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MiniReview
Factors affecting mass transfer during osmotic dehydration of fruits

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Abstract: Research applications of osmotic dehydration to food processing in technology and in component transfer mechanisms are being carried out in several countries. Osmotic dehydration is a traditional process applied to food dewatering. It leads to attractive products that are ready to eat or can be applied as a pretreatment to the next process such as drying or freezing. The new osmotically dehydrated products and industrial applications require appropriate manufacturing procedures at the industrial level. Thus, an understanding of factors affecting mass transfer during osmotic dehydration is required for the process optimisation. In this review, the mechanism of osmotic dehydration is described. In addition, some factors that affect on mass transfer during osmotic dehydration such as types of osmotic agent, concentrations of osmotic agent, processing temperatures, agitation or stirring process, pretreatment methods and edible coating were reviewed.

Keywords: Osmotic dehydration, mass transfer, solid gain, water loss

Introduction

Water is a main constituent of foods, which affects food stability, microbial as well as chemical. It is responsible for the consumer perception of many organoleptic attributes such as juiciness, elasticity, tenderness and texture. Dehydration is an important process to preserve raw food materials and products in food industry. The basic objective in dehydration of food is the removal of water from the raw materials to extend the shelf life and reduce the water activity of food products. The lowering of water activity can be achieved in two ways, either by the addition of humectants or by the removal of solvent such as water. Researchers have a looked for new ways to improve the quality of preserved food products. One of these methods is osmotic dehydration. Osmotic dehydration has shown the potential to obtain better food products by removing water at low temperature (Shi and Xue, 2009). It has been widely used as a pretreatment step in food drying process since it can reduce the overall the energy requirement for further drying process (Khin *et al*., 2006).

Nowadays, fresh fruits and vegetables have been increasing in popularity for consumption compared to canned fruits. To satisfy the growing market demand for commodities in a freshlike state, minimal processing such as osmotic dehydration will be increasingly used. The active research in the area of osmotic dehydration of fruits is continuing all over the world. Some researches have tried to increase the rate of osmotic mass transfer to reduce the processing time (El-Aouar *et al*., 2006; Moreira *et al*., 2007; Ispir and Togrul, 2009; Devic *et al*., 2010; Bchir *et al*., 2011; Mundada *et al*., 2011). However, some researches concern to minimize the uptake of osmotic solids, as it can severely alter organoleptic and nutritional characteristics such as the loss vitamin and mineral salt of the products (Shi and Xue, 2009; Jalaee *et al*., 2010). During osmotic dehydration, a high osmotic rate would make the process more efficient and practical. Most previous studies have focused attention on rapid and effective removal of desired amount of water from food materials such as fruits by adjustment some factors or the operation parameter (El-Aouar *et a*l., 2006; Moreira *et al*., 2007; Ispir and Togrul, 2009; Devic *et al*., 2010; Bchir *et al*., 2011; Mundada *et al*., 2011). Some factors have been employed to speed up water transfer such as using a high concentration of osmotic solution, low molecular weight of osmotic agent, high processing temperature, stirring process or some pretreatment techniques. Thus, these factors were important to review. However, another concern in osmotic dehydration is currently to minimise the uptake of osmotic solids, as it can severely alter organoleptic and nutritional characteristics of the product. Numerous studied have attempted to reduce large solute uptake by using edible coating material prior to osmotic dehydration (Khin *et al*., 2007; Garcia *et al*., 2010; Jalaee *et al*., 2010; Singh *et al*., 2010). Hence, the influence of edible coating on mass transfer during osmotic dehydration was also reviewed. The aim of this review is to describe some factors affecting the mass transfer during osmotic dehydration process of fruit.

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Mechanism of osmotic dehydration

Osmosis is the movement of water molecules through a selectively-permeable membrane down a water potential gradient. More specifically, it is the movement of water across a selectively- permeable membrane from an area of high water potential (low solute concentration) to an area of low water potential (high solute concentration) (Rastogi *et al*., 2002; Shi and Xue, 2009). Osmotic treatment is actually a combination of dehydration and impregnation processes, which can minimise the negative modifications of fresh food components. It is the partial removal of water by direct contact of a product with a hypertonic medium such as a high concentration of sugar or salt solution for fruit and vegetable. After immersing a water-rich fresh food material in a hypertonic solution, the driving force for water removal is the concentration gradient between the solution and the intracellular fluid. If the membrane is perfectly semipermeable, the solute is unable to transfer through the membrane into the cells. However, it is difficult to obtain a perfect semipermeable membrane in food material because of their complex internal structure and possible damage during processing. During osmotic processing, two major countercurrent flows take place simultaneously. The first major one is water flow the inside of the samples into the osmotic solution, and the second flow is the osmotic agent diffusion into the opposite direction, which is flowing from solution into the product (Figure 1). This is another flow which is not much considerable, and consists of substances such as vitamins, organic acids, saccharides and mineral salts which flow from food into osmotic solution. Although, this third flow has no considerable amount in the mass exchange, it can influence the final nutritive values and organolepic properties of food (Lazarides, 2001; Khin *et al*., 2005).

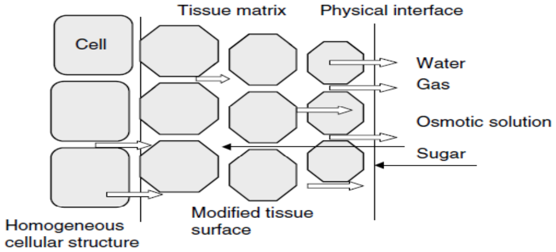

Figure 1. Schematic cellular material tissue representation and mass transfer pattern. (Source: Shi and Xue, 2009)

In general, liquid diffusion occurs in nonporous solids whereas capillary movement occurs in porous solids. The transport of water in liquid solution takes place only by molecular diffusion. In capillary–porous biological materials, mass transfer occurs in gas-filled cavities, capillaries, cell walls as well as extracellular and intracellular spaces. When cellular biological materials are immersed in a high concentration of osmotic solution, osmotic treatment is actually a multicomponent transfer process in which simultaneous, countercurrent solution flows with a combination of dehydration, leaching, and impregnation processes occurring in the biological tissue matrix. The mass transfer process of each component in the solid–liquid system is affected by operation parameters and by the presence of other components (Shi and Xue, 2009).

