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Osmotic dehydration in fruit and vegetable processing

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The basic principles which control osmotic dehydration of fruit and vegetables are reported together with the most important parameters and their influence on the process.

The effects of osmosis as a pre-treatment, mainly related to the improvement of nutritional, sensorial and functional properties of the products, are analyzed. The distinctive aspect of this process, when compared to other dehydration methods, is the 'direct formulation' achievable through the selective incorporation of solutes, without modifying the food integrity. By balancing the two main osmotic effects, water loss and soluble solids uptake, the functional properties of fruit and vegetables could be adapted to many different food systems.

Present applications of the process are shown and problems related to a further industrial development are analyzed.

Keywords: osmotic-dehydration, drying, freezing, appertization, quality, fruit, vegetables.

INTRODUCTION

Osmotic dehydration is a useful technique for the concentration of fruit and vegetables, realized by placing the solid food, whole or in pieces, in sugars or salts aqueous solutions of high osmotic pressure. It gives rise to, at least, two major simultaneous counter-current flows: an important water flow out of the food into the solution and a simultaneous transfer of solute from the solution into the food (Fig. 1), which are both due to the water and solute activity gradients across the cell's membrane.

In an ideal osmotic situation a semi-permeable membrane would be permeated by the solvent molecules but not by the solute molecules. In fruits or vegetables, the cell wall membranes are living biological units which can stretch and expand under the influence of growth and turgor pressure generated inside the cells. These cellular membranes, which are composed mainly of parenchyma cells, freely allow the solvent molecules to pass through but they also allow, to a lesser degree, the passage of some of the solute molecules. This type of membrane could be classified differentially permeable, rather than semi-permeable.

In natural food systems there is also some leakage of solute (sugars, organic acids, minerals, salts, etc.) across the membrane. Though quantitatively negligible, it may be essential as far as organoleptic or nutritional qualities are concerned.

Therefore, compared to single drying processes, osmotic dehydration achieves a twofold transformation of the food item, by both a decrease in water content and a solute incorporation, which may result in a subsequent weight reduction.

Some of the osmotic syrup may not actively migrate into the cells but may simply penetrate into the intercellular spaces, because of the wide modification of the permeability and selectivity of the tissue structures due to maturity and storage conditions or heat and chemical pre-treatments.

This 'impregnation' effect may be important (Monzini & Maltini, 1986; Maltini *et al.*, 1992) and the term 'dewatering–impregnation soaking in concentrated solutions' (DII) instead of 'osmotic

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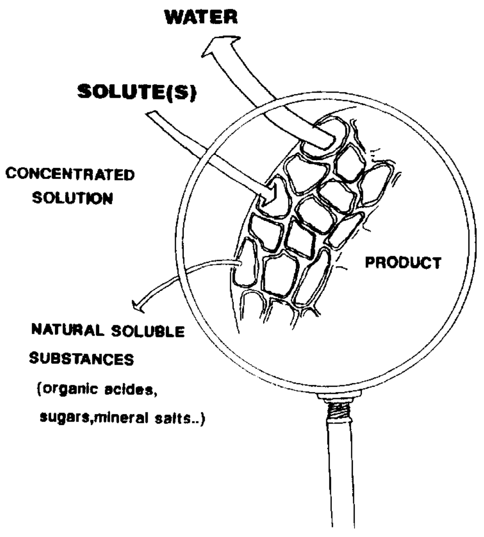

Fig. 1. Mass transport phenomena during the osmotic process.

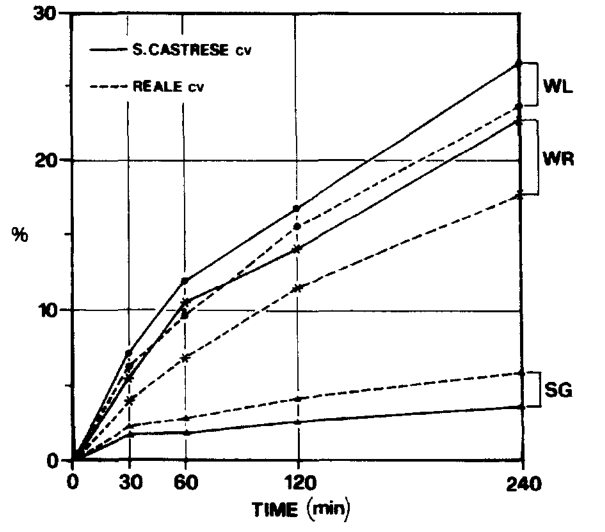

Fig. 2. Water loss (WL), weight reduction (WR) and solid gain (SG), g/100 g fresh fruit, during osmotic dehydration at room temperature of two cultivars of apricot (halved).

dehydration' has been recently proposed by Raoult-Wack and Guilbert (1990).

Through the incorporation of solute into the food system it is possible, to a certain extent, to change its nutritional and functional properties, achieving a specific formulation of the product without modifying its integrity. This 'direct formulation', together with a partial dehydration, is the distinctive aspect of the process when compared to other dehydration methods.

Old techniques such as candying or salting are based on the same principles of osmotic dehydration, but generally they are long-term processes and they favour the solute penetration and limit the water removal.

Recently, wider prospects for osmotic dehydration have arisen as a pre-step to further processing.

PROCESS VARIABLES

The influence of the main process variables (pre-treatments, temperature, nature and concentration of the dehydration solutions, agitation, additives, etc.) on the mass transfer and on the product quality have been reviewed by Ponting *et al.* (1966), Karel (1975) and more recently by Lerici *et al.* (1985*b*), Le Maguer (1988) and Raoult-Wack and Guilbert (1990).

In the light of published literature, some general rules can be pointed out.

Water loss and solid gain are mainly controlled by the raw material characteristics (Fig. 2) (Torreggiani *et al.*, 1986*a,b*, 1988*a,b*), certainly influenced by the possible pre-treatments. The great variability observed among the different fruits is mostly related to the tissue compactness (Giangiacomo, 1987), initial insoluble and soluble solid content (Lenart & Flink, 1984*a,b*), intercellular spaces, presence of gas, ratio between the different pectic fractions (water soluble pectin and protopectin) (Forni *et al.*, 1986), gelification level of pectin (Moy *et al.*, 1978) and enzymatic activity (Giangiacomo *et al.*, 1987) of the fruit.

It is usually not worthwhile using osmotic dehydration for more than a 50% weight reduction because of the decrease in the osmosis rate with time. Water loss mainly occurs during the first 2 h and the maximum solid gain within 30 min (Conway *et al.*, 1983; Torreggiani *et al.*, 1986*a,b* 1988*a,b*; Giangiacomo *et al.*, 1987; Guenneugues, 1986).

