PRESENT AND FUTURE IN PROCESS CONTROL AND OPTIMIZATION OF OSMOTIC DEHYDRATION

FROM UNIT OPERATION TO INNOVATIVE COMBINED PROCESS: AN OVERVIEW

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I. INTRODUCTION

Consumer demand has increased for processed products that keep more of their original characteristics. Translated into industrial terms, this requires the development of operations that minimize the adverse effects of processing. Conventional and new food processing techniques should enhance the nutritional, hygienic, and sensory quality of food products; improve the processing characteristics of raw materials and semifinished products; increase the variety of products; and take into account the economic and environmental aspects of food processing. Traditional techniques such as chilling, freezing, convective drying, pasteurization, and sterilization are the major processes employed for food preservation. However, there is a vast literature that refers to the deterioration in sensory quality, to vitamins, microelements, and aroma losses, and to oxidation and so on due to a severe treatment or one not suitable for the nutritional characteristics of a certain product. Every type of treatment should have as its goal the preservation of the sensory characteristics that are an important aspect of the processed food and of the nutritional elements associated with it. It is common knowledge that, today, not all the technological preserving processes are adequate enough to reach this objective.

Because the aforementioned points are becoming key aspects in food processing, there has been an increasing interest in osmotic dehydration mainly, but not only, for fruit and vegetable processing. In fact, since the early 1990s, significant developments have taken place to perfect this process as a cost-effective drying unit operation, either free standing or combined with other preservation processes. The question that arises is how can an osmotic step, such a simple and old practice, reproposed by Ponting *et al.* (1966), help in such a complex matter as the quality improvement of processed food? The reason for this renewed interest is the high versatility of the process, due mainly to the twofold transformation of the food item, that could be achieved.

The process involves placing the solid food (whole or in pieces) into solutions of high sugar or salt concentration. Le Maguer (1988), Raoult-Wack (1994), Fito and Chiralt (1997), Behsnilian and Spiess (1998), Spiess and Behsnilian (1998), Lazarides *et al.* (1999), and Torreggiani and Bertolo (2002) have reviewed the basic principles, modeling and control, and specific applications of osmotic dehydration on fruit and vegetables. Additionally, the most recent research advances in this field can be obtained from the European-founded network on "osmotic treatments" (FAIR, 1998).

It is well known that when solid food is immersed in a hypertonic solution, a driving force for the diffusion of water from the food into the solution is set up because the food cellular surface structure acts as a

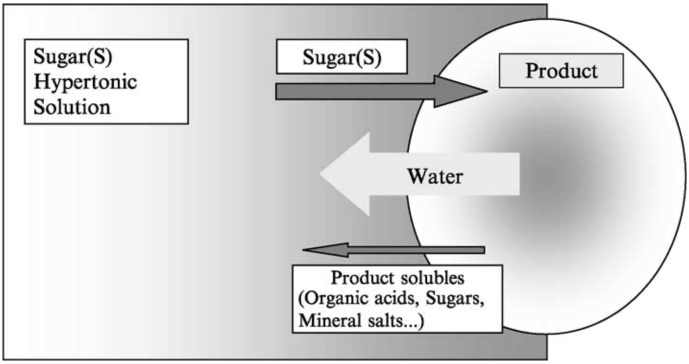

FIG. 1 Mass transport phenomena during the osmotic process.

semipermeable membrane (Figure 1). The diffusion of water is accompanied by the simultaneous counterdiffusion of solute from the osmotic solution into the food. As long as the tissue membranes are intact, osmosis will be the mechanism controlling any transfer phenomena initiated by concentration differences, with the plasma membrane as the major resistance to mass transfer (Le Maguer and Yao, 1995). Because the membrane responsible for osmotic transport is not perfectly selective, other solutes (sugar, organic acids, minerals, salts, etc.) present in the food are also leached into the osmotic solution. Although quantitatively negligible, solute leakage may be essential as far as sensory and nutritional qualities are concerned. Some of the osmotic syrup may not migrate into the cell actively, but simply penetrate into the intercellular spaces. This impregnation effect may be important, and the term "dewatering—impregnation—soaking in concentrated solutions" (DIS) instead of "osmotic dehydration" has been proposed by Raoult-Wack and Guilbert (1990).

The main unique feature of osmotic dehydration, compared to other dehydration processes, is the penetration of solutes into the food material. Through a calculated incorporation of specific solutes into the food system, it is possible, to a certain extent, to change nutritional, functional, and sensory properties, making it more "suitable" to processing by

- Adjusting the physical–chemical composition of food by reducing water content or adding water activity-lowering agents.
- Incorporating ingredients or additives with antioxidant, or other preservative properties, into the food.
- Adding solutes of nutritional or sensory interest.
- Providing a larger range of food consistency.