When a cellular solid material is immersed in hypertonic solution (sucrose solution), the cells in the first layer of the material contact the hypertonic solution and begin to lose water because of the concentration gradient between the cells and hypertonic solution; then, they begin to shrink. After the cells in the first layer lose water, a “chemical potential difference of water” between the first layer of cells and second layer of cells is established. Subsequently, the second layer cells begin to pump water to the first layer cells and then shrink. The phenomena of mass transfer and tissue shrinkage are spread from the surface to the center of the material as a function of the operation time. Finally, the cells in the material center lose water and the mass transfer process tends to equilibrate after a long period of solid–liquid contact. The mass transfer and the shrinkage of tissue occur simultaneously during osmotic dehydration process. Thus, for a certain operating time, mass transfer and tissue shrinkage are related to a specific part of the whole material (Le Maguer *et al*., 2003; Shi and Xue, 2009).

After food material is immersed in the osmotic solution, water is transported by several mechanisms simultaneously: molecular diffusion, liquid diffusion, vapor diffusion (through gas flow), hydrodynamic flow, capillary transport, surface diffusion, and most frequently a combination of these mechanisms. The transfer processes of food material can be considered as follows: (Chiralt and Talens, 2005; Shi and Xue, 2009).

1. Water and solutes are transported by diffusion in the osmosis process because of concentration gradients.
2. Water and solutes are transported by capillary flow because of the differences in total system pressure which caused by external pressure, shrinkage, and capillarity.
3. Hydrodynamic flow occurs in pores.
4. Water vapor diffusion occurs within partly filled pore because of the capillary–condensation mechanism.
5. Water diffusion occurs at pore surfaces because of gradients at the surfaces.

Factors affecting mass transfer during osmotic dehydration of fruit

Osmotic dehydration has recently received increasing attention as a potential pretreatment to conventional drying and freezing processes for improving the quality of fruit. It is a slow process suggesting the need for enhancing mass transfer without affecting the food quality negatively. Pretreatment such as blanching, freezing, high pressure, high intensity pulsed electric field and ultrasound have been reported to enhance mass transfers (Tedjo *et al*., 2002; Bchir *et al*., 2011). However, another problem taking place during osmotic dehydration is a large solute uptake. Solids uptake modifies final product composition (*i.e*. sugar to acid ratio) and taste. The solids uptake blocks the surface layers of the product, posing an additional resistance to mass transfer and lowering the rates of complementary dehydration (Lazarides *et al*., 1995; Matuska *et al*., 2006). The importance of solid gain with respect to both the rate of water removal and the quality characteristics of the final product has attracted extensive research interest. It has been shown that the damage of plant cells due to pretreatment process results in extensive uptake of solids from the osmotic solution. Besides process temperature, type of osmotic agent and osmotic solution concentration show a central role to solute uptake. Furthermore, coating has been suggested as a means of preventing solid gain. All detail regarding to these factors will be discussed.

Type of osmotic agent

The type of osmotic agent is very important factor that determines the rate of diffusion. The common solute types used as an osmotic agent are sucrose, glucose, sorbitol, glycerol, glucose syrup, corn syrup and fructo-oligosaccharide. Generally, low molecular weight osmotic agent easier penetrates into the cell of fruit compared to high molecular weight osmotic agent. El-Aouar *et al*. (2006) studied the influence of the osmotic agents (sucrose and corn syrup solid) on mass transfer during osmotic dehydration of papaya. It was found that sample dehydrated in sucrose solution had values of solid gain and water loss higher than that obtained from the samples processed in corn syrup solution. The fact is corn syrup solution had visually higher viscosity and molecular weight than sucrose. In addition, the comparison between effects of fructo-oligosaccharide and sucrose as osmotic agents in osmotic dehydration of apple cubes were reported by Matusek *et al*. (2008). The solid gain in case of fructo-oligosaccharide was less than half of the solid gain in case of sucrose. Regarding to the difference in chemical composition and structure which make the osmotic behaviour of fructo-oligosaccharide differs from sucrose. This probably due to fructo-oligosaccharide had a higher molecular weight than sucrose, resulting in lower rate of diffusion. Ispir and Togrul (2009) studied the effect of osmotic agent on mass transfer during osmotic dehydration of apricot. Various osmotic agents such as sucrose, glucose, fructose, maltodextrin and sorbitol were used. They reported that the highest and the lowest water loss were obtained by sucrose and sorbitol solutions, respectively. On the other hand, the highest and the lowest solid gain were obtained by maltodextrin and fructose solutions, respectively. Sorbitol is obtained by reduction of glucose changing the aldehyde group to an additional hydroxyl group hence it can be named as sugar alcohol. Molecular weight of sorbitol ($C_6H_{14}O_6$) is smaller than sucrose ($C_{12}H_{22}O_{11}$). Sucrose has α-glucose and fructose, joined by glycosidic bond. Sucrose supplies reverse characteristics compared to sorbitol. This can be explained in two ways. One is molecular weight and shape of sucrose. Another is pore structure of apricot. Although maltodextrin has higher molecular weight than the other, maltodextrin can be absorbed as good as glucose. High solid gain in case of using maltodexrin can be explained with its high absorption characteristic. In addition to supplying low solid gain, fructose supplies high osmotic pressure in fruit by virtue of water bonding capacities. Thus, sucrose and fructose solutions are the best in osmotic dehydration of apricots due to high water loss and low solid gain. Pattanapa *et al.* (2010) studied the effect of sucrose and glycerol mixtures in the osmotic solution on mass transfer of mandarin. Peeled mandarin samples were immersed in osmotic solution prepared from various ratios of sucrose solution (60%) to glycerol solution (60%), specifically, 9:1, 8:2, 7:3, 6:4 and 5:5 w/w. It was found that the highest water loss was obtained when the osmotic solution of 5:5 was used. This is because of glycerol having a lower molecular weight than sucrose. Increasing the amount of glycerol increased the osmotic pressure gradient and thereby increased the water loss. Additionally, an increase in solid gain was observed when the sucrose/glycerol ratio was decreased to 5:5. This indicated that a decrease in the molecular size of the solute could enhance the solid gain. In fact, mass transfer of the solute depends on the effective diffusion coefficient that can be affected by the radius of molecules.

