EJAST 1(1): 1-15 (2010)

REVIEW PAPER

Going beyond conventional osmotic dehydration for quality advantage and energy savings

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(**Received in revised form: November 16, 2010)**

ABSTRACT

Osmotic drying is a partial dehydration process, often considered more as a treatment, to give the product a quality improvement over the conventional drying process. The osmotic treatment involves soaking of a food in hypertonic solution of sugar and/or salt for specific times under controlled temperature condition. The process involves two counter-current mass transfers, a loss of water from the food to the solution and the simultaneous migration of solids from solution to the food. Such mass transfer phenomena are governed by pretreatment, osmotic solution, product and osmotic environment related factors. The method has two major advantages when combined or compared with other drying methods. The quality of osmotically dehydrated products is better and shrinkage is considerably lower as compared to products from conventional drying processes. Secondly, the technique helps to conserve the overall energy relative to other drying procedures. The first aspect has been widely studied while the energy aspects are addressed rather scarcely. The major objective of this paper is to discuss the advantage of osmotic dehydration in terms of energy reduction and its potential contribution to maximize profit by reducing the associated costs. The osmotic dehydration step can be done before, during or after the conventional drying process to enhance the mass transfer rate or to shorten the duration of drying time. After the osmotic treatment, the moisture content of fruits and vegetable are usually reduced by 30-50% (wet basis). The amount of residual moisture in the product determines the duration and the energy required to finish dry the product to achieve the desired product stability. This reduction in moisture has a significant impact in conservation of energy when the technique complements other conventional drying methods like convective, freeze, microwave and vacuum drying. Moisture removal by phase change (evaporation of water) is an energy intensive process due to high latent heat of vaporization of water. During osmotic dehydration, there is no phase transition and the process can be done with minimum supply of energy, which is the principal reason for the energy savings. Novel approaches in food drying are constantly being explored to minimize the energy demand and maximize profit.

***Keywords*: Osmotic, dehydration, drying energy, efficiency**

INTRODUCTION

Osmotic dehydration (OD) is a dehydration process of foods that involves soaking a food in hypertonic sugar and/or salt solution to reduce the moisture content of foods before actual drying process. OD is performed to reduce the moisture content of food products in minimal processing under ambient or modified environment conditions (Escriche *et al.*, 2000). During the process two simultaneous counter-current flows may occur; water-flow out of the food into the solution, the simultaneous transfer of water soluble solutes from the solution into the food, and migration of natural solutes (sugars, organic acids, vitamins, reducing sugars, some flavor compounds, volatiles, minerals, etc.,) from the food into the solution (Le Maguer and Biswall, 1988). The process can be represented as shown in Fig 1. Since the hypertonic solution has higher osmotic pressure with reduced water activity, it serves as a driving force for water withdrawal from the cells solution to the osmo-active solution. The removal of water during osmotic process is mainly by diffusion and capillary flow, whereas solute uptake or leaching is only by diffusion (Rahman, 2007). All these mass exchanges between the osmotic solution and foodstuff may have an effect on the overall yield and quality of the dehydrated product.

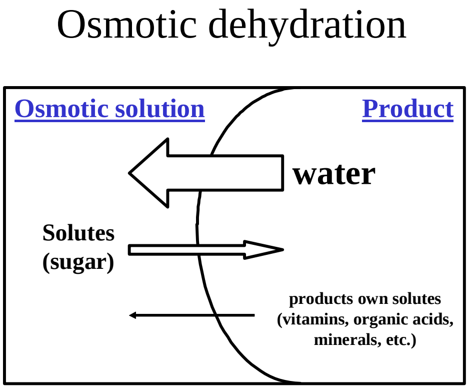

Figure 1. Osmotic dehydration principles and relative mass flow of water and solutes.

In perfectly semi-permeable membrane, the solution is unable to transfer through the membrane into cells, but it is hardly to obtain such type of membrane in food materials due to its complex internal structure and possible damages during processing (Shi, 2008). Hence, such conditions are important in osmotic dehydration processes to allow counter flow of solutes and water. In plants due to semi-permeable nature of plant tissue and low molecular size of water molecules the flux of water coming out of the food is much larger than solute gain from osmo-active substance. This result in a decrease of water content of the product with time till equilibrium condition is established. Therefore, the weight of the foodstuff will decrease, as well the water activity. According to some works, it is reported that up to 50% reduction in the fresh weight of fruits or vegetables can be achieved by osmotic dehydration (Rastogi and Raghavararo, 1997).

FACTORS AFFECTING MASS TRANSFER KINETICS

Osmotic dehydration as a mass transfer process it is affected by different factors. The kinetics of mass transfer is usually described using terms such as water loss (WR), solids or solutes gain (SG) and weight reduction (WR) (Shi, 2008). The overall mass transfer kinetics during osmotic dehydration is affected by several factors. By manipulating processing factors affecting mass transfer, and nature of the product subjected to dehydration it is possible to reach different levels of dehydration or impregnation of the material under treatment. In the following subsections the effects of those various variables will be briefly discussed.

Pre-treatment factors

Pre-treatment conditions before osmotic dehydration process affect product inherent integrity which has an effect on mass transfer process. Osmotic dehydration rate is largely affected by cell membrane permeability (Toupin and Le Maguer, 1989). Good membrane permeability ultimately will lead to more rapid osmotic dehydration. However, the cellular membrane of plant cells exerts high resistance to transfer of water and solutes and slows down the overall osmotic drying rate (Erle and Shubert, 2001). Therefore, the partial damage of cell membranes using different pre-treatment methods can be advantageous for acceleration of mass transfers process. Blanching (Islam and Flink, 1982; Allali *et al.*, 2009), peeling, coating (Lewicki *et al.*, 1984; Camirand *et al.*, 1992; Ishikawa and Nara, 1993; Wong *et al.*, 1994; Lazarides, 2001; Matuska *et al.*, 2006), freeze/thawing (Ponting, 1973; Hilderbrand, 1992; Lazarides and Mavroudis, 1995; Sormani *et al.*, 1999; Maestrelli *et al.*, 2001), high pressure from 100-800 MPa (Dornenburg and Knorr, 1993, 1998; Rastogi *et al.*, 1994, 2000; Lazarides, 2001; Tedjo *et al.*, 2002), and high intensity electric field pulses (Rastogi *et al.*, 1999; Taiwo *et al.*, 2003) are some of the pre-treatment operations which are used before osmotic dehydration process to enhance mass transfer.