The rate of mass exchanges increases with temperature but above 45°C enzymatic browning and flavour deterioration begins to take place. High temperatures, i.e. over 60°C, modify the tissue characteristics so favouring impregnation phenomena and thus the solid gain (Farkas & Lazar, 1969; Bongirwar & Sreenivasan, 1977; Lenart & Flink, 1984*b*; Heng *et al.*, 1990; Lenart & Lewicki, 1990*a,b*; Vial *et al.*, 1991). High temperature short time (HTST) treatments, at 80–85°C for 1–3 min, combine the osmotic effect with enzymatic inactivation by blanching (Lerici *et al.*, 1986).

The best processing temperature depends on the food: for example for green beans (Biswal *et al.*,

1991) 40°C is too high a temperature and 20°C gives better results.

Acceleration of water loss without modification of sugar gain when temperature is increased, has been observed by many authors (Ponting, 1966; Bongirwar & Sreenivasan, 1977; Hawkes & Flink, 1978; Islam & Flink, 1982; Vial *et al.*, 1991). The phenomenon is essentially due to the diffusional differences between water and sugar as related to their different molar masses. Raoult-Wack *et al.* (1989) describe an antagonistic effect of water and solute transfers, probably due to the combination of sugar penetration by diffusion and sugar transportation by the water flow, as a function of the water flow rate.

Mass exchanges are favoured by using high concentration solutions (Ponting *et al.*, 1966; Farkas & Lazar, 1969; Bongirwar & Sreenivasan, 1977; Heng *et al.*, 1990; Videv *et al.*, 1990; Vial *et al.*, 1991) and by reducing the particle size of the fruit up to a certain level, above which solid gain is highly favoured (Islam & Flink, 1982; Lerici *et al.*, 1985*a*). Increasing the solution concentration favours water loss more than solid gain (Ponting *et al.*, 1966; Hawkes & Flink, 1978; Islam & Flink, 1982; Conway *et al.*, 1983; Lenart & Flink, 1984*a*; Pavasovic *et al.*, 1986; Raoult-Wack & Guilbert, 1990).

Phenomena which modify the tissue permeability, such as overripeness, pre-treatments with chemicals (SO_2), blanching or freezing, favour the solid gain compared to water loss because impregnation phenomena are enhanced: permeability increases and selectivity decreases (Ponting, 1973; Karel; 1975; Islam & Flink, 1982).

The kind of sugar utilized as osmotic substance strongly affects the kinetics of water removal, the solid gain and the equilibrium water content. By increasing the molar mass of the solutes, a decrease of solid gain and an increase of water loss is obtained, so favouring weight loss and the 'dehydration' aspect of the process (Contreras & Smyrl, 1981; Islam & Flink, 1982; Bolin *et al.*, 1983; Lerici *et al.*, 1985*a*; Heng *et al.*, 1990). Low molar mass saccharides (glucose, fructose, sorbitol etc.) favour the sugar uptake because of the high velocity of penetration of the molecules so that solid enrichment instead of dehydration is the main effect of the process.

Addition of NaCl to osmotic solutions increases the driving force for drying owing to the a_w lowering capacity of the salt. Synergistic effects between sugar and salt have also been observed (Lenart & Flink, 1984*b*).

APPLICATIONS

The effects of osmotic dehydration as a pre-treatment are mainly related to the improvement of some nutritional, organoleptic and functional properties of the product.

As osmotic dehydration is effective at ambient temperature, heat damage to color and flavor is minimized and the high concentration of the sugar surrounding fruit and vegetable pieces prevents discoloration.

Furthermore, through the selective enrichment in soluble solids high quality fruit and vegetables

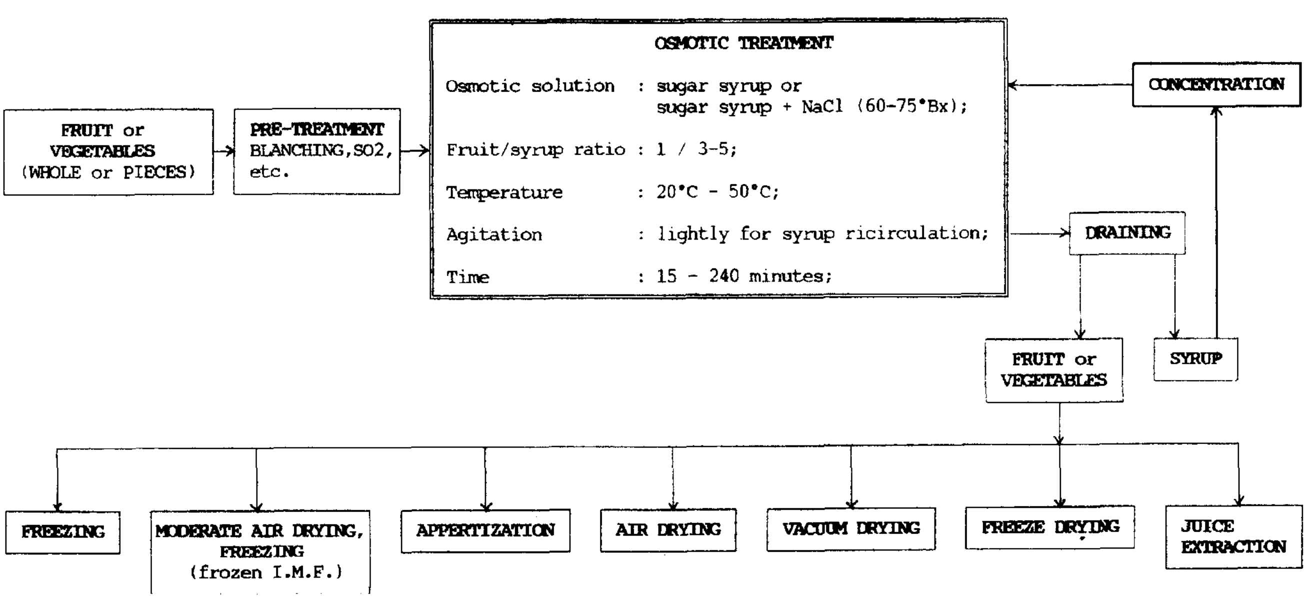

Fig. 3. Applications of osmotic dehydration in fruit and vegetable processing.

are obtained with functional properties 'compatible' with different food systems.

These effects are obtained with a reduced energy input over traditional drying process. The main energy-consuming step is the reconstitution of the diluted osmotic solution that could be obtained by concentration using multiple-effect evaporators or by addition of sugar. In the first case only about 25% as much energy is required for water removal, as compared to conventional hot air dehydration (Huxsoll, 1982; Bolin *et al.*, 1983; Lenart & Lewiki, 1988*b*). In the second the cost is regained as 'solid gain' in the end product.

Various applications of the technique as a unit operation in the food area are summarized in Fig. 3 together with the processing parameters regarded as optimal in the light of the published literature.