Concentration of osmotic agent

One interesting variable to evaluate is the concentration of osmotic agent that can influence on mass transfer kinetics. During extended osmotic treatment, the increase of solute concentrations results in the increase in water loss and solid gain rates. Lazarides *et al*. (1995) studied the effect of sucrose concentration (45%, 55% and 65%) on mass transfer during osmotic dehydration of apple. The result showed that the increase in sucrose concentration resulted in higher of water loss and solid gain throughout the osmotic period. This result is in accordance with the work of Falade *et al*. (2007). They monitored the mass transfer during osmotic dehydration of watermelon slabs. The process was carried out at three different sucrose concentrations (40°Brix, 50°Brix and 60°Brix). Water loss and solid gain increased with the osmotic solution concentration increase. Watermelon slabs immersed into 60°Brix sucrose solution showed higher water loss and solid gain compared to those immersed in 40°Brix and 50°Brix solutions. Ispir and Togrul (2009) studied the mass transfer during osmotic dehydration of apricot. Apricot was soaked in different sucrose concentrations (40%, 50%, and 60%). They reported that increase in sucrose concentration resulted in an increase in the osmotic pressure gradients and, hence, higher water loss and solid gain uptake values throughout the osmotic period were obtained. Mundada *et al*. (2011) studied effect of sucrose concentration on mass transfer during osmotic dehydration of pomegranate arils. Osmotic dehydration was done in osmotic solution of sucrose having different concentration (40°Brix, 50°Brix and 60°Brix). The increase in water loss and solid gain was also observed with increase of osmotic solution concentration. Pomegranate arils immersed into 60°Brix sucrose solution showed higher water loss and solid gain compared to those immersed in 40°Brix and 50°Brix osmotic solution. Results suggested that, the increase in solid gain and water loss with the solute concentration is due to the highly different in concentration between the fruit sample and osmotic solution which increased the rate of diffusion of solute and water exchange. Increased solution concentration resulted in the increase in the osmotic pressure gradients and higher water loss (Azoubel and Murr, 2004). Moreover, the increased mass transfer of sugar molecules with increasing concentration is possible due to membrane swelling effect, which might increase the cell membrane permeability. These results indicate that by choosing a higher concentration medium, some benefits in terms of faster water loss could be achieved. Additionally, a much greater gain of solid is observed. However, some works reported that high concentration of osmotic agent may not enhance the solid gain. Giraldo *et al*. (2003) studied the mass transfer during osmotic dehydration of mango. The processes were carried out at 30°C, using 35°Brix, 45°Brix, 55°Brix and 65°Brix sucrose. They reported that water transfer rate increased when the concentration of sucrose increased up to 45°Brix, whereas, this effect did not appear between 55°Brix and 65°Brix, the rate constant being slightly greater for the treatment at 55°Brix. A case hardening effect could be responsible for the mass transfer reduction at the highest sucrose concentration. When external solution is more concentrated, the external liquid penetration is more limited by viscosity. Additionally, the rigidity of external cell layers increases more quickly due to their faster concentration (case hardening effect).

Temperature during osmotic dehydration

It is well recognised that diffusion is a temperature-dependent phenomenon. Higher process temperature seems to promote faster water loss through swelling and plasticising of cell membranes, faster water diffusion within the product and better mass (water) transfer characteristics on the surface due to lower viscosity of the osmotic medium. Kaymak-Ertekin and Sultanogli (2000) studied the effect of temperature on mass transfer during osmotic dehydration of apple. To examine the effect of temperature on osmosis behaviour, experiment was carried out at 20°C, 30°C, 40°C and 50°C in 60% sucrose solution. The water loss increased with temperature while solid gain did not change significantly. However, the solid gain increased with temperature higher than 50°C. Devic *et al*. (2010) also studied the effect of temperature (45°C and 60°C) on mass transfer during osmotic dehydration of apples in a 60°Brix sucrose solution. The result showed that water loss increased over time and was accelerated by a higher temperature. In addition, Falade *et al*. (2007) studied the effect of osmotic temperature on water loss and solid gain of watermelon slabs immersed into sucrose solution (50°Brix). Water loss and solid gain increased with the solution temperature. Higher water loss and solid gain were observed at 40°C compared to those at 20°C and 30°C. Ispir and Togrul (2009) studied the mass transfer during osmotic dehydration of apricot. Apricot was soaked in 40% sucrose solution at different temperatures such as 25°C, 35°C and 45°C. It was observed that temperature had increasing effect on the osmotic dehydration of apricot. The increasing of osmotic medium temperature caused the increase in water loss and solid gain. Moreover, Mundada *et al*. (2011) studied the effect of temperature on mass transfer during osmotic dehydration of pomegranate arils. Osmotic dehydration was done in osmotic solution of sucrose having different solution temperatures (35°C, 45°C and 55°C). It was found that higher water loss and solid gain were observed at 55°C compared to those at 45°C and 35°C. The increase in solid gain and water loss when samples were immersed into a high temperature solution is due to the increase in the rate of diffusion. Moreover, fruit sample has a porous structure so that high temperature would also release the trapped air from the tissue resulting in more effective to the removal of water by osmotic pressure. This enhances the removal of water and uptake of solids. Moreover, the increase in temperature decreases the viscosity of osmotic solution, decreases the external resistance to mass transfer rate at product surface. Thus, it facilitates the outflow of water from fruit and in high diffusion rates of solute into fruit.

Agitation or stirring process during osmotic dehydration

The use of highly concentrated viscous sugar solutions creates major problems such as floating of food pieces, hindering the contact between food material and the osmotic solution, causing a reduction in the mass transfer rates. Thus, to enhance mass transfer, agitation or stirring process can be applied during osmotic dehydration (Moreira *et al*., 2007). Some reports mentioned that degree of agitation had a significant effect on water loss. Water loss was higher in turbulent flow region than in the laminar flow region. The effect of agitation was studied by Mavroudis *et al*. (1998) and Moreira *et al*. (2007). They compared the effect of agitation and non-agitation treatments. The agitated samples exhibited greater weight reduction, consequently water loss, than non-agitated product. Moreira *et al*. (2007) studied the effect of stirring during osmotic dehydration process of chestnut in glycerol solution. In order to evaluate mass transfer, the static and dynamic conditions have been tested (0 rpm, 40 rpm and 110 rpm). Water loss and solid gain were monitored as an adequate index in order to evaluate the effectiveness of the osmotic process (Lazarides *et al*., 1997; Matuska *et al*., 2006). Higher in water loss and solid gain was found in the dynamic condition when compared to static condition. The agitation or stirring process can promote the turbulent flow, resulting in the increment of liquid diffusion during osmotic dehydration. Turbulent flow can enhance the hydrodynamic flow mechanism during osmotic dehydration (Mavroudis *et al*., 1998; Morrira *et al*., 2007; Shi and Xue, 2009). Therefore, the agitation or stirring process could be a good alternative way to enhance mass transfer, leading to the reduction of the contact time to achieve determined moisture content in the food materials.