Product related factors

On the product side, species, variety, and maturity level all have a significant effect on natural tissue structure, in cell membrane structure, protopectin to soluble pectin ratio, amount of insoluble solids, intercellular spaces, tissue compactness, entrapped air and etc (Lazarides, 2001). Furthermore chemical composition (protein, carbohydrate, fat, and salt), physical structure (porosity, arrangement of the cells, fiber orientation, and skin), may affect the kinetics of osmosis in food (Rahman, 2007). Particularly porosity of the raw material has a significant effect on shrinkage phenomena and mass transfer rates (Mavroudis *et al.*, 1998a) as well as rehydration ratio. The shape/geometry and size (Contreras and Smyrl, 1981) of product affect the surface area to volume ratio of the product with the solution. Since solute impregnation is a surface-controlled phenomenon, high specific surface values favour solute uptake (Lerici *et al.*, 1985; Torreggiani, 1993).

Osmotic solution related factors

Osmotic process is also affected by the physicochemical properties of the solutes employed, because differences in efficiency of dehydration arises mainly from differences in molecular weight, ionic state, and solubility of solute in water (Rahman, 2007). The selection of the solute must consider the following three main factors: (i) solute impact on sensory characteristics of the product, (ii) the relative cost of solute in relation to the final value of the product, and (3) the molecular weight of the solute. Some of the solutes often used in osmotic dehydration processes are sodium chloride, saccharose, glucose, and corn syrup.

Penetration studies showed that the rate of solute penetration is directly related to the solution concentration and inversely related to the size of the sugar molecule (Panagiotou *et al.*, 1999; Giraldo *et al.*, 2003). For instance by using higher molecular weight sugars (i.e., lower dextrose equivalent corn syrup solids) it was possible to zero net solute gain (Lazarides and Mavroudis, 1995) and allows only migration of moisture. In other works confirmed that glucose resulted in higher amounts of water loss and solid gain than sucrose (Bolin *et al.*, 1983; Lerici *et al.*, 1985; Garrote and Bertone, 1989; Panagiotou *et al.*, 1999; Taiwo *et al.*, 2003). Lenart and Flink, (1984) found that mixed sucrose/salt solutions gave a greater decrease in product water activity than pure sucrose solutions, although water transport rates were similar. The pH of the solution can also affect the osmotic process. Acidification increases the rate of water removal by changes in tissue properties and consequential changes in the texture of fruits and vegetables (Moy *et al.*, 1978).

Osmotic environment related factors

Environmental conditions during osmotic dehydration process are main factors that play important role in rate of water withdrawal and solutes migration processes. Among several environmental factors, temperature, duration of treatment time and other environmental factors are the most important parameters influences the kinetics of water loss and solute gain. The positive effect of temperature and time on the removal of water from the food during osmotic treatment has been shown by several works. Water loss increases with increase in temperature, whereas solid gain is less affected by temperature (Beristain, 1990; Li and Ramaswamy, 2006a). During osmotic dehydration of potatoes, increasing process temperature up to 45°C resulted in increased WL and SG rates, in favor of higher WL/SG ratios (Lazarides, 2001). Obviously with an increase in osmotic treatment time, mass transfer process increased till both water and solute concentrations attain their equilibrium conditions. Osmotic dehydration for a short contact time minimized color losses during convective air-drying of blueberries (Nsonzi and Ramaswamy, 1998). However a longer contact time of the samples with the sugar solution gives a higher solids gain and a higher moisture loss (Nieuwenhuijzen *et al.*, 2001). Osmotic dehydration can be enhanced by agitation or circulation of the syrup around the sample (Lenart and Flink, 1984; Mavroudis *et al.*, 1998b). Turbulent solution flow due to agitation may result in higher WL/SG ratios (Lazarides, 2001).

Vacuum osmotic dehydration results in a change of behaviour of mass transfer in fruit sugar or salt solution systems (Shi and Maupoey, 1994; Shi *et al.*, 1995). The reduction in pressure causes the expansion and escape of gas enclosed in the pores, and pores can be occupied by osmotic solution, thus increasing mass transfer rate (Fito et al., 1994; Chiralt *et al.*, 1999; Rahman, 2007). Effect of vacuum on enhanced rate of OD of different foods is indicated in different works (Fito, 1994; Rastogi and Raghavarao, 1994; Shi and Fito, 1994; Shi *et al.*, 1995; Moreno *et al.*, 2000; Taiwo, *et al.*, 2003). Ultrasound also used as a means to enhance mass transfer process during osmotic dehydration of fruits (Simal *et al.*, 1998; Rodrigues *et al.*, 2009). Rodrigues *et al.* (2009) elucidate the effect of ultrasonic waves with analogy of the sponge effect. According to him the wave can cause a rapid series of alternate compressions and expansions, in a similar way to a sponge when it is squeezed and released repeatedly. Continuous compression and relaxation of the wave may be the main cause for the creation of microscopic channels in porous materials such as fruits (Fuente-Blanco *et al.*, 2006). Furthermore, cavitation, a phenomenon produced by sonication, consists of the formation of bubbles in the liquid, which can explosively collapse and generate localized pressure and this effect accelerates and completes degassing, resulting in increased diffusion in the osmotic process (Taiwo *et al.*, 2003). Generally temperature, duration of treatment time, osmotic solution concentration, and vacuum level are the most important variables in the osmotic process (Corrêa *et al.*, 2010).

BENEFITS OF OSMOTIC DEHYDRATION

There are two major advantages of osmotic dehydration process in the food industry (i) quality aspect (improvement in terms of color, flavor, texture, product stability and retention of nutrients during storage and (ii) energy efficiency. The importance of osmotic dehydration in terms of quality aspects extensively discussed in several articles. In the following sub-section more focus is given to discuss from energy efficiency point of view.