Drying

Air drying following osmotic dipping is commonly used in tropical countries for the production of so-called 'semi-candied' dried fruits. The combination has also been proposed by many authors (Ponting *et al.*, 1966; Jackson & Mohamed, 1971; Bongirwar & Sreenivasan, 1977; Speck *et al.*, 1977; Nanjundaswamy *et al.*, 1978; Islam & Flink, 1982; Lerici *et al.*, 1983, 1988; Mazza, 1983; Lenart & Lewicki, 1988*a,b*; Guilbert, 1989; Crivelli *et al.*, 1989; Kim, 1990; Riva & Masi, 1990; Shahab Uddin *et al.*, 1990; Maltini *et al.*, 1991).

The sugar uptake, owing to the protective action of the saccharides, limits or avoids the use of SO_2 (Ponting *et al.*, 1966; Crivelli *et al.*, 1989; Maltini *et al.*, 1991) and increases the stability of pigments during processing and subsequent storage period (Kim, 1990).

The organoleptic qualities of the end product could also be improved because some of the acids are removed from the fruit during the osmotic bath, so a blander and sweeter product than ordinary dried fruits is obtained (Ponting *et al.*, 1966).

Comparing osmodehydrated products to fresh ones, they present lower water removal rates (Islam & Flink, 1982; Lerici *et al.*, 1988). When water activities of 0·6–0·7 have to be reached, the drying time is shortened by 10–65%, depending on the kind of material, osmotic substance and the time of osmotic treatment (Lenart & Lewicki, 1988*b*; Lerici *et al.*, 1988).

Owing to weight and volume reduction, loading of the drier can be increased 2–3 times (Lenart & Lewicki, 1988*b*). Furthermore the solid gain increases the total yield.

Using high temperature fluidized bed (HTFB) dehydration of osmotically dehydrated blueberries, fruits with a soft and raisin-like texture were obtained by Kim and Toledo (1987). With the same technique, apples were simultaneously puffed and dried and a crunchy and sulfur-free fruit was obtained, suitable for such products as cereal flakes (Torreggiani & Toledo, 1990).

The combination of osmosis with solar drying has been put forward, mainly for tropical fruit (Islam & Flink, 1982; Levi *et al.*, 1983).

A 24-h cycle has been suggested combining osmodehydration, performed during the night, with solar drying during the day (Islam & Flink, 1982).

To obtain dried tropical fruits, Mujumdar & Grabowski (1991) indicated a number of schemes to accomplish solar assisted concentration of the spent syrup, which is recirculated for osmotic dehydration, and subsequent solar drying of the partially dehydrated fruit. Two–three-fold increase in the throughput of typical solar driers is feasible, while enhancing the nutritional and organoleptic quality of the fruits.

Osmotic dehydration followed by vacuum drying was proposed by Ponting (1973), Dixon *et al.* (1976), Bongirwir and Sreenivasan (1977), Dixon & Jen (1977), Moy *et al.* (1978), Ramamurthy *et al.* (1978), Jezek & Smyrl (1980), Adambounou and Castaigne (1983). Puffy products with a crisp, honeycomb-like texture can be obtained at a cost comparatively less than freeze-drying.

Commercial feasibility of the process on bananas has been studied, based on the results of semi-pilot plant-scale operations (Bongirwar & Sreenivasan, 1977). The process scheme is reported in Figure 4. Osmotically dried bananas retained more puffiness and a crispier texture than simple vacuum dried ones, and the flavour lasted longer (1 year instead of 2 months) at ambient temperature. The natural flavor is retained even better than in freeze-drying and color remains bright with reduced sulfur dioxide treatment.

The combination of osmotic dehydration with freeze-drying has been proposed only at laboratory scale (Lee *et al.*, 1967; Flink, 1975, 1980; Lerici *et al.*, 1977; Hawkes & Flink, 1978). Owing to the solid gain and the volume reduction of the osmodehydrated products there is a threefold increase in the freeze-drier load and the process yield. An increase of up to 25% of soluble solids content greatly improves the retention of volatiles.

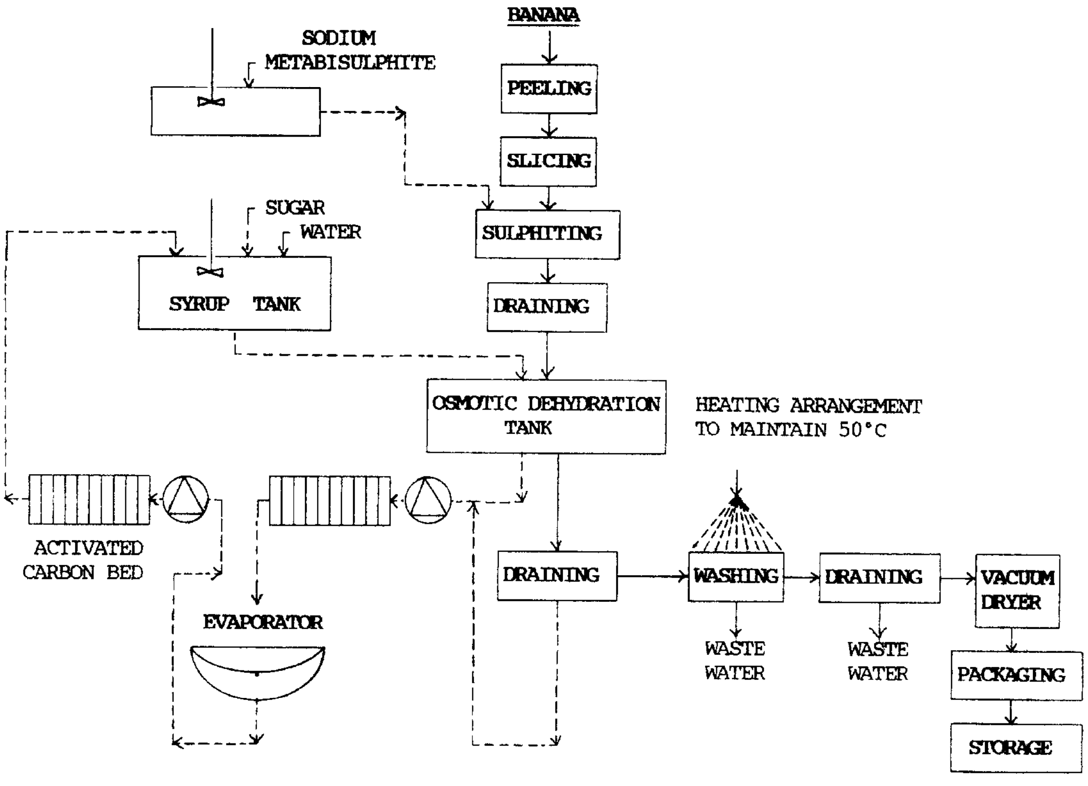

Fig. 4. Flow diagram for osmotic dehydration and vacuum drying of bananas (Bongirwar & Sreenivasan, 1977).

Recently a raisin-type product has been prepared from low bush blueberries combining osmodehydration, freeze-drying with abrupt release of vacuum and thermal plasticizing (Yang *et al.*, 1987). Final products exhibit good flavour, texture and overall quality and a long shelf stability.