Pretreatment method

The cellular membrane exerts high resistances to transfer and slows down the rate of osmotic dehydration (Erule and Shubert, 2001). Thus, a number of techniques have also been tried to improve mass transfer rate during osmotic dehydration. These techniques include blanching, freezing, high pressure, ohmic heating, pulsed electric field, and ultrasound (Rastogi *et al*., 2000; Taiwo *et al*., 2003; Amami *et al*., 2006; Falade and Adelakun, 2007; Allali *et al*., 2010; Bchir *et al*., 2011). Applying different treatments before or during osmotic dehydration of fruit would be important effect on mass transfer controlling. Application of some pretreatment methods can be used to damage or modify cell structure of fruit for enhancing mass transfer during osmotic dehydration (Kowalska *et al*., 2008).

Blanching is a cooking term that describes a process of food preparation. It normally uses for vegetable or fruit by soaking into hot water. Blanching is responsible for the changes in quality attributes of fruit tissue, particularly texture. These changes are probably associated with: (1) losses of turgor resulting from thermal degradation of cellular membranes, (2) cell separation due to thinning or complete breakdown of the interlamellar layer of cell walls; and (3) expulsion of trapped air that expands with heat and is further displaced from intercellular spaces by sap leaking from damaged cells. Thus, blanching is a pretreatment technique that can be applied for accelerating mass transfer during osmotic dehydration. Del Valle *et al*. (1998) studied the effect of blanching on mass transfer during osmotic dehydration of apple. The blanching was studied by exposing apple cylinders to steam (97.3°C at 94.6 kPa). It was found that blanched sample showed higher water loss than raw sample. They attributed these results to losses of material associated with extensive damage of cellular tissue caused by high temperature blanching. Kowalska *et al.* (2008) studied the effect of blanching on mass transfer during osmotic dehydration of pumpkin. Pumpkin was blanched in water at 80°C for 1 min before osmotic dehydration process. Water loss from raw and blanched pumpkin proceeded similarly with no significant statistical differences. On the other hand, blanching before osmotic dehydration of pumpkin proved to increase solid gain in comparison with samples without pretreatment. It means that blanching destroyed pumpkin tissue structure, resulting in the promotion of solid uptake during osmotic dehydration.

In the case of the conventional blanching, generation of heat within the solid particles depends of the thermal conductivity of the liquid, thus, the overheating of the liquid is possible. It should be noted that a long blanching time has adverse effects on the quality of fruits and yield of the final product. The ohmic heating process can be used as an alternative blanching method for fruit and vegetable (Icier *et al*., 2006). The ohmic heating concept is not new and was already used in the beginning of the twentieth century for milk pasteurization by application of an electrical current through the product placed between two electrodes connected to a generator. Thus, the product behaves as an electrical resistance. The heat generated inside the food is directly related to the current induced by the voltage gradient in the field, and the electrical conductivity of the product (Sastry and Li, 1996). Ohmic heating appears to be an effective method for enhancement of processes controlled by mass transfer since it affects the integrity of biological tissue by solubilizing the pectic substances constituting the cellular wall and by providing electroporation of cell membranes (Praporscic *et al*. 2006). Allali *et al*. (2010) studied the effect of ohmic heating as a pretreatment before osmotic dehydration on mass transfer of strawberry and apple. The treatment by ohmic heating (Figure 2) was applied to a mixture of fruit cubes and syrup with a solid to liquid ratio of 1/2. The syrup and fruits were heated from room temperature 20°C up to 85°C. The duration of fruit holding at constant temperature (85°C) was 1 min. The intensity of electric field was fixed at 66 V cm^{-1}, and the frequency used was 50 Hz to limit the risks of product electrolysis. When blanching was complete, the pre-treated apple cubes were gently immersed in cold syrup (4°C) for cooling. After that, the fruit samples were immersed in sucrose solution (70°Brix) for osmotic dehydration process. It was found that ohmic heating influenced the mass transfer during osmotic dehydration of strawberry and apple as evidenced by higher water loss and solid gain was found in sample treated with ohmic heating when compared to the non-treated sample. This result can be explained by the ability of ohmic heating to permeabilise efficiently the cellular membranes. Thus, the coupling of ohmic heating with osmotic dehydration makes it possible to obtain higher water and sugar diffusion rates.

Freezing is another technique that can be used as a pretreatment method before osmotic dehydration. It has been reported to enhance mass transfer during osmotic dehydration (Falade and Adelakun, 2007; Kowaslska *et al*., 2008). Lazarides and Mavroudis (1995) reported that freeze-thawing did not improve water loss rates but had a strong positive effect on solid gain during osmotic dehydration. Falade and Adelakun (2007) investigated the effect of pre-freezing on mass transfer during osmotic dehydration of apple. Before osmotic dehydration, apple was frozen at -16°C for 48-50 h. It was found that pre-freezing treatment of apple enhanced mass transfer especially in the first 30 min to 2 h of immersion. Additionally, Kowalska *et al*. (2008) studied the effect of freezing on osmotic dehydration of pumpkin. They reported that pretreatment by freezing before osmotic dehydration of pumpkin proved to increase solid gain in comparison with samples without pretreatment. Moreover, Bchir *et al*. (2011) studied the effect of prefreezing method prior to osmotic dehydration process of pomegranate seeds. Freezing before osmotic dehydration provided 1.4 and 3.5 times more water loss and solid gain, respectively, than an untreated sample at the beginning of the process. As a consequence, the process could be stopped after 20 min, implying a substantial gain of time and thermal energy. This is due to cellular structure disruption of fruit pulp as a result of the freeze-thaw ice water transformation and thus favour high solute uptake.

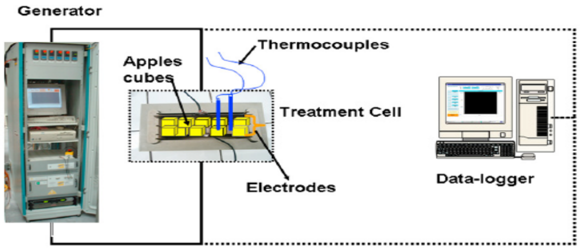

Figure 2. Experimental set up for ohmic heating applied for osmotic dehydration of fruit (Source: Allali *et al*. 2010)