Quality issues

Osmotic pre-concentration is an effective way to reduce water content with minimal damage on fresh product quality. This is largely due to the use of a mild product treatment at relatively low process temperatures (30-50°C); such temperatures do not affect the semi-permeable characteristic of cell membranes, which is an essential requirement for maintaining the osmotic phenomenon (Lazarids, 2001). Because of constant product immersion in the osmotic medium, the plant or animal tissue is not exposed to oxygen; therefore, there is no need to use antioxidants (i.e., sulfur dioxide in case of fruits) for protection against oxidative and enzymatic discoloration (Dixon *et al.*, 1976). Dehydration of foodstuffs by immersion in osmotic solutions before convective air-drying improves the quality of the final product since it prevents oxidative browning and/or loss of volatile flavouring constituents, reduces the fruit acidity (Ponting, 1973). On the other hand, partial dehydration and solute uptake have advantages in preventing structural collapse during subsequent drying processes (Lazarides and Mavroudis, 1995; Simal *et al.*, 1997).

Osmotic treatments prior to freezing are used to produce several kinds of fruits that can be stored for long periods of time with good retention of texture, colour and flavour after thawing (Sormani *et al.*, 1999; Maestrelli *et al.*, 2001) and prevent loss of extensive drip loss on freeze/thawing (Lazarides and Mavroudis, 1995). Water content reduction and sugar gain during osmotic dehydration have been observed to have some cryoprotectant effects on colour and texture in several fruits (Chiralt *et al.*, 2001). In addition to this it has been proven to be a good method to obtain minimally processed fruits, due to the great sensory similarity between the dehydrated and natural product. The use of osmotically dried fruits to make high quality chips is one application area to get good quality vacuum fried product. Because of the high sugar content of the product after osmotic dehydration, vacuum frying is a method to produce high-quality deep-fat fried fruit chips both in sensorial and textural quality parameters. The best mango chip in vacuum frying was produced with an osmotic solution concentration of 65% (w/v) and temperature of 40°C, which resulted in the highest water loss to sugar gain and provided a good texture characteristic (Nunes *et al.*, 2009).

Energy saving

Drying is one of the most energy intensive unit operations in food and non-food products processing industries. This is mainly because of high latent heat of vaporization of water to be removed from a product. According to Kudra (2004), for batch drying, the energy efficiency is therefore given as an average value over a drying time and for continuous drying the energy efficiency is averaged over the range of moisture content, or the dryer length, or volume, depending on dryer configuration. In all cases the drying efficiency and energy demand is associated with drying time, which is highly related with volume of moisture in a material to be removed or the rate at which drying accomplished.

OD has diverse application in fruit and vegetable processing industries. However this dehydration step generally does not produce product of low moisture content having long shelf life and stability. To get relatively stable product the technique should complement with other drying methods like; convective, freeze, microwave or vacuum drying steps. Therefore harmonization of osmotic dehydration with these energy demanding drying technologies has a merit in terms of maximizing energy use efficiency and reduction of production cost. In OD a significant amount of water is removed in liquid form (not in vapour form) which demands little or no external energy supply (Lazarids, 2001). By reducing the moisture content of a product to certain, extent either using mechanical or OD method, ultimately reduce the energy demand required to remove the moisture. In this section the benefit of OD in terms of energy efficiency point of view will be discussed for the common hybrid (osmo-) drying methods.

Osmo-convective drying

The majority of artificial drying operations are based on hot air drying, where air is heated by the combustion of fossil fuels or using electric heater prior to being forced through the product. According to Mujumdar and Beke, (2003), typical convective dryers account for about 85% of all industrial dryers. Heating of air before drying is the most energy-intensive processes in food processing industries. Thus, novel thinking in the technology of drying methods to minimize the energy demand is very important. The food industry could save much money by avoiding costly energy demand and waste. Beedie (1995) stated that, improving energy efficiency by only 1% could result in as much as 10% increase in profits. According to this author, energy can be saved by (a) reducing drying time, (b) avoiding heat losses, (heat loss with the exhaust air, heat loss with the product, radiation heat loss from the dryer, heat loss due to leakage of air from the dryer, and heat loss due to over drying of products, and (c) heat recovery from exhaust gas and dried product. By reducing the moisture content before final drying step, the drying time and heating load can be significantly reduced. Therefore, OD as an upstream pre-treatment step of convective air drying process enables to reduce the energy demand for heating and evaporation of the product moisture.

Removal of water in its liquid state rather than the vapour state allows the latent heat of vaporization to be captured, and only a small amount of sensible heat is lost with the condensate (Rahman and Perera, 2007). Mujumdar (2007) indicated that, almost 99% of the applications in drying involve removal of water which has higher energy consumption because of high latent heat of vaporization of water, which is 2676 kJ/kg at 100^{o}C. The more water needs to be removed during convective drying process, the more latent heat of vaporization of energy is demanded. But by reducing the volume of moisture removed from the product on upper stream of actual drying process through OD, the demand for energy can be reduced. For instance fresh fruits and vegetables contain 75 to 95% water and one way to reduce this high water content, before actual drying process is the use OD. As stated before, OD can remove up to 50% (Rastogi and Raghavararo, 1997) of the water in the original fruits or vegetables. Hence, as compared to the original moisture content the energy demand to remove the remaining moisture to the desired level of drying is by far less than what has been required for osmotically untreated product.

Osmotically dehydrated apples shows no constant rate convective drying period, because the water content is below its critical value, and it reduces the total energy consumption by 24 to 75%, depending on the process conditions and the method to reconstitute the hypertonic solution (Kudra, 2009). According to the same author convective drying of apples consumes ~5000 kJ/kg evaporated water, and nearly 40% of the water evaporated during the constant rate period, even though there is 10 to 25% reduction in drying time due to surface layer of concentrated syrup. The energy use efficiency of osmo-convective drying as compared to conventional convective drying method of apple slices indicated in (Strumillo and Adamiec, 1996). The result confirmed that the significant benefit of osmotic treatment before convective drying method to minimize the energy demand required in the overall drying process. Furthermore Grabowski *et al*. (2002) noted that drying of fresh cranberries starts at a high moisture content of about 87% (wet basis) but the finished drying of osmotically dehydrated cranberries begin at a moisture content of about 50% of wet bases. This means energy saving of about 2150 kJ of energy per kilogram fresh berries can be obtained when convective vibrating fluid bed or pulsed fluid bed drying methods followed OD process (Kudra, 2009).