Combined processes

A 'combined' process in which a limited air dehydration step is preceded by an osmotic treatment in sugar solutions has been proposed for the preparation of a new type of fruit ingredient at reduced water activity (0·7–0·8) called 'frozen intermediate moisture fruits' (FIMF) (Torreggiani *et al.*, 1988*c*). Blanching of the raw fruit and storage at freezing temperature for long-term preservation are also part of the process.

Compared to simple air dehydration, a softer dried product could be obtained (Fig. 5), more pleasant to eat out of the hands as a snack item or to incorporate in such products as pastry, ice cream, etc. If a concentrated fruit juice is used as osmotic solution, an even softer product is obtained (Fig. 5) because of the higher content of monosaccharides in the fruit juices compared to that of syrups from starch hydrolysis, and the higher relative water content at a determined a_w. The product is totally of fruit origin and this feature may be relevant under the merceological aspects (Maltini *et al.*, 1990).

'FIMF', have to be stored at freezing temperature to avoid the use of chemicals, preservatives and/or heat treatments usually needed for intermediate moisture foods. However, an ice phase will hardly ever form in this product, as in a frozen

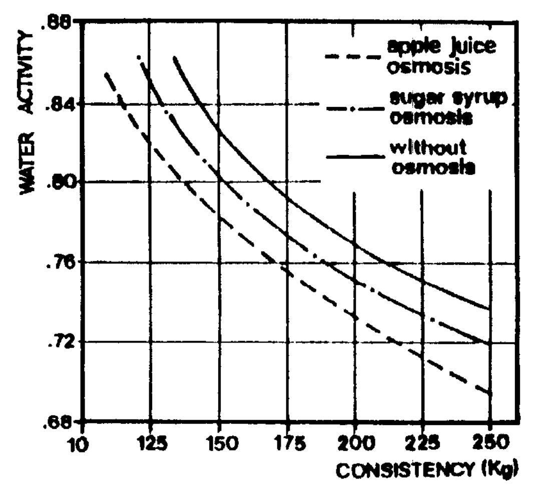

Fig. 5. Consistency index of processed apples cubes as related to their final water activity (Torreggiani *et al.*, 1988*c*).

system the equilibrium water activity, which is only temperature dependent, is 0·84 at −18°C and 0·78 at −25°C, thus higher than that of the products.

Considering the economics of the process, there is no latent heat to be removed in the freezing step and dehydration reduces the volume to be stored from one half to one third of the original.

A wide range of water and soluble solids contents in the final products could be achieved in order to prepare fruit ingredients with functional properties suitable for specific food systems.

The 'suitability' of food ingredients is mainly dependent on water activities of components to avoid diffusion of moisture between the fruit and the food and to control the product's shelf life. A typical case of detrimental moisture diffusion is the soggy pastry in fruit pie. On the other hand, in same cases, a controlled rate of moisture uptake by the partially dehydrated fruit pieces is useful, for example to avoid whey separation in yogurt containing fruit (Torreggiani *et al.*, 1991*b*).

The specific role of the osmotic pre-step in the proposed process is the enrichment in soluble solids, rather than the removal of water. In this way a lowering of the water activity, which is dependent on soluble solids concentration, is obtained with only a limited decrease in the water content and thus a limited increase of consistency. Texture, in fact, is associated with the plasticizing and swelling effect of water on the pectic and cellulosic matrix of the fruit tissue, so it mainly depends on the insoluble solid and water content rather than on soluble solids and water activity. By favouring the soluble solid uptake, lower water activities may be achieved while maintaining an acceptable consistency.

On this basis, the relationship existing among processing, phase composition after processing,

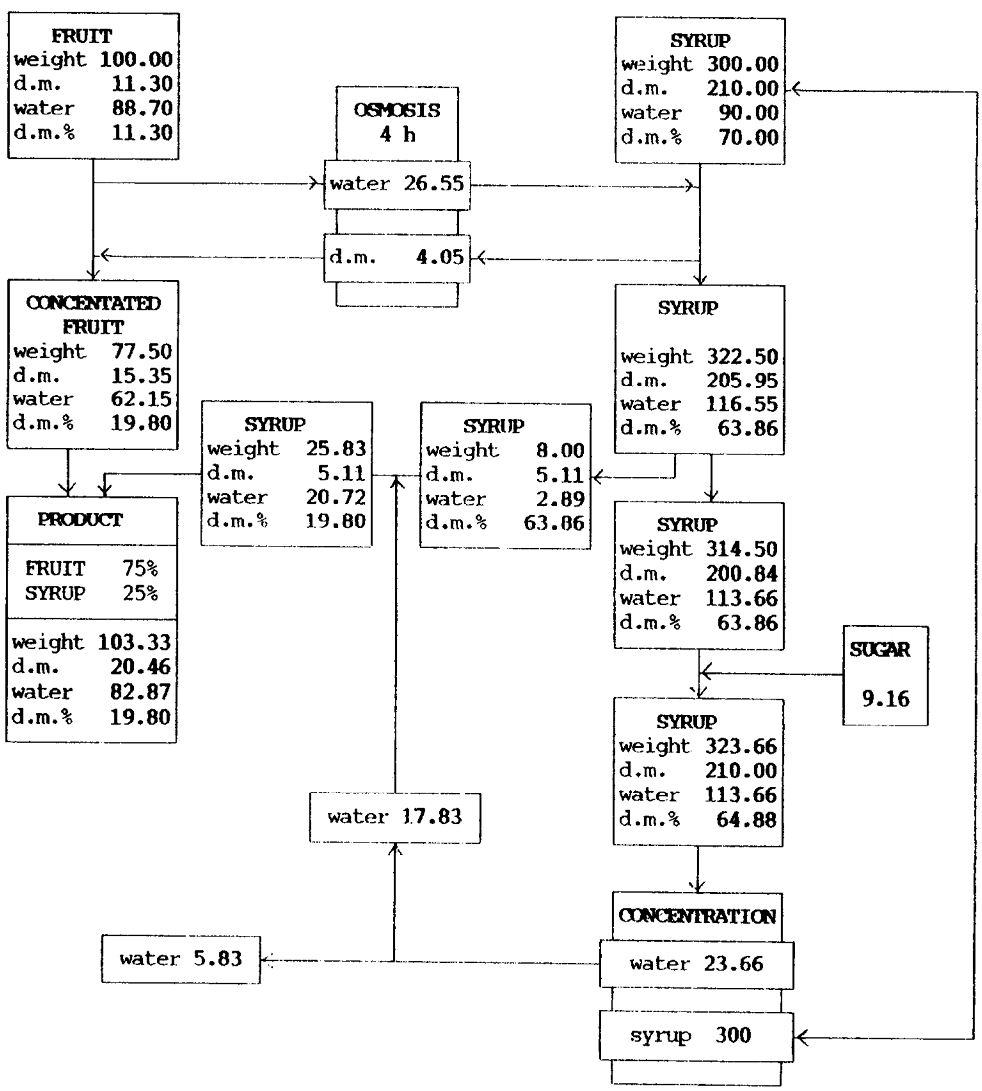

Fig. 6. Weight balance flow sheet of osmo-appertization of peach slices (Maltini & Torreggiani, 1985).

and functional properties have been defined for some fruits (Maltini *et al.*, 1992). Functional properties are expressed as diagrams relating the phase composition (soluble solids, insoluble solids and water) and the range of consistencies obtainable at various water activities.