The behaviour of mass transfer during osmotic dehydration is controlled by the microstructural properties of fruits. At the beginning of immersion, porosity has an effective influence on mass transfer because gas is entrapped in the fruit tissue. Treating the fruit prior to osmotic dehydration assists in degassing as well as increasing the permeabilisation of the cells. The application of high pressure (HP) (100-800 MPa) damages the cell wall structure (primarily the non-covalent bonds), leaving the cells more permeable resulting in the increase of mass transfer rates during osmotic dehydration compared to untreated samples (Rastogi *et al*., 2000; Tangwongchai *et al*., 2000). Taiwo *et al*. (2003) investigated the mass transfer during osmotic dehydration of high pressure treated strawberry halves (200 MPa) and untreated strawberry halves. Higher water loss and solid gain were found in high pressure treated strawberry halves compared to untreated samples. In addition, Rastogi and Niranjan (1998) investigated the effect of high pressure level (0, 100, 300, 500 and 700 MPa) on mass transfer during osmotic dehydration of pineapple. The result showed that an increase in solid gain and water loss was observed when increasing the pressure level. Moreover, the effect of high pressure level (0, 200 and 400 MPa) on mass transfer during osmotic dehydration of potato was also studied by Rastogi *et al*. (2000). It was found that an increase in solid gain and moisture loss was also observed when increasing the pressure level. This indicated that the application of high pressure resulted in cell permeabilisation facilitating diffusion. The osmotic dehydration of high pressure-treated potato samples was faster than the untreated one since the combined effect of cell permeabilisation due to osmotic stress (as the dehydration proceeds) and high-pressure-induced permeabilisation, resulting in the promotion of solid uptake and the release of water from the cell (Dornenburg and Knorr, 1993; Eshtiaghi *et al*., 1994). Thus, from the results can be confirmed that application of high pressure can enhance mass transfer rate during osmotic dehydration.

The application of high intensity electric field pulses is another novel non-thermal pretreatment method which was reported to enhance mass transfer during dehydration. This is probably due to increased permeability of cells (Ade-Omowaye *et al*., 2001). The application of sufficiently high intensity electric field pulses results in pore formation and breakage of cell membranes. Taiwo *et al*. (2003) investigated the effect of high intensity electric field pulses as a pretreatment on mass transfer during osmotic dehydration of strawberry halves. Water loss and solid gain of control and high intensity electric field pulses-treated samples were compared. It was found that higher water loss and solid gain was observed in high intensity electric field pulses-treated samples compared to control. The acceleration kinetics of water and solute transfer during osmotic dehydration of apple after treated with high intensity electric field pulses was reported by Amami *et al*. (2006). An increase in water loss and solid gain was found after high intensity electric field pulses were observed. Additionally, the effect of high intensity electric field pulses was more pronounced for the water loss by apple tissue comparatively to the gain of solute. Moreover, Rastogi *et al*. (1999) investigated the effect of high intensity electric field pulses at different electrical field strength as a pretreatment on mass transfer during osmotic dehydration of carrot. The carrot pieces were subjected to high intensity electric field pulses treatment at four electrical field strengths (0.22, 0.64, 1.09 and 1.60 kV/cm). Water loss and solid gain of control and high intensity electric field pulses-treated samples were compared. Water loss and solid gain increased as applied electrical field strength increased. This can be explained by high intensity electric field pulses application affected the cell wall structures leaving the cells more permeable for water and solute transfer.

In recent years, the applications of ultrasound have been investigated. Cavitation, phenomenon produced by sonication, consists in the formation of bubbles in the liquid which can explosively collapse and generate localized pressure. This effect increases the diffusion and osmotic processes, and accelerates and completes degassing. In a solid medium, the sound waves cause a series of rapid and successive compressions and rarefactions, with the rates depending on their frequency. This mechanism is of great relevance to drying and dewatering. The mechanical and physical effects of sound can be used to enhance many processes where diffusion takes place (Simal *et al*., 1998; Fernandes and Rodrigues, 2007). Ultrasound waves can cause a rapid series of alternative compressions and expansions, in a similar way to a sponge when it is squeezed and released repeatedly (sponge effect). In addition, ultrasound produces cavitation which may be helpful to remove strongly attached moisture. Deformation of porous solid materials, such as fruits, caused by ultrasound waves is responsible for the creation of microscopic channels that increase the mass transfer in the fruit (Fuente-Blanco *et al*., 2006). Thus, the ultrasound technique can be used to reduce the initial water content or to modify the fruit tissue structure in a way that the dewatering time becomes faster. Normally, the ultrasound-assisted osmotic dehydration process involves the immersion of the fruit in water or in a hypertonic aqueous solution to which ultrasound is applied. The advantage of using ultrasound is that the process can be carried out at ambient temperature and no heating is required, reducing the probability of food degradation. Simal *et al*. (1998) reported a 14–27% increase of water loss in apple cubes (depending on the temperature) by using 3 h of ultrasound treatment compared with agitation. The effect of ultrasound on the solid gain was similar to the water loss. The result showed that a 23% increase in solid gain when ultrasound was applied for 3 h compared with the solid gain without ultrasound treatment. Additionally, Taiwo *et al*. (2003) also reported that the ultrasound treatment promoted the kinetics of water and solute transfer during osmotic dehydration of strawberry halves. Higher water loss and solids gain were observed in samples treated with ultrasound compared to untreated samples. Moreover, Francisca *et al*.

(2010) applied ultrasound treatment during osmotic dehydration of Malay apple. They reported that the amount of solid gain was higher when ultrasound was applied than without application of ultrasound. Thus, ultrasound-assisted osmotic dehydration can be carried out at lower solution temperature to obtain higher water loss and solid gain rates, while preserving the natural flavour, colour and heat-sensitive nutritive components (Rastogi *et al*., 2002).

Coating material

A large solute uptake is considered undesirable for osmotic dehydration purposes, because it has a negative impact on the natural product profile (taste and nutrition value) (Matuska *et al*., 2006). A number of studies have been conducted aiming to control a large solid uptake. Relevant research includes (1) controlling the geometry and size of the product (Lerici *et al*., 1985; Torreggiani, 1993), (2) using mixed salt-sugar solutions (Lenart and Flink, 1984), (3) using high molecular weight osmotic agent (Hughes *et al*., 1958; Lazarides *et al*., 1995) and (4) coating treatment prior to osmotic dehydration by using edible coating materials (Lenart and Debrowska, 1997, 1999). Among these methods, the use of coating as a barrier is very promising. It was reported that the appropriate coating materials could efficiently inhibit the extensive solid uptake without affecting too much on the water removal (Khim *et al*., 2006).

