while maintaining the same optimal PEF conditions as before. Higher water loss and solid gain were observed in PEF-pretreated samples compared with control samples, with water loss being more pronounced than solid gain. The researchers emphasized that PEF pre-treatment accelerates the kinetics of water and solute transfer during convection and diffusion stages of OD.

In an preparatory study, WIKTOR et al. (2013) investigated the influence of pretreatment with PEF on the drying kinetics of apple tissues submitted to convection drying (70°C; air velocity 2 m s^{-1}). PEF was applied to the slices using a ERTEC prototype generator at an electric field strength of 5 or 10 kV cm^{-1} (capacitance 0.25 mF) and 10 or 50 monopolar pulses. Under the best PEF pretreatment conditions (10 kV cm^{-1} and 50 pulses), the dimensionless moisture content after 60 min of drying was 0.18 for treated apples compared with 0.26 for untreated counterparts and the overall drying time was reduced by up to 12% in comparison with the untreated controls. In a follow-up study, WIKTOR et al. (2014) investigated the effects of the previously described PEF pre-treatments on apple tissues subjected to OD with 65° Brix sucrose solution in a water-bath at 40°C agitated at 100 rpm. When PEF was applied before OD, water loss was increased significantly after 60 min of the process, whereas no significant solid gain was observed. The highest OD efficiency ratio, i.e. water loss/solid gain, was obtained with samples pre-treated with 10 pulses of an electric field of strength 5 kV cm^{-1}.

The effects of PEF pre-treatment on mass transfer, water distribution and physicochemical characteristics of osmotically dehydrated organic strawberries have been investigated by TYLEWICZ et al. (2017). The PEF treatments were carried out at low electric field strengths (100, 200 and 400 V cm^{-1}) employing 100 rectangular-shaped pulses of 100 μs duration and 10 ms repetition time, while the OD treatments were performed in 40% w/w hypertonic solutions of sucrose or trehalose. The results showed that PEF pre-treatment positively affected the mass transfer during OD, even at the lowest electric field strength applied, partially preserving cell viability and the fresh-like characteristics of the strawberries.

Treatment with gamma radiation prior to OD

OD is usually a slow process that requires hastening in order to prevent undesirable effects and microbial/pest contamination of the final dried product. Exposure to gamma radiation is an alternative non-thermal approach for breaking the resistance and increasing the permeability of cell membranes in fruits and vegetables with a view to improving mass flow and transfer rate during OD. High-energy gamma rays emitted by Cobalt 60 or Cesium 137 induce ionizations in living cells that damage DNA and cellular structures. Such disruption may even inactivate or destroy the harmful microorganisms that cause spoilage of food and, potentially, disease in consumers (AMAMI et al., 2005; RASTOGI et al., 2005; AHMED et al., 2016).

Gamma irradiation is an effective, environmentally friendly and energy-efficient method of pre-treatment because cell disruption is provoked solely by oxidation-reduction reactions. No additional chemicals are required that could change the physicochemical properties of the end product and no residues are left behind. Furthermore, the total water content of the food material remains unchanged because of the absence of heating effects during irradiation (BYUN et al., 2008). Indeed, LING et al. (2020) have recently emphasized that gamma-irradiation is particularly useful in enhancing dehydration performance.

There is a great deal of misinformation relating to food and nutrition, and the public in general are easily influenced by unsubstantiated opinions and fake facts. Many of the concerns regarding food irradiation are based on fears that the treated materials become radioactive, and so it needs to be routinely stated that irradiated fruits and vegetables are not radioactive. Such concerns could be readily eradicated if the public could understand the fundamentals and uses of this technology (BEVELACQUA & MORTAZAVI, 2020).

The use of ionizing radiation for the preservation of fruits and vegetables is based on sound scientific principles and the technology is both safe and subject to high levels of control. For all forms of electromagnetic radiation, the shorter the wavelength (or the higher the frequency), the greater is the energy transmitted in a given period of time. Hence, any harmful effects of radiation are essentially dose-dependent. For example, visible light in the wavelength range 400-700 nm is not potent enough to cause serious damage unless exposure is prolonged. In Brazil, the Agência Nacional de Vigilância Sanitária (ANVISA; Resolution RDC no. 21 of 26th January 2001) is responsible for regulating the sources of radiation used in food processing, with doses used in the treatment of foods being classified as low (< 1 kGy), medium (1 to 10 kGy) and high (> 10 kGy). It should be noted that many other countries, including Australia, China, the European Union (27 countries), India, Indonesia, Japan, Malaysia, Mexico, South Africa, Thailand, the United Kingdom, the United States of America and Vietnam, restrict the use of radiation in foods (LELIEVELD & ANDERSEN, 2020). Perhaps these restrictions, along with public concern, explain the low number of reports on the use of gamma irradiation as a pre-treatment in OD processes, especially in the case of fruits.

According to WANG & CHAO (2002), the higher the dose of irradiation from a ^{60}Co source, the greater the rate of dehydration of apple slices during hot air drying. The results of a subsequent study (WANG & CHAO, 2003) showed that irradiation dose, temperature of the drying air and thickness of the apple slices significantly affected the appearance quality and vitamin C content of the dried slices, as well as the dehydration rate and the rehydration ratio. Thus, higher doses increased the dehydration rate but decreased the vitamin C content and rehydration ratio, while higher air temperatures or thinner apple slices increased the dehydration rate but reduced the rehydration ratio. According to these researchers, the results obtained can be attributed to the damage and alterations in the tissue structure caused by irradiation.