Appertization

A combination of osmotic dehydration with appertization has been proposed to improve canned fruit preserves (Andreotti *et al.*, 1985).

The feasibility of a process, called osmo-appertization, to obtain high quality fruit in syrup, has been assessed on a pilot plant scale (Maltini & Torreggiani, 1985; Forni *et al.*, 1986; Torreggiani *et al.*, 1986*a,b*, 1988*a,b*, 1990*b*; Crivelli *et al.*, 1989; Senesi *et al.*, 1989). The weight balance scheme is reported in Figure 6.

The key point of this technique is the pre-concentration of the fruit to about 20–24°Brix, that causes, together with the enhancement of the natural flavor, an increase of the resistance of the fruit to the following heat treatment, especially for color and texture stability. The products obtained are stable up to 12 months at room temperature and show a higher organoleptic quality than canned preserves. Furthermore, because of their higher specific weight and diminished volume, the filling capacity of jars or pouches is increased.

Freezing

The frozen fruit and vegetable industry uses much energy in order to freeze the large quantity of water present in fresh product. As pointed out by Huxsoll (1982), a reduction in moisture content of the material reduces refrigeration load during freezing. Other advantages of partially concentrating fruits and vegetables prior to freezing include savings in packaging and distribution costs and achieving higher product quality because of the marked reduction of structural collapse and dripping while thawing.

The products obtained are termed 'dehydrofrozen' and the concentration step is generally realized through conventional air drying, whose additional cost has to be taken into account.

Osmotic dehydration could be used instead of air drying to obtain an energy saving or a quality improvement especially for fruit and vegetables sensitive to air drying (Farkas & Lazar, 1969; Huxsoll, 1982; Andreotti *et al.*, 1983, 1985; Tomasicchio *et al.*, 1986; Forni *et al.*, 1990; Pinnavaia *et al.*, 1988; Biswal & Bozorgmehr, 1989; Garrote & Bertone, 1989; Tomasicchio & Andreotti, 1990; Biswal *et al.*, 1991; Torreggiani *et al.*, 1991*a*).

Air dehydration to about 50% weight reduction of kiwi fruit, even at 45–50°C, causes considerable color and consistency defects. A 'yellowing' of the fruit is observed together with a 'woody' texture (Torreggiani *et al.*, 1987). A 2-h osmotic treatment at room temperature gives high quality dehydrofrozen kiwi fruit in terms of natural color and flavor. Sugar uptaken during osmosis protect the color during storage at −20°C up to 9 months (Forni *et al.*, 1987).

The osmosis temperature could be increased up to 40°C without detrimental effects on the organoleptic (color) and nutritional (ascorbic acid) characteristics of kiwi fruit (Vial *et al.*, 1991).

Extraction of juices

According to Guilbert *et al.* (1990) an osmotic pre-step before juice extraction gives highly aromatic fruit or vegetable juice concentrates.

This technique has also been proposed for wine musts. The acid and astringent compounds are reduced, improving the sugar/acid ratio. The wine obtained from the fermentation of this 'modified' must shows better organoleptic qualities (Vyas *et al.*, 1989; Moutounet *et al.*, 1991).

FURTHER DEVELOPMENTS

So far only applications on a pilot plant scale are reported in the literature. For further developments on a larger scale, theoretical and practical problems should be solved.

In the last few years numerous studies have been undertaken on the osmotically induced mass transfers (Conway *et al.*, 1983; Magee *et al.*, 1983; Lewicki *et al.*, 1984; Biswal & Bozorgmehr, 1988; Raoult-Wack, 1988, 1991; Biswal & Le Maguer, 1989; Raoult-Wack *et al.*, 1989, 1991*a,b,c*; Toupin & Le Maguer, 1989; Toupin *et al.*, 1989; Beristain *et al.*, 1990; M'Rani, 1990; Isse & Schubert, 1991), but a full understanding and a mathematical modeling of the mechanisms involved in simultaneous interacting counter-current flows is still lacking.

The industrial application of the process faces engineering problems related to the movement of great volumes of concentrated sugar solutions and to equipment for continuous operations. The use of highly concentrated sugar solutions creates two major problems. The syrup's viscosity is so great that agitation is necessary in order to decrease the resistance to the mass transfer on the solution side. The difference in density between the solutions (about 1·3 kg/liter) and fruit and vegetables (about 0·8 kg/liter), makes the product float.

Brimelow & Brittain (1977) and Pavasovic *et al.* (1986) have proposed continuous equipment based on a column with hydraulic transport in co-current and in counter-current, while Hong & Le Maguer (1989) used a pilot-scale belt-type continuous contactor in a counter-current osmotic dehydration. The latter was divided into three sections and the solution was sprayed on the top of carrot cubes and recirculated in each section.

Another important aspect, so far not investigated, is the microbial safety of the process, which should be studied thoroughly before further industrial development.

REFERENCES

Adambounou, T. L. & Castaigne, F. (1983). Déshydratation partielle par osmose des bananes et détermination de courbes de sorption isotherme. *Labensm.-Wiss.u.-Technol.*, **16**, 230–52.

Andreotti, R., Tomasicchio, M. & Macchiavelli, L. (1983). Disidratazione parziale della frutta per osmosi. *Industria Conserve*, **58**, 90–95.

Andreotti, R., Tomasicchio, M., De Giorgi, A. & Palmas, D. (1985). Conservazione di pesche parzialmente disidratate per osmosi diretta. *Industria Conserve*, **60**, 96–8.

Beristain, C. I., Azuara, E., Cortes, R. & Garcia, H. S. (1990). Mass transfer during osmotic dehydration of pineapple rings. *Int. J. Food. Sci. Technol.*, **25**, 576–82.

Biswal, R. N. & Bozorgmehr, K. (1988). Mass transfer in osmotic dehydration with sodium chloride. International Summer Meeting of the ASAE, paper no. 88–6015.

Biswal, R. N. & Bozorgmehr, K. (1989). Intermediate moisture frozen vegetables through osmotic dehydration. In *Proc. Int. Conf. 'Technological Innovations in Freezing and Refrigeration of Fruit and Vegetables'*, 9–12 July, Davis, California, USA, pp. 259–65.

Biswal, R. N. & Le Maguer, M. (1989). Mass transfer in plant materials in contact with aqueous solutions of ethanol and sodium chloride equilibrium data. *J. Food Process Eng.*, **11**, 159–76.

Biswal, R. N., Bozorgmehr, K., Tompkins, F. D. & Liu, X. (1991). Osmotic concentration of green beans prior to freezing. *J. Food Sci.*, **56**, 1008–12.