Edible coatings are made of one to four major materials including: lipids, polysaccharides, resins and proteins and also a mixture of these materials forms the new composite edible coatings, that can limit lipid, oxygen, water vapour and flavour migration between food and the surroundings (Boldwin, 1995; Jalaee *et al*., 2010). Aqueous solutions of potato starch, corn starch, sodium alginate, low methoxy pectin, high methoxy pectin, chitosan, ethyl cellulose, carboxyl methyl cellulose and maltodextrin were used for coating fruits and vegetables to control solute uptake (Camirand *et al*., 1992; Emam-Djomech *et al*., 2006; Khin *et al*., 2007). As the coating serves as an extra barrier to the mass transfers during osmotic dehydration, it is well anticipated that both solid gain and water loss could be reduced in coated food materials. For the purposes of the osmotic membrane process, edible coatings should have the following properties: good mechanical strength (gel strength), satisfactory sensory properties, easy and rapid film formation with simple techniques, high water diffusivity and maintenance (of the coating) in the intact state without dissolving into the osmotic solution (Camirand *et al*., 1992). The right choice always depends on the desired barrier properties. The advantages of coating materials applied for osmotic dehydration process may include the following: (1) it may reduce the extensive solute uptake, (2) it may reduce losses of desired constituents such as colourant, flavour compounds and nutrients, (3) coating may provide greater product integrity and physical strength to food pieces, which can withstand mixing (throughout processing) and physical impact (during handling, storage and transportation), (4) it may also minimise microbial contamination and oxidation activity and (5) it may give greater esthetic appeal, especially for products with clear polysaccharide coatings (Matuska *et al*., 2006).

Polysaccharide based coating materials usually apply to coat the fruit prior to the osmotic dehydration process. Coating materials affected the mass transfer as indicated by solid gain or water loss during osmotic dehydration process. Ogonek and Lenart (2001) investigated the mass transfer during osmotic dehydration of strawberries with edible coatings. Low-methylated pectin, potato starch and a mixture of these two substances were used for preparing aqueous solutions at a concentration of 4%. They observed that the water loss and solid gain of strawberries coated with low-methylated pectin and pectin–starch mixture were lower than uncoated strawberries. Jalaee *et al*. (2010) studied the influence of different edible coating materials such as low-methoxyl pectinate (LMP), carboxyl-methyl cellulose (CMC), corn starch, and an osmotic sucrose solution with two concentrations of 50% and 60% (w/w) on mass transfer of apple rings. Experimental results showed that coating on apple could be a solution for reducing the solid gain without affecting much on the water removal in comparison with uncoated samples. Apple coated with LMP, CMC and corn starch and osmotic dehydrated in 50% and 60% sucrose solution had lower solid gain than the uncoated sample in the same conditions. The changes in water loss/solid gain of samples depend on the chemical potential or mass transfer driving force of water and solute between sample and osmotic solution. Moreover, the molecular structures of coating materials also influence the rate of water loss/solid gain ratio. The effects of coating with CMC, corn starch and LMP on the water loss/solid gain ratio are different, because the structures of these three edible coatings are also different and permeability of water and solute in these coatings are different. Coating of a sample with CMC and LMP can cause high water loss/solid gain ratio than starch coating, regardless of the concentration of the osmotic solution. This is for acting of CMC and LMP coatings as a good barrier that can decrease the solid gain and somewhat reduce water loss of the samples. Starch coated samples can decrease the level of water removal less than two other coated samples (CMC and LMP). This might be due to the starch coating solution produced low viscosity than CMC and LMP solution, thus it cannot produce good adhering layer to the surface of the samples and cannot improve barrier properties against the water and solid transfer.

Chitosan, a linear polymer of 2-amino-2-deoxy-β-D-glucan, is a deacetylated form if chitin, a naturally occurring cationic biopolymer (Lin and Zhao, 2007). Application of chitosan include as flocculating agent, clarifier, thickener and coating material (Dong, 2000). Application of chitosan as a coating material prior to osmotic dehydration process was studied by Garcia *et al*. (2010). Papaya was selected as a model to study. Papaya cubes (1 cm^3) were divided into three groups depending on the treatments: without chitosan coatings; with chitosan coatings at 1% (w/v) in lactic acid 1% (v/v) and Tween 80 at 0.1% (v/v) and with chitosan coatings at 1% (w/v) in lactic acid 1% (v/v), Tween 80 at 0.1% (v/v) and oleic acid at 2% (v/v). It was observed that coated papaya samples with emulsion presented a lower in solids gain than papaya samples without coating. In the case of the coated papaya, the solids accumulation on the coatings surface, limited its penetration inside the fruits. It did not happen in the sample without coatings, where a great amount of soluble penetrated inside the fruits. The accumulation of solid, together with the use of coatings, may create a crust which constitutes a barrier to mass transfer, limiting the dehydration regime and consequently the solid gain. The above assumptions could explain the difference of dehydration regimes and material transfer between the coated and uncoated samples. This study showed that chitosan coating improved the efficiency of osmotic dehydration process, increasing the water loss and decreasing the solid gain.

In addition, maltodextrin, a polysaccharide can be used as a coating material. Khin *et al*. (2007) studied the effect of maltodextrin coating on mass transfer during osmotic dehydration of apple cubes. The result showed that coated apple cube samples presented a lower in solid gain than the uncoated samples. This probably due to the presence of coating around the sample impeded the uptake of sucrose into the sample or it could be that the diffusion of the coating material into the osmotic medium opposed the movement of the sucrose molecules into the sample.

Alginic acid, also called algin or alginate, is an anionic polysaccharide distributed widely in the cell walls of brown algae, where it, through binding water, forms a viscous gum. It can be used as an edible coating. Singh *et al*. (2010) investigated the effect of edible coating (sodium alginate) on mass transfer during osmotic dehydration of pineapple. Pineapple cubes were coated with 0.5% to 5.0% (w/v) (0.5, 1, 2, 3, 4 and 5%, w/v) sodium alginate solution. The samples coated with sodium alginate resulted in higher water loss and lower solid gain than uncoated samples. Water loss of the coated samples treated with coating solution ranging from 0.5% to 2% were more than the uncoated sample, whereas values of samples coated at 3% to 5% were less than the uncoated samples. The increase in concentration from 3% and above led to low values of water loss and resulted in less water loss than the uncoated samples. This may be attributed to the fact that a high concentration of coating agent resulted in moisture barrier during osmotic dehydration. An increase in the concentration of the coating solution from 0.5 to 2% led to decrease in the solid gain and then increased up to a level of 5%. In addition, water loss/solid gain increased as the concentration of coating agent increased. Increase in the value of water loss/solid gain by using the coating solution indicated that the purpose of coating the pineapple samples was achieved as the coating was performed to increase the water loss and decrease the solid gain. Increase in water loss/solid gain verifies the fact that the coating helps to obstruct the entry of sucrose molecules into the pineapple sample while ensuring the loss of water from the pineapple sample into the osmotic solution during the process of osmotic dehydration. Thus, edible coatings can be used to inhibit extensive solute uptake during osmotic processing of fruit.