Osmo-freeze drying

The freeze drying process consists mainly of two stages: (1) the product is frozen, and (2) the product is dried by direct sublimation of ice under reduced pressure. Freeze-dried products that have been adequately packaged can be stored for longer time, maintaining most of the desirable physical, chemical, biological, and sensorial properties of the fresh product. In freeze drying, frozen material is subjected to a pressure below the triple point and heated to cause ice sublimation to vapor. The method is usually used for high-quality dried products, which contain heat-sensitive components. Furthermore the virtual absence of air and low temperature prevents deterioration due to oxidation or chemical modification of the product and gives very porous products, with high rehydration rates. However, freeze drying is a slow and expensive (high capital and operating costs) process and mainly used for high-value products (Cohen and Yang, 1995) and due these reasons its application on wide range of fruits and vegetables has been limited (Hammami and Rene, 1997). In addition to this the long processing time requires additional energy to run the refrigeration and compressor units, which makes the process very expensive for commercial use. The extended processing time during freezing and condensation processes is mainly due to high water content nature of fruit and vegetable crops. By reducing the moisture level to some extent there is a possibility to shorten the required processing time and associated energy demands.

Robbers *et al*. (1997) carried out an experiment to evaluate the effect of OD of kiwi fruit during freezing process. They conducted the experiment first by immersing fresh kiwi fruits in 68% (w/w) aqueous sucrose solution to dehydrate for 3 h, then subjecting to an air-blast freezer with an air velocity of 3 m/s and temperature of -3°C. The experiment showed that freezing began at a lower temperature in the dehydrated product and the temperature of the dehydrated samples was reduced to -18°C in 19–20 min, which was about 20–30% faster compared to untreated kiwi, which required the freezing time of 23–24 min. Generally speaking, lower water content of dehydrated food always induces a lower freezing point and a shorter freezing time as there is less water to freeze and consequently less heat to remove (Spiazzi, 1998). This confirms that a reduction in moisture content of food can reduce refrigeration load during freezing which has a significant impact on energy reduction.

The energy distribution and consumption of individual operations of freeze-drying was established by Liu *et al.* (2008), they investigated the effects of various operation conditions on the energy losses in the three stages of freeze-drying operations. According to their result the energy consumption in the primary drying reaches 35.7%, in vapor condensing reaches 31.8% and 23.3% in the vacuum pumping of the total energy input. According to them about 67% of the total energy input is used in primary drying phase and condensation of the vapour. Therefore by reducing the volume of moisture frozen through OD the volume of water to be evaporated during primary drying and condensation operations can be minimized. Reduction in moisture content through OD contributes in reducing freezing, primary drying and condensation loads, and consequently a reduced energy demand for overall freeze drying operation.

Osmo-microwave drying

The major draw-back of hot-air drying method, from an energy efficiency point of view, is the longer drying period, higher drying temperature and therefore high energy consumption, which may be as high as 6000 kJ/kg of water evaporated (Mujumdar and Menon, 1995; Alibas, 2007). To cope up these limitations microwave assisted drying is used as an alternative solution. The removal of moisture by microwave drying has the following benefits when compared with convective drying: fast and volumetric heating, higher drying rate, shorter drying time, more homogenous energy distribution throughout the material and higher quality of the product and reduced energy consumption (Sanga *et al.*, 2000; Zhang *et al.*, 2006). However, the microwave-drying process can have very high capital costs. In addition to this the technology requires relatively expensive electricity energy, and due to this limitations it is only used in the final stages of drying (finish drying), where it can be used more efficiently than hot air (Gunasekaran, 1999).

Microwave radiation generates rapid volumetric heating of a wet material by altering the electromagnetic field to interact primarily with polar water molecules and ions in food materials (Varith *et al.*, 2007). In comparison of convective air drying microwave drying offers significant energy savings, with a potential reduction in drying time up to 50% in addition to the inhibition of surface temperature of treated material (McLoughlin *et al.*, 2003). Because of its special heating behaviour and high heating efficiency, microwave fields have been applied successfully to assist many drying processes. Several studies have shown that using pre-treatments prior to microwave drying could decrease drying time and thus drying costs (Drouzas and Schubert, 1996). To improve microwave-assisted drying, there are many combinations to be considered for study. Among these combinations, researchers have shown that osmotic drying prior to microwave-assisted drying leads to lower energy consumption and better qualities of dried product (Venkatachalapathy and Raghavan, 1999; Prothon *et al.*, 2001; Beaudry *et al.*, 2003). A combination of OD with microwave-convective drying appears as a promising possibility in production of dried fruits and vegetables with energy reduction benefits. These days partial dehydration by osmosis has been widely employed prior to microwave drying, as a means of reducing processing time, and thus limiting energy consumption and improving sensory characteristics (Erle and Schubert, 2001; Piotrowski *et al.*, 2004).

According to work of Al-Harashan *et al.* (2008), on tomato pomace (33% seed, 27% peel and 40% pulp) osmotic pre-treatment before microwave drying experiment, found that the dielectric properties of the product were modified with increase in dielectric loss factor and decrease in dielectric constant which eventually enhanced the drying rate. Dielectric constant reflects the capacity and ability of the material to store electric energy when it is in an electromagnetic field. Dielectric loss factor reflects the resistance and ability of the material to dissipate electric energy in the form of heat during electromagnetic heating. OD performed on mushroom with salt solutions of 10 and 15% reduced microwave dehydration by 10–20% (Torringa *et al.*, 2001). In addition to this, Prothon *et al.* (2001) demonstrated, osmotically dried apple cubes in 50% (w/w) sucrose, and then dried them in a microwave-assisted drier reduced drying time required to reach 10% moisture.

As reported by Li and Ramaswamy (2006b) simultaneous microwave heating and OD have double fold advantages in accelerating the moisture lose and reduction of solid gain under immersion mode of apple cylinders in osmotic solution. Further, Azarpazhooh and Ramaswamy (2010) compared osmotic drying effect under different osmo-drying conditions: osmo-microwave drying under spray mode, osmo-microwave drying under immersion mode, conventional osmotic drying under spray and conventional osmotic drying under immersion modes at two sucrose concentration and temperature combinations (40°Brix/40°C and 50°Brix/50°C). The moisture lose under microwave spray mode was around 35% as compared to conventional spray and immersion drying methods having moisture lose of less than 12% after 30 min of drying.