Bolin, H. R., Huxsoll, C. C., Jackson, R. & Ng, K. C. (1983). Effect of osmosis agents and concentration on fruit quality. *J. Food Sci.*, **48**, 202–5.

Bongirwir, D. R. & Sreenivasan, A. (1977). Studies on osmotic dehydration of bananas. *J. Food Sci Technol. India*, **14**, 104–12.

Brimelow, C. J. B. & Brittain, J. E. (1977). Procédé et appareil pour imprégnation d'un matiére alimentaire. Nestlè SA, brevet no. 4004/1976, Int. CI. A 23 PI/100, A 23B7/100, BOPI 34.

Contreras, J. M. & Smyrl, T. G. (1981). An evaluation of osmotic concentration of apple rings using corn syrup solids solutions. *Can. Inst. Food Sci. Technol. J.*, **14**, 301–14.

Conway, J., Castaigne, F., Picard, G. & Voxan, X. (1983). Mass transfer considerations in the osmotic dehydration of apples. *Can. Inst. Food Sci. Technol. J.*, **16**, 25–9.

Crivelli, G., Torreggiani, D., Senesi, E., Forni, E., Bertolo, G. & Maestrelli, A. (1989). Researches on the osmotic dehydration of apricots. In *IX Int. Symposium on Apricot Culture*, Caserta, Italy, p. 146.

Dixon, G. M. & Jen, J. J. (1977). A research note—changes of sugar and acids of osmo-dried applies slices. *J. Food Sci.*, **42**, 1126–7.

Dixon, G. M., Jen, J. J. & Paynter, V. A. (1976). Tasty apple slices result from combined osmotic-dehydration and vacuum-drying process. *Food Product Development*, **10**, 60–66.

Farkas, D. F. & Lazar, M. E. (1969). Osmotic dehydration of apple pieces: effect of temperature and syrup concentration on rates. *Food Technol.*, **23**, 688–90.

Flink, J. M. (1975). Process conditions for improved flavor quality of freeze dried foods. *J. Agr. Food Chem.*, **23**, 1019–26.

Flink, J. M. (1980). Dehydrated carrot slices: influence of osmotic concentration on drying behaviour and product quality. *Food Process Eng.*, **1**, 412–18.

Forni, E., Torreggiani, D., Battiston, P. & Polesello, A. (1986). Research into changes of pectic substances in apricots and peaches processed by osmotic dehydration. *Carbohydrate Polymers*, **6**, 379–93.

Forni, E., Torreggiano, D., Crivelli, G., Maestrelli, A., Bertolo, G. & Santelli, F. (1990). Acta horticulturae n. 282, ed. A. R. Ferguson, ISHS, Wageningen, The Netherlands, pp. 425–34.

Garrote, R. L. & Bertone, R. A. (1989). Osmotic concentration at low temperature of frozen strawberry halves. Effect of glycerol, glucose and sucrose solutions on exudates loss and thawing. *Lebensm.-Wiss.u.-Technol.*, **22**, 264–7.

Giangiacomo, R., Torreggiani, D. & Abbo, E. (1987). Osmotic dehydration of fruit: Part 1. Sugars exchange between fruit and extracting syrups. *J. Food Proc. Pres.*, **11**, 183–95.

Guenneugues, P. (1986). Etude thermodynamique des transfers de masse en déshydratation osmostique. DEA, ENSIA, Massy, France.

Guilbert, S. (1989). Procédés de fabrication de tranches semi-confites de kiwi-fruits. Brevet européen 89/440055.

Guilbert, S., Perez, A. & Crouzet, J. (1990). Procédé de fabrication de concentré de fruits ou légumes, notamment de tomate, Brevet francais 90/04634.

Hawkes, J. & Flink, J. M. (1978). Osmotic concentration of fruit slices prior to freeze dehydration. *J. Food Proc. Pres.*, **2**, 265–84.

Heng, W., Guilbert, S. & Cuq, J. L. (1990). Osmotic dehydration of papaya: influence of process variables on the quality. *Sciences des Aliments*, **10**, 831–48.

Hong, Q. & Le Maguer, M. (1989). Osmotic study of carrot cubes in a continuous counter-current process. In *Proc. Fifth Int. Cong. Engineering and Food (ICEF 5)*, Cologne, Germany, p. 177.

Huxsoll, C. C. (1982). Reducing the refrigeration load by partial concentration of food prior to freezing. *Food Technol.*, **5**, 98–102.

Islam, M. N. & Flink, J. N. (1982). Dehydration of potato II. Osmotic concentration and its effect on air drying behaviour. *J. Food Technol.*, **17**, 387–403.

Isse, M. G. & Schubert, H. (1991). Osmotic dehydration of mango: mass transfer between mango and syrup. 4ème Congrès Mondial de Génie Chimique, June 1991, Karlsruhe, Germany.

Jackson, T. H. & Mohamed, B. B. (1971). The shambat process—New development arising from the osmotic dehydration of fruits and vegetables. *Sudan J. Food Sci. Technol.*, **3**, 18–23.

Jezek, E. & Smyrl, T. G. (1980). Volatile changes accompanying dehydration of apples by the Osmovac process. *Can. Inst. Food Sci. Technol. J.*, **13**, 43–4.

Karel, M. (1975). Osmotic drying. In *Principles of Food Science—Part II*, ed. O. R. Fennema, M. Dekker, New York, pp. 348–57.

Kim, M. H. (1990). Osmotic concentration of apples and its effect on browning reaction during air dehydration. *J. Korean Soc. Food Nutrition*, **19**, 121–6.

Kim, M. H. & Toledo, R. T. (1987). Effect of osmotic dehydration and high temperature fluidized bed drying on properties of dehydrated rabbiteye blueberries. *J. Food Sci.*, **52**, 980.

Lee, C. Y., Salunkhe, D. K. & Nury, F. S. (1967). Some chemicals and histological changes in dehydrated apples. *J. Sci. Food Agric.*, **18**, 89–93.

Le Maguer, M. (1988). Osmotic dehydration: review and future directions. In *Proc. Int. Symposium 'Progress in Food Preservation Processes'*, CERIA, Brussels, Belgium, Vol. 1, pp. 283–309.

Lenart, A. & Flink, J. M. (1984*a*). Osmotic concentration of potato. I-Criteria for the end point of the osmotic process. *J. Food Technol.*, **19**, 45–63.

Lenart, A. & Flink, J. M. (1984*b*). Osmotic concentration of potato. II Spatial distribution of the osmotic effect. *J. Food Technol.*, **19**, 65–89.

Lenart, A. & Lewicki, P. P. (1988*a*). Osmotic preconcentration of carrot tissue followed by convection drying. In *Preconcentration and Drying of Food Materials*, ed. S. Bruin. Elsevier Science Publishing Company, New York, pp. 307–8.

Lenart, A. & Lewicki, P. P. (1988*b*). Energy consumption during osmotic and convection drying of plant tissue. *Acta Alim. Polonica*, **14**, 65–72.