High hydrostatic pressure (HHP)-assisted OD

Pre-treatment with HHP is another approach to optimize mass transfer during OD. During the osmotic removal of water from fruits and vegetables, cells that are in direct contact with the osmotic solution lose water and become plasmolysed, giving rise to cell disruption and softening of the surface layer. Electrical impedance analysis has shown that treatment with HPP enhances cell permeability such that the cell permeabilization index increases according to the time of treatment. During OD, the state of cell membranes in samples pretreated with HPP within the range 100 to 800 MPa, change from being partially to totally permeable, and this leads to modifications in tissue architecture with consequential increase in mass transfer rates in comparison with untreated samples (RASTOGI, 2000).

Treatment of food stuff with HHP is an innovative and promising technology for decreasing drying time, improving product stability by inhibiting microorganisms and enzymatic activities, augmenting the physicochemical qualities of fruit-based products, especially purées and jams (LANDL et al, 2010), and for optimizing the nutritional value of human diets (MCINERNEY et al., 2007; VEGA-GÁLVEZ et al., 2011; NUÑEZ-MANCILLA et al., 2013). For example, YUCEL et al. (2010) employed a range of HHP treatments (100 to 300 MPa; 5 to 45 min; 20 and 35°C) prior to drying apple samples in a hot-air tunnel dryer (27 to 85 °C) at different air velocities (0.4 to 0.8 m s^{-1}). These researchers reported that the pre-treatments produced significant decreases in the drying times of apples, an effect that was partially masked when drying was performed at high temperature but was particularly noticeable with low temperature drying.

The usefulness of HHP in combination with OD in the fruit processing industry is shown by the growing body of research performed on strawberry (NUÑEZ-MANCILLA et al., 2013), banana (VERMA et al., 2014) and Chinese plum (LUO et al., 2018). Thus, NUÑEZ-MANCILLA et al. (2013) reported that the simultaneous application of HPP (100 to 500 MPa; 10 min duration) and OD in sucrose solution (40° Brix) is particularly attractive for preserving the antioxidant activity and bioactive constituents of dried strawberries. The authors claimed that HHP-assisted OD optimized dehydration and solid gain until equilibrium was achieved, at which point fluid transport phenomena were no longer significant. The highest levels of radical scavenging activity and total phenolic content were obtained with HHP at 400 mPa, while the vitamin C content was maintained under all pressure treatments. The study demonstrated that the quality profiles of strawberries submitted to simultaneous HHP/OD at 300 to 500 MPa showed minimal differences when compared with those of samples that had not been subjected to HHP.

VERMA et al. (2014) described the effects on the OD of banana slices following pretreatment with HHP using response surface methodology. The HHP conditions were 100 to 500 MPa with a dwell time of 5 min at 26 °C, while OD was performed in sucrose solutions in the range 30 to 70 °Brix, with immersion times between 5 and 9 h and immersion temperatures 30 to 70°C. The HHP-treated samples showed significantly higher water loss and solid gain during OD, and this was attributed to the rupture of cell walls and increased permeability with applied pressure as demonstrated by scanning electron microscopy. The optimized conditions were found to be HHP at 200 MPa and OD in a sucrose solution of 60 °Brix with immersion time of 4 h and immersion temperature of 40 °C. The HHP pretreatment reduced dehydration time and energy and resulted in a final dried product with superior quality in terms of reduced bulk, improved flavor and decreased water activity.

More recently, LUO et al. (2018) investigated the effects of HHP pre-treatment (50 to 400 MPa; 10 min duration) on the mass transfer kinetics, cell viability and water diffusivity and distribution in Chinese plums during OD in sucrose solution (40° Brix) for up to 6 h at 22 °C. The results showed that HHP was efficient in accelerating mass transfer during the OD process since it increased the initial rates and equilibrium values of both water loss and solid gain, although the effect was not proportional to the pressure applied. Nuclear magnetic resonance of the samples revealed that HHP promoted the redistribution of water in vacuoles, cytoplasm/extracellular spaces and cell wall/membranes. Pressures greater than 200 MPa resulted in the loss of cell viability, while cell membranes likely suffered some irreversible damage at 400 MPa. The researchers concluded that HHP is an effective technique to increase mass transfer in Chinese plums during OD.

CONCLUSIONS

OD is a well-known method for the partial removal of moisture from foods. The absorption of solute and leaching of food constituents during the process result in the modification of the original composition of the products and improvement of nutritional, functional and organoleptic properties. OD is considered a method of choice for the production of minimally processed fruits because it preserves the freshness characteristics of the natural product. Other advantages of OD include minimization of nutrient degradation, reduction in enzymatic browning and diminution of processing costs. The resulting dehydrated products are nutritious, healthy and can be made available in all seasons of the year. However, the effects of OD depend on the type, maturity and geometry of the fruit as well as on the pre-treatment applied and the temperature, concentration and nature of osmotic agents involved, all of which can affect mass transfer during the process. The application of ultrasound, liquid nitrogen, PEF, gamma radiation and HHP in combination with OD accelerate mass transfer, improve the permeability of cell membranes and reduce the drying rate of fruits. In summary, combined OD approaches significantly reduce operating times and costs compared with conventional OD alone.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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