Increase in power absorbed during microwave heating results to increase in the energy consumption rate per unit mass of water during microwave assisted drying. An equation for energy consumption rate per unit mass of water during microwave assisted intermittent power supply was proposed by Beaudry *et al.* (2003) and Yongsawatdigul and Gunasekaran, (1996). However it does not account for the energy supplied by hot air (Beaudry *et el.*, 2003) and energy demand from the vacuum (Yongsawatdigul and Gunasekaran, 1996) during drying process. It was reported that higher power level (Drouzas and Schubert, 1996) and lower initial moisture content of osmotically treated food will yield better energy conservation.

In addition to microwave-convictive drying, microwave-vacuum drying technology is investigated as an alternative method to reduce the cost and improve the food quality (Drouzas *et al.*, 1999). The use of microwaves help us to overcome the common problem associated with poor heat transfer in vacuum drying. The dehydration rate for microwave-vacuum-drying is always faster and takes 33 min to dry carrot slices from 91.4 % to 10 % (wet base) with microwave-vacuum, as compared to 8 and 72 h with hot air and freeze-drying, respectively (Lin *et al.*, 1998). The application of an osmotic treatment prior to microwave-vacuum drying combines the advantages of both unit operations in a unique way. Since no phase transition takes place in OD, energy consumption is especially low, even if the diluted solution needs to be reconcentrated by evaporation (Erle and Schubert, 2001). Based up on this, osmo-microwave-vacuum drying hybrid technology is used to produce dehydrated high quality products with reduced energy cost. This hybrid method creates food products with properties comparable to freeze drying, in shorter time and thus, at lower costs. In comparison to other advanced drying technologies (i.e. freeze drying) microwave vacuum drying is more economic, as drying progress is much faster and thus allows a higher throughput for the same plant dimensions (Ahrens *et al.*, 2006).

Osmotic-vacuum drying

In vacuum drying method the food is subjected to a low pressure and simultaneous low heating source. The vacuum allows the water to vaporize at a lower temperature than at atmospheric conditions, thus foods can be dried without exposure to high temperature and low level of oxygen in the atmosphere diminishes oxidation reactions during drying. In general, color, texture, and flavor of vacuum or vacuum-freeze dried products are improved as compared with air-dried products.

Pressure driven flow is the major moisture removal mechanism from a food. Because of the need of creating reduced pressure in a drying chamber the technique is more expensive and often used as a secondary dryer. The duration of vacuum drying process mainly depends up on the level of moisture to be removed and level of reduced pressure maintained. The energy and reduced pressure demand to remove moisture from a food can be minimized by combining osmotic treatment before actual vacuum drying. This method mainly more advantageous for fruits and vegetables which are very rich in moisture, but OD can enable us to reduce the percentage of original moisture by 30-50%. For fruits with high water activity (aw) and high porosity, the application of OD with vacuum pressure found to be advantageous compared to atmospheric pressure drying process, (Mǘjica-Paz *et al.*, 2003). Meanwhile Shi *et al.* (1995) evaluated the influence of vacuum treatment on mass transfer during OD of fruits, and they confirmed that OD under vacuum makes it possible to obtain a higher diffusion rate of water transfer at lower solution temperatures for fruits with high porosity. Beaudry *et al.* (2004) they compared four drying methods of drying (osmo-vacuum, osmo-microwave, osmo-freeze and osmo-convective) and found that the drying rate of osmo-vacuum treated cranberries is the higher following osmo-microwave drying method. Moreover reduction in pressure causes the expansion and escape of gas enclosed in the pores, and pores can be occupied by osmotic solution, thus increasing mass transfer rate (Rahman, 2007). The process strongly favors solute uptake through an effective increase of mass transfer surface, caused by replacement of gas in the pores with osmotic solution (Fito *et al.*, 1994; Chiralt *et al.*, 1999). Therefore the advantage of OD at vacuum pressures over atmospheric OD is that the solid–liquid interface area and the mass transfer between both phases can be increased (Fito *et al.*, 2002). Hence the cumulative sum of the above benefits enhance rate of drying and rapid mass transfer which have a significant effect in energy reduction process of osmo-vacuum drying method as compared to conventional vacuum drying.

CONCLUSIONS

Osmotic dehydration is a simultaneous mass transfer process which mainly promotes the flow out of water molecules from the food to osmo-active solution and some migration of solutes from the solution into the food. Different factors can influence the overall mass transfer kinetics during dehydration process. In the process the flux out of water from the product to the osmotic solution is by far greater than the solute gain and this result in partial dehydration of the product. Moisture content of fruits and vegetables are high (75-95%). Osmotic dehydration as an upstream partial dehydration process can reduce this moisture content by 30 to 50% for which energy in the form of latent heat need not be supplied. Subjecting a product to osmotic dehydration treatment on upper stream of the drying process therefore plays a significant role in terms of improving the energy use efficiency during drying process. In these days of political and economic arena, energy is the key issue and the cost of energy is escalating from time to time. Reduction of costs associated with energy is one means to maximize profit in both food and non food processing industries. For instance energy saving in drying industries by 1% could result as high as 10% increase in profit margin (Beedie, 1995). Osmotic soaking reduce exposure to oxidation degradation and partial dehydration as well as solute uptake by the product prevents structural collapse during subsequent drying process and hence, osmotically dehydrated products have better color, flavour, texture and taste as compared to untreated ones.

REFERENCES

Ahrens, G, Kriszio, H, and Langer, G. 2006. Microwave Vacuum Drying in the Food Processing Industry. pp. 426-435. *In* Willert-Porada, M. Advances in Microwave and Radio Frequency Processing, Report from the 8th International Conference on Microwave and High Frequency Heating held in Bayreuth, Germany.

Al-Harashan, M, Al-Muhtaseb, AH and Magee, TRA. 2008. Microwave drying kinetics of tomato pomace: Effect of osmotic dehydration, *Journal of Chemical Engineering and Processing: Process Intensification* **48(1)**:524-531.

Alibas, I. 2007Microwave, air and combined microwave-air-drying parameters of pumpkin slices, *LWT-Food Science and Technology* **40**:1445–1451.

Allali, H, Marchal, L and Vorobiev, E. 2009. Effect of Blanching by Ohmic Heating on the Osmotic Dehydration Behavior of Apple Cubes. *Drying Technology* **27(6)**:739-746.