Lenart, A. & Lewicki, P. P. (1990*a*). Osmotic dehydration of apples at high temperature. In *Drying '89*, ed. A. S. Mujumdar. Hemisphere Publishing Corporation, Bristol, PA, USA, pp. 7–14.

Lenart, A. & Lewicki, P. P. (1990*b*). Osmotic dehydration of carrot at high temperature. In *Engineering and Food, Preservation Processes and related techniques*, Vol. 2, ed. W. E. L. Spiess & H. Schubert. Elsevier Science Publishers, London, pp. 731–40.

Lerici, C. R., Pepe, M. & Pinnavaia, G. (1977). La disidratazione della frutta mediante osmosi. *Industria Conserve*, **52**, 125–9.

Lerici, C. R., Pinnavaia, G., Dalla Rosa, M. & Mastrocola, D. (1983). Applicazione dell'osmosi diretta nella disidratazione della frutta. *Industrie Alimentari*, **3**, 184–90.

Lerici, C. R., Pinnavaia, G., Dalla Rosa, M. & Bartolucci, L. (1985*a*). Osmotic dehydration of fruits: influence of osmotic agents on drying behaviour and product quality. *J. Food Sci.*, **50**, 1217–26.

Lerici, C. R., Riva, M., Maltini, E. & Torreggiani, D. (1985*b*). La disidratazione osmotica. In *Progressi delle tecniche di disidratazione di frutta e ortaggi*, ed. C. R. Lerici & C. Peri. CNR-IPRA, Rome, pp. 129–49.

Lerici, C. R., Mastrocola, D. & Pinnavaia, G. (1986). Esperienze di osmosi diretta ad alta temperatura per tempi brevi. *Industria Conserve*, **61**, 223–5.

Lerici, C. R., Mastrocola, D., Sensidoni, A. & Dalla Rosa, M. (1988). Osmotic concentration in food processing. In *Preconcentration and Drying of Food Materials*, ed. S. Bruin. Elsevier Science Publishing Company, New York, pp. 123–34.

Levi, A., Gagel, S. & Juven, B. J. (1983). Intermediate-moisture tropical fruit products for developing countries. I-Technological data on papaya. *J. Food Technol.*, **18**, 667–85.

Lewicki, P. P., Lenart, A. & Turska, D. (1984). Diffusive mass transfer in potato tissue during osmotic dehydration. *Annals of Warsaw Agricultural University Food Technology and Nutrition*, **16**, 25–32.

Magee, T. R. A., Hassaballah, A. A. & Murphy, W. R. (1983). Internal mass transfer during osmotic dehydration of apple slices in sugar solutions. *Int. J. Food Sci. Technol.*, **1**, 177–8.

Maltini, E. & Torreggiani, D. (1985). Possibilità di impiego della concentrazione osmotica par la preparazione di conserve di frutta. In *'Progressi delle tecniche di disidratazione di frutta e ortaggi'*, ed. C. R. Lerici & C. Peri. CNR-IPRA, Rome, pp. 149–83.

Maltini, E., Torreggiani, D., Forni, E. & Lattuada, R. (1990). Osmotic properties of fruit juice concentrates. In *Engineering and Food, Physical Properties and Process Control*, Vol. 1, ed. W. L. E. Spiess & H. Schubert. Elsevier Science Publishers, London, pp. 567–73.

Maltini, E., Pizzocaro, F., Torreggiani, D. & Bertolo, G. (1991). Effectiveness of antioxidant treatments in the preparation of sulfur free dehydrated apple cubes. In *8th World Congr. Food Sci. Technol.*, Toronto, Canada, p. 087.

Maltini, E., Torreggiani, D. & Rondo Brovetto, B. (1992). Functional compatibility maps of reduced moisture fruits as ingredients in various food systems. In *Proc. Fifth International Symposium on Properties of Water*, ISOPOW-V, 8–14 November 1992, Peniscola, Spain.

Mazza, G. (1983). Dehydration of carrots. Effects of pre-drying treatments on moisture transport and product quality. *J. Food Technol.*, **18**, 113–23.

Monzini, A. & Maltini, E. (1986). Nuovi orientamenti sulla trasformazione delgi ortofrutticoli. *Industria Conserve*, **61**, 265–72,

Moutounet, M., Roux, C. & Mourgues, J. (1991). Déshydratation osmotique du raisin destiné a la vinification. *Revue Francaise d'Oenologie*, **31**, 39–43.

Moy, J. H., Lau, N. B. H. & Dollar, A. M. (1978). Effects of sucrose and acids on osmotic dehydration of tropical fruits. *J. Food Proc. Pres.*, **2**, 131–5.

M'Rani, I. (1990). Transfert de matière et d'énergie dans les milieux déformable. Structure interne du gel d'agar, modélisation mathématique. DEA Systèmes energétiques, de Procédé au matériau, Université des Sciences et Techniques du Languedoc.

Mujumdar, A. S. & Grabowski, S. (1991). Solar-assisted osmotic dehydration of fruits. In *8th World Congr. Food Sci. Technol.*, Toronto, Canada, p. 152.

Nanjundaswamy, A. M., Radhakrishnaiah, S. G., Balanchandran, C., Saroja, S. & Murthy, R. K. B. S. (1978). Studies on development of new categories of dehydrated products from indigenous fruits. *Indian Food Packer*, **1**, 91–9.

Pavasovic, C., Stefanovic, M. & Stevanovic, R. (1986). Osmotic dehydration of fruit. In *Drying '89*, ed. A. S. Mujumdar. Hemisphere Publishing Corporation, New York, pp. 761–4.

Pinnavaia, G., Dalla Rosa, M. & Lerici, C. R. (1988). Dehydrofreezing of fruit using direct osmosis as concentration process. *Acta Alim. Polonica*, **14**, 51–7.

Ponting, J. D. (1973). Osmotic dehydration of fruits—Recent modifications and applications. *Proc. Biochem.*, **8**, 18–20.

Ponting, J. D., Walters, G. G., Forrey, R. R., Jackson, R. & Stanley, W. L. (1966). Osmotic dehydration of fruits. *Food Technol.*, **20**, 125–8.

Ramamurthy, M. S., Bongirwar, D. R. & Bandyopadhyay, C. (1978). Osmotic dehydration of fruits: possible alternative to freeze drying. *Indian Food Packer*, **1**, 108–11.

Raoult-Wack, A. L. (1988). Déshydratation et confisage par effect de concentration: etude des transferts de matiere sur aliment modele. DEA de l'Universite des Sciences et Techniques du Languedoc.

Raoult-Wack, A. L. (1991). Les procédé de Déshydratation-Imprégnation par Immersion dans des solutions concentrées (DII). Etude experimentale et modelisation des transferts d'eau et de solute sur gel modele. PhD thesis, Université Montpellier II, Sciences et Techniques du Languedoc, France.