Conclusion

Osmotic dehydration is one of the potential preservation techniques for producing high quality products. This provides minimum thermal degradation of nutrients due to low temperature water removal process. To optimise process and product quality, it is important to understand factors affecting mass transfer during osmotic dehydration. Some factors affecting mass transfer during osmotic dehydration are depending on types of osmotic agent, concentrations of osmotic agent, processing temperatures, agitation or stirring process, pretreatment methods and the use of edible coating. Firstly, low molecular weight osmotic agent tends to easier penetrate into the fruit tissue than high molecular weight osmotic agent. In addition, increased osmotic agent concentrations result in the increment of solid gain and water loss. The increase in the processing temperature facilitates the mass transfer process during osmotic dehydration. Additionally, the agitation process had a significant effect on the increase in water loss during osmotic dehydration. Pretreatment methods affect the integrity of natural tissue. It has a severe effect on water loss and solid gain. Blanching, freezing, high pressure, ohmic heating, high intensity electric field pulses and ultrasound favor solid gain. On the other hand, application of hydrophilic coating prior to osmotic dehydration could limit intensive solid gain without a serious negative effect on the rate of water removal. Finally, it can be concluded that factors such as using low molecular weight osmotic agent, high concentration of osmotic agent, high processing temperature, agitation process and pretreatment techniques as mentioned previously can be used to promote mass transfer during osmotic dehydration while the using of edible coating can be applied to reduce a large solute in a product. Therefore, this knowledge can be used to optimise osmotic dehydration process and product quality.

References

Ade-Omowaye, O.I.B., Angersbach, A., Taiwo, A.K. and Knorr, D. 2001. Use of pulsed electric field pretreatment to improve dehydration characteristics of plant beased foods. Trends in Food Science and Technology 12: 285-295.

Allali, h., Marchal, L. and Vorobiev, E. 2010. Effect of vacuum impregnation and ohmic heating with citric acid on the behaviour of osmotic dehydration and structural changes of apple fruit. Biosystem Engineering 106: 6-13.

Allali, h., Marchal, L. and Vorobiev, E. 2010. Blanching of strawberries by ohmic heating: Effects on the kinetics of mass transfer during osmotic dehydration. Food Bioprocess Technology 3: 406-414.

Amami, E., Vorobiev, E. and Kechaou, N. 2006. Modeling of mass transfer during osmotic dehydration of apple tissue pre-treated by pulsed electric field. LWT-Food Science and Technology 39: 1014-1021.

Azoubel, P.M. and Murr, F.E.X. 2004. Mass transfer kinetics of osmotic dehydration of cherry tomato. Journal of Food Engineering 61: 291-295.

Bchir, B., Besbes, S., Attia, H. and Blecker, C. 2011. Osmotic dehydration of pomegranate seeds (*Punica Granatum* L.): Effect of freezing pretreatment.(in press).

Boldwin, E.A. 1995. Edible coatings for lightly processed fruits and vegetables. Journal of Hortscience. 30: 35-37.

Camirand, W., Krochta, J.M., Pavlath, A.E., Wong, D. and Cole, M.E. 1992. Properties of some edible carbohydrate polymer coatings for potential use in osmotic dehydration. Carbohydrate Polymers 17: 39-49.

Chiralt, A. and Talens, P. 2005. Physical and chemical changes induced by osmotic dehydration in plant tissues. Journal of Food Engineering 67: 167-177.

Del Valle, M.J., Aranguiz, V. and Leon, H. 1998. Effect of blanching and calcium infiltration on PPO activity, texture, microstructure and kinetics of osmotic dehydration of apple tissue. Food Research International 31: 557-569.

Devic, E., Guyoi, S. Daudin, J. and Bonazzi, C. 2010. Effect of temperature and cultivar on polyphenol retention and mass transfer during osmotic dehydration of apples. Journal of Agricultural and Food Chemistry 58: 606-614.

Dong, Y., Yuan, Y., Qiu, W., Wu, Y., Wang, M. and Xu, C. 2000. Application of chitin/chitosan and their derivatives in food industry. Food Science and Technology 5: 28-31.

Dornenburg, H. and Knorr, D. 1993. Cellular permeabilisation of cultured plant tissue by high electric field pulse and ultra high pressure for recovery of secondary metabolites. Food Biotechnology 7: 35-48.

El-Aouar, A.A., Azoubel, M.P., Barbosa, L.J. and Murr, X.E.F. 2006. Influence of osmotic agent on the osmotic dehydration of papaya (*Carica papaya* L.). Journal of Food Engineering 75: 267-274.

Emam-Djomech, Z., Dehghannya, J. and Gharabagh, R.S. 2006. Assessment of osmotic process in combination with coating on effective diffusivities during drying of apple slices. Drying Technology 24: 1159-1164.

Erule, U. and Shubert, A. 2001. Combined osmotic and microwave vacuum dehydration of apples and strawberries. Journal of Food Engineering 49: 193-199.

Eshtiaghi, M.N., Stute, R. and Knorr, D. 1994. High pressure and freezing pretreatment effects on drying, rehydration, texture and colour of green beans, carrots and potatoes. Journal of Food Science 59: 1168-1170.

Falade, K.O. and Adelakun, A.T. 2007. Effect of pre-freezing and solutes on mass transfer during osmotic dehydration and colour of oven-dried African star apple during storage. International Journal of Food Science and Technology 42: 394-402.

Falade, K.O., Igbeka, J.C. and Ayanwuyi, F.A. 2007. Kinetics of mass transfer and colour changes during osmotic dehydration of watermelon. Journal of Food Engineering 80: 979-985.

Fernandes, N.A.F. and Rodrigues, S. 2007. Ultrasound as pre-treatment for frying of fruits: dehydration of banana. Journal of Food Engineering 82: 261-267.

Francisa, I.P., Oliveira, M.I. and Gallao, S.F.N. 2010. Dehydration of Malay apple (*Syzygium malaccense* L.) using ultrasound as pre-treatment. Food Bioprocess Technology 4: 610-615.

Fuente-Blanco, S., Sarabia, E.R.F., Acosta-Aparicio, V.M., Blanco-Blanco, A. and Gallego-Juarez, J.A. 2006. Food drying process by power ultrasound. Ultrasonics Sonochemistry 44: 523-537.

Garcia, M., Diaz, R., Martinez, Y. and Casariego, A. 2010. Effects of chitosan coating on mass transfer during osmotic dehydration of papaya. Food Research International 43: 1656-1660.

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

Hughes, R.E., Chichester, C.O. and Sterking, C. 1958. Penetration of maltosaccharides in processed Clingstone Peaches. Food Technology 12: 111-115.

Icier, F., Yildiz, H and Baysal, T. 2006. Peroxidase inactivation and colour changes during ohmic blanching of pea puree. Journal of Food Engineering 74: 424-429.

Ispir, A. and Togrul, T.I. 2009. Osmotic dehydration of apricot: Kinetics and the effect of process parameters. Chemical Engineering Research and Design 87: 166-180.