Azarpazhooh, E, and Ramaswamy, HS.2010. Microwave-Osmotic Dehydration of Apples Under Continuous Flow Medium Spray Conditions: Comparison with Other Methods. *Drying Technology* **28(1)**:49-56.

Beaudry, C, Raghavan, GSV, and Rennie, TJ. 2003.Microwave finished drying of osmotically dehydrated cranberries. *Drying Technology* **21**:1797-1810.

Beaudry, C, Raghavan, GSV, Ratti, C and Rennie, TJ.2004. Effect of Four Drying Methods on the Quality of Osmotically Dehydrated Cranberries'. *Drying Technology* **22(3)**:521-539.

Beedie, M. 1995. Energy saving-a question of quality. *South African Journal of Food Science and Technology* **48(3)**:14.

Beristain, CIE, Azuara, RC and Garcia, HS.1990. Mass transfer during osmotic dehydration of pineapple rings. *International Journal of Food Science and Technology* **25**:575.

Bolin, HR, Huxsoll, CC, Jackson, R. and Ng, KC. 1983. Effect of osmotic agents and concentration on fruit quality. *Journal of Food Science* **48**:202–205.

Camirand, W, Krochta, JM, Pavlath, AE, Wong, D and Cole, ME. 1992. Properties of some edible carbohydrate polymer coatings for potential use in osmotic dehydration. *Carbohydrate Polymers* **17**:39–49.

Chiralt, A, Fito, P, Andre´s, A, Barat, JM, Martı´nez-Monzo´, J, and Martı´nez-Navarrete, N. 1999. Vacuum impregnation: a tool in minimally processing of foods. pp. 341–356. In F. AR. Oliveira, and JC. Oliveira (eds.), Processing of foods: Quality optimization and process assessment Boca Rato´n, FL: CRC Press.

Chiralt, A, Martínez-Navarrete, N, Martínez-Monzó, J, Talens, P, Moraga, G, Ayala, A and Fito, P. 2001. Changes in mechanical properties throughout osmotic processes cryoprotectant effect. *Journal of Food Engineering* **49**:129-135.

Cohen, JS and Yang, TCS. 1995. Progress in food dehydration. *Trends in Food Science and Technology* **6**:20–25.

Contreras JE and Smyrl, TG. 1981. An evaluation of osmotic concentration of apple rings using corn solids solutions. *Canadian Institute of Food Technology Journal* **14**:310.

Corrêa, JLG, Pereira, LM, Vieira, GS and Hubinger MD. 2010. Mass transfer kinetics of pulsed vacuum osmotic dehydration of guavas. *Journal of Food Engineering* **96(4)**:498-504.

Dixon, GM, Jen, JJ, and Paynter, VA. 1976. Tasty apple slices result from combined osmotic-dehydration and vacuum-drying process. *Food Product Development* **10(7)**:60,62, 64.

Dornenburg, H, and Knorr, D.1993. Cellular permeabilization of cultured plant tissues by high electric field pulses or ultra high pressure for the recovery of secondary metabolites. *Food Biotechnology* **7(1)**:35-48.

Dornenburg, H, and Knorr, D. 1998. Monitoring the impact of highpressure processing on the biosythesis of plant metabolites using plant cell cultures. *Trends in Food Science and Technology* **9(10)**:355– 361.

Drouzas, AE and Schubert, H. 1996. Microwave Application in Vacuum Drying of Fruits. *Journal of Food Engineering* **28(2)**:203-206.

Drouzas, AE, Tsami, E, Saravacos, GD. 1999. Microwave/vacuum drying of model fruit gels. *Journal of Food Engineering* **39**:117-122.

Escriche, I, Chiralt, A, Moreno, J, Serra, JA. 200. Influence of Blanching-Osmotic Dehydration Treatments on Volatile Fraction of Strawberries. *Journal of Food Science* **65**:107.

Erle, U and Schubert, H. 2001. Combined osmotic and microwave-vacuum dehydration of apples and strawberries. *Journal of Food Engineering* **49**:193-199.

Fito, P. 1994. Modelling of vacuum osmotic dehydration of food. *Journal of Food Engineering* **22**:313-328.

Fito, P, Andres, A, Pastor, R, and Chiralt, A. 1994. Vacuum osmotic dehydration of fruits. In: Singh, R. P. and Oliveira, F. A. R. (Eds), *Minimal Processing of Foods and Process* Optimization. An Interface. Boca Raton, FL: CRC Press, pp. 107–122.

Fito, P, Chiralt, A, Barat, JM, and Martinez-Monzo´, J. 2002. Mass transfer and deformation-relaxation phenomena in plant tissues. pp. 235–252. *In* Welti-Chanes, J, Barbosa-c, Canovas, GV and Aguilera JM (Eds.), Engineering and food for the 21st century, CRC Press, Boca Raton, FL, USA.

Fuente-Blanco, S, Sarabia, ERF, Acosta-Aparicio, VM, Blanco-Blanco A, and Gallego-Ju´arez, JA. 2006. Food drying process by power ultrasound. *Ultrason Sonochem* **44**:523–527.

Garrote, RL, Bertone, RA.1989. Osmotic concentration at low temperature of frozen strawberry halves; Effect of glycerol, glucose and sucrose solution on exudates loss during thawing. *Food Science and Technology* **22**:264–267.

Giraldo, G, Talens, P, Fito, P, Chiralt, A.2003. Influence of sucrose solution concentration on kinetics and yield during osmotic dehydration of mango. *Journal of Food Engineering* **58**:33–43.

Gunasekaran, S.1999. Pulsed microwave-vacuum drying of food materials. *Drying Technology* **17(3)**:395–412.

Hammami, C, Rene, F. 1997. Determination of freeze-drying process variables for strawberries. *Journal of Food Engineering* **32 (2)**:133–154.

Hilderbrand,. KS.1992.Fish Smoking Procedures for Forced Convection Smokehouse, Special Report 887, Oregon State University Extension Service, pp. 1–41.

Ishikawa, M and Nara, H.1993. Osmotic dehydration of food by semi-permeable membrane coating. pp. 73–77. *In* Singh, RP and Wirakartakusuman, MA. (eds). Advances in Food Engineering. London: CRC Press.

Islam, MN and Flink, JN. 1982. Dehydration of potato II. Osmotic concentration and its effect on air drying behaviour. *Journal of Food Technology* **17**:387.