Raoult-Wack, A. L. & Guilbert, S. (1990). La Déshydratation Osmotique ou procédé de Déshydratation-Imprégnation par Immersion dans des solutions concentrées. *Les Cahiers de L'Ensbana 'L'eau dans les procédés de transformation et de conservation des aliments'*, **7**, 171–92.

Raoult-Wack, A. L., Lafont, F., Rios, G. & Guilbert, S. (1989). Osmotic dehydration: study of mass transfer in terms of engineering properties. In *Drying '89*, ed. A. S. Mujumdar & M. Roques, Hemisphere Publishing Corporation, New York, pp. 487–95.

Raoult-Wack, A. L., Guilbert, S., Le Maguer, M. & Rios, G. (1991*a*). Simultaneous water and solute transport in shrinking media—Part 1: application to dewatering and impregnation soaking process analysis (osmotic dehydration). *Drying Technol.*, **9**, 589–612.

Raoult-Wack, A. L., Petitdemange, F., Giroux, F., Rios, G., Guilbert, S. & Lebert, A. (1991*b*). Simultaneous water and solute transport in shrinking media—Part 2: a compartmental model for the control of dewatering and impregnation soaking processes. *Drying Technol.*, **9**, 613–30.

Raoult-Wack, A. L., Botz, O., Guilbert, S. & Rios, G. (1991*c*). Simultaneous water and solute transport in shrinking media—Part 3: a tentative analysis of the spatial distribution of the impregnating solute in the model gel. *Drying Technol.*, **9**, 630–42.

Riva, M. & Masi, P. (1990). Osmodehydration of grapes. In *'Engineering and Food', Preservation processes and Related Techniques*, Vol. 2, ed. W. L. E. Spiess & H. Schubert. Elsevier Science Publishing Company, London, pp. 711–22.

Senesi, E., Forni, E., Torreggiani, D., Bertolo, G. & Lanzi, S. (1989). Ricerche sulla produzione di conserve di albicocche osmodisidratate. *Annali istitute Sperimentale Valorizzazione Tecnologica Prodotti Agricoli (I.V.T.P.A.), Milano*, **20**, 57–68.

Shahab Uddin, M., Hawlander, M. N. A. & Rahman, M. S. (1990). Evaluation of drying characteristics of pineapple in the production of pineapple powder. *J. Food Proc. Pres.*, **14**, 375–91.

Speck, P., Escher, F. & Solms, J. (1977). Effect of salt pretreatment on quality and storage stability of air-dried carrots. *Lebensm. W. u.-Technol.*, **10**, 308–13.

Tomasicchio, M. & Andreotti, R. (1990). Studio suk deidrocongelamento del mango. *Industria Conserve*, **65**, 127–30.

Tomasicchio, M., Andreotti, R. & De Giorgi, A. (1986). Disidratazione parziale della frutta per osmosi II ananas, fragole e susine. *Industria Conserve*, **61**, 108–14.

Torreggiani, D. & Toledo, R. T. (1990). Simultaneous puffing and dehydration of osmotically pre-treated apple cubes in a high temperature fluidized bed (HFTB) drier. Paper no. 1712, 19th Int. Cong. Chemical Engineering 'CHISA '90', Praga, CS.

Torreggiani, D., Giangiacomo, R., Bertolo, G. & Abbo, E. (1986*a*). Ricerche sulla disidratazione osmotica della frutta. I Idoneità varietale delle ciliege. *Industria Conserve*, **61**, 101–7.

Torreggiani, D., Giangiacomo, R., Bertolo, G. & Abbo, E. (1986*b*). Ricerche sulla disidratazione osmotica della frutta. II. Idoneità varietale delle albicocche. *Industria Conserve*, **61**, 226–32.

Torreggiani, D., Forni, E., Crivelli, G., Bertolo, G. & Maestrelli, A. (1987). Researches on dehydrofreezing of fruit. Part 1. Influence of dehydration levels on the products quality. In *Proc. XVII Int. Cong. of Refrigeration*, Wien, Austria, Vol. C, pp. 461–7.

Torreggiani, D., Forni, E. & Rizzolo, A. (1988*a*). Osmotic dehydration of fruit. Part 2. Influence of the osmosis time on the stability of processed cherries. *J. Food Proc. Pres.*, **12**, 27–4.

Torreggiani, D., Giangiacomo, R., Bertolo, G. & Abbo, E. (1988*b*). Ricerche sulla disidratazione osmotica della frutta. III. Idoneità varietale delle percoche. *Industria Conserve*, **63**, 223–8.

Torreggiani, D., Maltini, E., Bertolo, G. & Mingardo, F. (1988*c*). Frozen Intermediate Moisture Fruits: studies on techniques and products properties. In *Proc. Int. Symposium 'Progress in Food Preservation Processes'*, CERIA, Brussels, Belgium, Vol. 1, pp. 71–78.

Torreggiani, D., Senesi, E., Forni, E. & Bertolo, G. (1990*b*). Influence of pasteurization on the quality of osmodehydrated fruit: cherry, apricot, clingstone peach. In *'Engineering and Food', Preservation Processes and Related Techniques*, Vol. 2. ed. W. L. E. Spiess & H. Schubert. Elsevier Science Publishers, London, pp. 722-30.

Torreggiani, D., Forni, E., Maestrelli, A. & Quadri, F. (1991*a*). Influence of firmness of raw fruit on quality of osmodehydrofrozen kiwifruit disks. In *8th World Congr, Food Sci. Technol.*, Toronto, Canada, p. 155.

Torreggiani, D., Giangiacomo, R., Messina, G., Maltini, E. & Maestrelli, A. (1991*b*). Use of osmodehydrofrozen fruit cubes in fruit yogurt: preliminary studies. In *8th World Congr. Food Sci. Technol.*, Toronto, Canada, p. 154.

Toupin, C. J. & Le Maguer, M. (1989). Osmotically induced mass transfer in plant storage tissues: A mathematical model—Part 2. *J. Food Eng.*, **10**, 97–121.

Toupin, C. J., Marcotte, M. & Le Maguer, M. (1989). Osmotically induced mass transfer in plant storage tissues: a mathematical model—Part 1. *J. Food Eng.*, **10**, 13–38.

Vial, C., Guilbert, S. & Cuq, J. (1991). Osmotic dehydration of kiwifruits: influence of process variables on the color and ascorbic acid content. *Sciences des Aliments*, **11**, 63–84.

Videv, K., Tanchev, S., Sharma, R. C. & Joshi, V. K. (1990). Effect of sugar syrup concentration and temperature on the rate of osmotic dehydration of apples. *J. Food Sci. Technol. India*, **27**, 307–8.

Vyas, K. K., Sharma, R. C. Joshi, V. K. (1989). Application of osmotic technique in plum wine fermentation: effect on physico-chemical and sensory qualities. *J. Food Sci. Technol., India*, **26**, 126–8.

Yang, A. P. P., Wills, C. & Yang, T. C. S. (1987). Use of combination process of osmotic dehydration and freeze drying to produce a raisin type lowbush blueberry product. *J. Food Sci.*, **56**, 1615–64.

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