Jalaee, F., Fazeil, A., Fatemain, H. and Tavakolipour, H. 2010. Mass transfer coefficient and the characteristics of coated apples in osmotic dehydrating. Food and Bioproducts Processing (in press)

Kaymak-Ertekin, F. and Sultanoglu, M. 2000. Modeling of mass transfer during osmotic dehydration of apples. Journal of Food Engineering 46: 243-250.

Khin, M.M., Weibiao, Z. and Perera, C. 2005. Development in the combined treatment of coating and osmotic dehydration of food: a review. International Journal of Food Engineering 1-19.

Khin, M.M., Zhou, W. and Perera, C. 2006. A study of mass transfer in osmotic dehydration of coated potato cubes. Journal of Food Engineering 77: 84-95.

Khin, M.M., Zhou, W. and Perera, C. 2007. Impact of process conditions and coatings on the dehydration efficiency and cellular structure of apple tissue during osmotic dehydration. Journal of Food Engineering 79: 817-827.

Khin, M.M., Zhou, W. and Yeo, S. 2007. Mass transfer in the osmotic dehydration of coated apple cubes by using maltodextrin as the coating material and their textural properties. Journal of Food Engineering 81: 514-522.

Kowalska, H., Lenart, A. and Leszczyk. D. 2008. The effect of blanching and freezing on osmotic dehydration of pumpkin. Journal of Food Engineering 86: 30-38.

Lazarides, H.N. 2001. Reasons and possibilities to control solid uptake during osmotic treatment of fruit and vegetables. In Fito, P., Chiralt, A., Barat, M.J., Spiess, E.W. and Behsnillian, D. Osmotic dehydration and vacuum impregnation. Technomic Publishing Company. USA.

Lazarides, H.N., Katsanides, E. and Nicolaides, A. 1995. Mass transfer kinetics during osmotic preconcentration aiming at minimal solid uptake. Journal of Food Engineering 25: 151-166.

Lazarides, H.N. and Mavroudis, N.E. 1995. Freeze/thaw effects on mass transfer during osmotic dehydration. Journal of Food Science 60: 826-828.

Le Maguer, M., Shi, J. and Fernandez, C. 2003. Characterization of mass transfer behaviour of plant tissues during osmotic dehydration. Food Science and Technology International 9: 187-192.

Lenart, A. and Debrowska, R. 1997. Osmotic dehydration of apples with polysaccharides coatings. Poland Journal of Food and Nutrition Science 6: 103-111.

Lenart, A. and Debrowska, R. 1999. Kinetics of osmotic dehydration of apples with pectin coatings. Drying Technology 17: 1359-1373.

Lenart, A. and Flink, J.M. 1984. Osmotic concentration of potato. II. Spatial distribution of the osmotic effect. Journal of Food Technology 19: 65-89.

Lerici, C.R., Pinnavaia, G., Dalla Rosa, M. 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.

Lin, D. and Zhao, Y. 2007. Innovations in the development and application of edible coatings for fresh and minimally processed fruits and vegetables. Food Science and Food Safety 6: 60-75.

Matusek, A. Czukor, B. and Meresz, P. 2008. Comparison of sucrose and fructo-oligosaccharides as osmotic agents in apple. Innovative Food Science and Emerging Technologies 9: 365-373.

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

Mavroudis, N.E., Gekas, V. and Sjoholm, I. 1998. Osmotic dehydration of apple-effects of agitation and raw material characteristics. Journal of Food Engineering 35: 191-209.

Moreira, R., Chenlo, F., Torres, M.D. and Vazquez, G. 2007. Effect of stirring in the osmotic dehydration of chestnut using glycerol solutions. LWT-Food Science and Technology 40: 1507-1514.

Mundada, M., Hathan, S.B. and Maske, S. 2011. Mass transfer kinetics during osmotic dehydration of pomegranate arils. Journal of Food Science 76: 31-39

Ogonek, A. and Lenart, A. 2001. Influence of selective edible coatings on osmotic dehydration of strawberries (in polish). Zywnose 28: 62-74.

Pattanapa, K., Therdthai, N., Chantrapornchai, W. and Zhou, W. 2010. Effect of sucrose and glycerol mixtures in the osmotic solution on characteristics of osmotically dehydrated mandarin cv. (Sai-Namphaung). International Journal of Food Science and Technology 45: 1918-1924.

Praporsoic, I., Lebovka, N.I., Ghnimi, S. and Vorobiev, E. 2006. Ohmically heated, enhanced expression of juice from soft Engineering. 93: 199-204.

Rastogi, N.K., Angersbach, A. and Knorr, D. 2000. Synergistic effect of high hydrostatic pressure pretreatment and osmotic stress on mass transfer during osmotic dehydration. Journal of Food Engineering 45: 25-31.

Rastogi, N.K., Eshtiaghi, N.M. and Knorr, D. 1999. Accelerated mass transfer during osmotic dehydration of high intensity electrical field pulse pretreated carrots. Journal of Food Science 64: 1020-1023.

Rastogi, N.K. and Niranjan, K. 1998. Enhanced mass transfer during osmotic dehydration of high pressure treated pineapple. Journal of Food Science 63: 508-511.

Rastogi, N.K., Raghavarao, K.S.M.S., Niranjan, K. and Knorr, D. 2002. Recent developments in osmotic dehydration: methods to enhance mass transfer. Trends in Food Science and Technology 13: 48-59.

Sastry, S.K. and Li, Q. 1996. Modelling the ohmic heating of foods. Food Technology 50: 246-248.

Shi, X.Q. and Fito, P.M. 1994. Mass transfer in vacuum osmotic dehydration of fruits: mathematical model approach. LWT-Food Science and Technology 27: 67-72.

Shi, J. and Xue, J.S. 2009. Application and development of osmotic dehydration technology in food processing. In Ratti, C. (Ed). Advances in food dehydration. CRC Press. USA.

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

Singh, C., Sharma, K.H. and Sarkar, C.B. 2010. Influence of process conditions on the mass transfer during osmotic dehydration of coated pineapple samples. Journal of Food Processing and Perservation 34: 700-714.

Taiwo, A.K., Eshtiaghi, N.M., Ade-Omowaye, O.I.B. 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.

Tangwongchai, R., Ledward, D.A. and Ames, J.M. 2000. Effect of high pressure treatment on the texture of cherry tomato. Journal of Agricultural and Food Chemistry 48: 1434-1441.

Tedjo, W., Taiwo, K.A., Eshtiaghi, M.N. and 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 fruits and vegetable processing. Food Research International 26: 59-68.