Kudar, T. 2004. Energy Aspects in Drying. *Drying Technology* **22(5):**917-932.

Kudra, T. 2009. Energy Aspects in Food Dehydration. In: Cristina Ratti Ed. Advances in Food Dehydration, CRC Press, NW, U.S.A. pp.423-443.

Lazarides, HN. 1995. Osmotic preconcentration as a tool in freeze preservation of fruits and vegetables. pp. 88–98. *In Proceedings of the Second International Seminar on Osmotic Dehydration of Fruits and Vegetables.* Lenart, A and Lewicki, PP (eds), April 18–19, 1994, Warsaw.

Lazarides, HN and Mavroudis, N. 1995. Freeze/thaw effect on mass transfer rates during osmotic dehydration. *Journal of Food Science* **60(4)**:826–829.

Lazarides, HN. 2001. Reasons and possibilities to control solids uptake during osmotic treatment of fruits and vegetables. pp. 33–42. *In* Fito, P, Chiralt, A, Barat, JM Spiess, WEL and Behsnilian D (eds.), Osmotic dehydration and vacuum impregnation: Applications in food industries USA: Technomic Publ. Co.

Le Maruer, M and Biswall, CJ.1988. Multicomponent diffusion and vapour liquid equilibra of dilute organic components in aqueous sugar solutions. *American Institute of Chemical Engineering Journal* **18(3):**513-519.

Lenart, A and Flink, JM. 1984. Osmotic concentration of potato. I. Criteria for the end-point of the osmosis process *Journal of Food Technology* **19(1):**45.

Lerici, CR, Pinnavaia, G, Rosa, MD and Bartolucci, L. 1985. Osmotic dehydration of fruit: influence of osmotic agents on drying behaviour and product quality. *Journal of Food Science* **50**:1217-1219.

Lewicki, PP, Lenart, A, and Pakua, W.1984. Influence of artificial semi-permeable membranes on the process of osmotic dehydration of apples. Ann. Warsaw Agricult. Univ.-SGGW-AR. *Food Technology and Nutrition* **16**:17–24.

Li, HP and Ramaswamy, HS. 2006a. Osmotic dehydration of apple cylinders: I. Conventional batch processing conditions. *Drying Technology* **24(5)**:619-630.

Li, HP and Ramaswamy, HS. 2006b. Osmotic dehydration of apple cylinders: III. Continuous medium flow microwave heating conditions. *Drying Technology* **24(5)**:643-651.

Lin, TM, Durance, TD and Scarman, CH. 1998. Characterisation of Vacuum-microwavey Air and Freeze Dried Carrot Slices. *Food Research International* **31(2)**:111-117.

Liu, YZ, Zhao, YF, Feng, X. 2008. Exergy analysis for a freeze-drying process. *Applied Thermal Engineering* **28**:675–690.

Maestrelli, A, Lo Scalzo, R, Lupi, D, Bertolo, G and Torregiani, D. 2001. Partial removal of water before freezing: Cultivar and pre-treatments as quality factors of frozen muskmelons (*Cucumis melo*, cv reticulates Naud.). *Journal of Food Engineering* **49**:255.

Matuska, M, Lenart, A, and Lazarides, HN. 2006. On the use of edible coatings to monitor osmotic dehydration kinetics for minimal solids uptake. *Journal of Food Engineering* **72**:85–91.

Mavroudis, NE, Gekas, V, and Sjöholm, I. 1998a. Osmotic dehydration of apples. Effects of agitation and raw material characteristics. *Journal of Food Engineering* **35:**191–209.

Mavroudis, NE, Gekas, V, and Sjöholm, I. 1998b. Osmotic dehydration of apples. Shrinkage phenomena and the significance of the initial structure on mass transfer rates. *Journal of Food Engineering* **38**:101–123.

McLoughlin, CM, McMinn, WAM and Magee, TRA. 2003. Microwave drying of multi-component powder systems. *Drying Technology* **21**:293–309.

Moreno, J, Chiralt, A, Escriche, I and Serra, JA. 2000. Effect of blanching/osmotic dehydration combined methods on quality and stability of minimally processed strawberries. *Food Research International* **33**:609–616.

Moy, JH., Lau NBH and Dollar, AM. 1978. Effects of sucrose and acids on osmovac-dehydration of tropical fruits. *Journal of Food Processing and Preservation* **2**:131.

Mứjica-Paz, H, Valdez-Fragoso, A, Lopez-Malo, Palou, AE, Welti-Chanes, J. 2003. Impregnation and osmotic dehydration of some fruits: effect of the vacuum pressure and syrup concentration. *Journal of Food Engineering* **57**:305–314.

Mujumdar, AS and Menon, AS. 1995. Drying of solids: principles, classification, and selection of dryers. pp. 1–39. *In* Mujumdar, AS (eds), Handbook of Industrial Drying, Marcel-Dekker Inc., New York, USA.

Mujumdar, AS and Beke, J.2003. Grain drying: basic principles. pp.119-139. *In* Handbook of Postharvest Technology: Cereals, Fruits, Vegetables, Tea, and Spices; Chakraverty, A, Mujumdar, AS, Raghavan, GSV, Ramaswamy, HS (eds), Marcel Dekker, Inc., NY.

Mujumdar, AS. 2007. Principles, classification and selection of dryers. pp. 3–32. In Handbook of Industrial Drying, 3rd ed., Mujumdar, AS, (eds)., Taylor and Francis, Boca Raton, FL.

Nunes, Y and Moreira, RG. 2009. Effect of Osmotic Dehydration and Vacuum-Frying Parameters to Produce High-Quality Mango Chips. *Food Engineering and Physical Properties* **24**:355-362.

Nsonzi, F and Ramaswamy, HS.1998. Quality evaluation of osmo-convective dried blueberries. *Drying Technology* **16(3-5)**:705-723.

Panagiotou, NM, Karathanos, VT and Maroulis, ZB. 1999. Effect of osmotic agent on osmotic dehydration of fruits. *Drying Technology* **17**:175–189.

Piotrowski, D, Lenart, A and Wardzynski, A. 2004. Influence of osmotic dehydration on microwave-convective drying of frozen strawberries. *Journal of Food Engineering* **65**:519–525.

Ponting, JP. 1973. Osmotic dehydration of fruits-recent modifications and applications. *Process Biochemistry* **8**:18.

Prothon, F, Ahrne, LM, Funebo, T, Kidma, S, Langton, M and Sjöholm, I. 2001. Effects of combined osmotic and microwave dehydration of apple on texture, micro- structure and rehydration characteristics'. *Lebensmittel-Wissenschaft und -Technol* **34(2)**: 95-101.

Rahman, MS, and Perera, CO. 2007.Drying and Food Preservation. pp.412. *In* Rahman MS, Handbook of food preservation, 2nd ed., CRC press.

Rastogi, NK and Raghavarao, KSMS. 1994. Effect of temperature and concentration on osmotic dehydration of coconut. *Lebensmittel Wissenschaft und Technologie* **27**:564–567.

Rastogi, NK, Raghavarao, K. 1997. Water and solute diffusion coefficients of carrot as a function of temperature and concentration during osmotic dehydration. *Journal of Food Engineering* **34**:429-440.

Rastogi, NK, Eshtiaghi, MN and Knorr, D. 1999.Accelerated mass transfer during osmotic dehydration of high intensity electrical field pulse pretreated carrots. *Journal of Food Science* **64**:1020.

Rastogi, NK, Angersbach, A, Niranjan, K, and Knorr, D. 2000. Rehydration kinetics of high pressure pretreated and osmotic dehydrated pineapple. *Journal of Food Science* **65(5)**:838–841.

Robbers, M, Singh, RP, Cunha, LM. 1997. Osmotic-convective dehydrofreezing process for drying kiwifruit. *Journal of Food Science* **62(5)**:1039–1047.

Rodrigues, S, Gomes, MCF, Gallão, MI and Fernandesc, FAN. 2009. Effect of ultrasound-assisted osmotic dehydration on cell structure of sapotas. *Journal of the Science of Food and Agriculture* **89**:665–670.

Sanga, E, Mujumdar, AS and Raghavan, GSV.2000.Principles and Applications of Microwave Drying. pp. 253-286. *In* Drying Technology in Agriculture and Food Sciences, edited by Mujumdar, A.S., Science Publishers, Inc. Enfield, NH.

Shi, XQ and Maupoey, PF. 1994. Mass transfer in vacuum osmotic dehydration of fruits: a mathematical model approach. *Food Science and Technology* **27**:67-72.

Shi, XQ, Fito, P and Chiralt, A. 1995. Influence of vacuum treatment on mass transfer during osmotic dehydration of fruits. *Food Research Intitute* **28(5)**:445-454.

Shi, J.2008. Osmotic Dehydration of Foods. pp. 275-295. *In* Hui, YH Clary, C, Farid, MM, Fasina, OO, Noomhorm, A, Welti-Chanes J. (eds), Food Drying Science and Technology: Microbiology, Chemistry, Applications, DES*tech* Publications, Inc. Pennsylvania, U.S.A.

Simal, S, Deya, E, Frau, M, and Rossello, C. 1997. Simple modelling of air drying curves of fresh and osmotically pre-dehydrated apple cubes. *Journal of Food Engineering* **33**:139–150.

Simal, S, Benedito, J, Sanchez, ES and Rossello, C.1998. Use of ultrasound to increase mass transfer rates during osmotic dehydration. *Journal of Food Engineering* **36**:323–336.

Sormani, AD, Maffi, GB and Torreggiani, D. 1999. Texture and structural changes of dehydrofreeze thawed strawberry slices: Effects of different dehydration pretreatments. *Food Science and Technology Intitute* **5**:479.

Spiazzi, EA, Raggio, I, Bignone, KA, Mascheroni, RH. 1998. Experiments on dehydrofreezing of fruits and vegetables: mass transfer and quality factors. Advances in the Refrigeration Systems. Food Technologies and Cold Chain, IIF/IIR 6:401–408.

Strumillo, C and Adamiec, J.1996. Energy and Quality Aspects of Food Drying. *Drying Technology* **14**:423-448.

Taiwo KA, Eshtiaghi, MN, Ade-Omowaye BIO and Knorr, D. 2003. Osmotic dehydration of strawberry halves: influence of osmotic agents and pretreatment methods on mass transfer and product characteristics. *International Journal of Food Science and Technology* **38**:693–707.

Tedjo, W, Taiwo, KA, Eshtiaghi, MN, Knorr, D. 2002. Comparison of pretreatment methods on water and solid diffusion kinetics of osmotically dehydrated mangos, *Journal of Food Engineering* 53:133–142.

Torreggiani, D.1993.Osmotic dehydration in fruit and vegetable processing. *Food Ressearch Intitute* **26**:59–68.

Torringa, E, Lourenco, F, Scheewe, I, and Bartels, P. 2001. Application of Microwave Drying after Osmotic Dehydration: Effect of Dielectric Properties on Heating Characteristics. pp.217-225. *In* Pedro Fito, Amparo Chiralt, Jose M. Barat, Walter E.L. Spiess and Diana Behsnilia, Ed. Osmotic Dehydration and Vacuum Impregnation, Technomic publishing company Inc., Pennsylvania, U.S.A.

Toupin, CJ and Le Maguer, M. 1989. Osmotically-induced mass transfer in plant storage tissues: A mathematical model. Part II. *Journal of Food Engineering* **10**:97-121.

Varith, J, Dijkanarukkul, P, Achariyaviriya, A, Achariyaviriya, S. 2007. Combined microwave-hot air drying of peeled longan. *Journal of Food Engineering* **81(2)**:459–468.

Venkatachalapathy, K, Raghavan, GSV. 1998. Microwave drying of osmotically dehydrated blueberries. *Journal of Microwave Power and Electromagnetic Energy* **33(2)**:95–102.

Wong, WS, Tillin, S, Hudson, JS, and Pavlath, E. 1994. Gas exchange in cut apples with bilayer coatings. *Journal of Agriculture and Food Chemistry* **10(42)**:2278–2285.

Yongsawatdigul, J and Gunasekaran, S. 1996. Microwave-vacuum drying of cranberries: Part 1. Energy use and efficiency. *Journal of Food Processing and Preservation* **20**:121-143.

Zhang, M, Tang, JM, Mujumdar, AS. 2006. Trends in microwave-related drying of fruits and vegetables. *Trends in Food Science and Technology* **17(10)**:524–534.