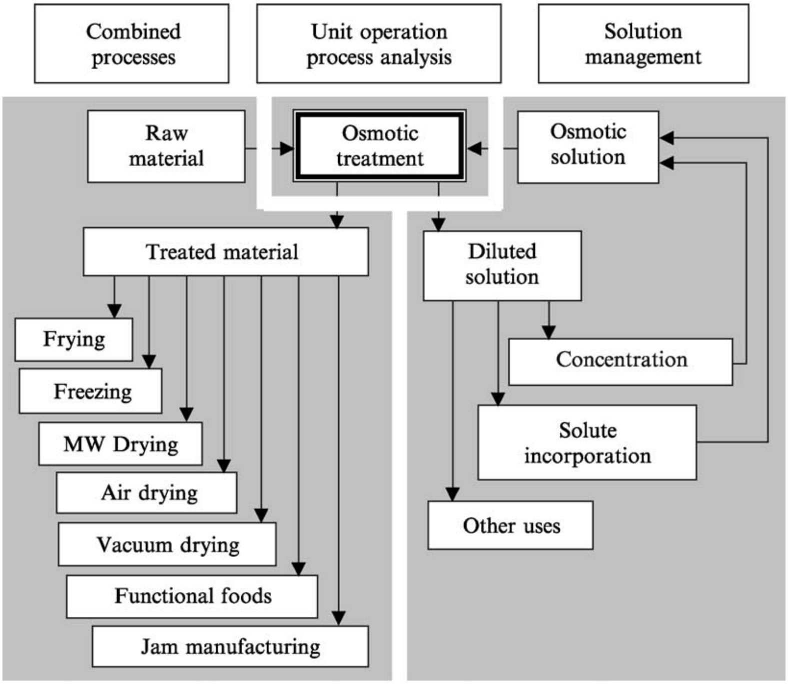

FIG. 2 Key research areas.

This direct formulation (Torreggiani, 1993; Torreggiani *et al.*, 1999c), together with a partial dehydration, is the distinctive aspect of the process and the way to develop a new product. There is also an economic interest in osmotic treatments, which focuses on reduced energy consumption for water removal without phase change, as compared to convective drying, and the possible reduction of the refrigeration load by partial concentration prior to freezing of fruit and vegetables.

There is already much practical experience available on the osmotic treatment itself. To fulfill consumer, industrial, and environmental expectations, however, some problems remain to be solved. Osmotic treatments have been applied frequently as a low-cost processing method neglecting process optimization, but the current interest in this technique and the development of industrial applications on a large scale demand controlled processes. For successful process control and optimization, efforts have to be made in the following key areas (Figure 2).

- Development of predictive models through better understanding of the mechanisms of mass transport responsible for the water removal and solute uptake, and the relationships among osmotic process variables and modifications achieved in the material.

- Prediction of the behavior of osmotically modified materials during further processing and storage.
- Response to environmental and economic questions for the management of osmotic solutions.

Scientific knowledge in these key areas was improved through the work of a concerted action, organized within the framework of the fourth EU-Framework program. In this action, 15 research centers and universities of 11 European counties, Israel, Poland, and Canada participated, and the project was funded by the Directorate General XII of the Commission of European Communities under Research Grant FAIR-CT96-1118.

The state of the art and the progress in the aforementioned key areas, specifically referring to fruit and vegetables, are discussed and evaluated in this review in the light of industrial, environmental, and consumer needs. There is just a hint on osmotic treatments of fish and meat products.

II. UNIT OPERATION/PROCESS ANALYSIS

A. PROCESS VARIABLES

As the name of the process indicates, osmosis is the mechanism responsible for high water losses with reduced solute uptake, at least as long as the tissue membranes are intact. The rate of water removal depends on many factors, such as the concentration and temperature of osmotic solution, contact time, the level of agitation in the solution, the size and shape of the food, the solution-to-food ratio, and the vacuum level, if applied. A number of publications have described the influence of the main processing variables on mass transfer and on product quality (Lazarides *et al.*, 1997; Panagiotou *et al.*, 1998; Rastogi and Raghavarao, 1997; Rastogi *et al.*, 1997, 2000a). However, all this previous knowledge has to be reviewed under a new light of complexity. First of all, the parameters for the cellular properties of the material (e.g., diffusivity, tortuosity, and porosity) have to be taken into account, in addition to the properties of the solution (e.g., viscosity, diffusivity, and density) and processing conditions (e.g., temperature and shape of the material). In fact, depending on the tissue and the operating conditions, such as temperature and pressure, diffusion, convection, and flux interactions may occur at the same time and contribute to the complexity of the process. Furthermore, modification in composition and structural changes (shrinkage, porosity reduction, cell collapse), taking place in the food material during osmotic treatment, modify the heat and mass transfer behavior in the tissue and must be considered. New concepts of the cellular level approach start from previously proven findings.

- Independently from the kind of raw material, the dewatering effect is always greater than the penetration of sugars into the plant tissue as long as the membrane is intact.
- Rates of water loss and solid gain reach their highest values at the beginning and drop drastically within the first hour to almost level off within 3 h of dehydration.
- Temperature has the largest effect on moisture and solute diffusivity, as confirmed by Kayamak-Ertekin and Sultanğlu (2000) on apple ring slices. Tissue damage due to too high a temperature causes a dramatic decrease in dehydration efficiency through increased solute and decreased moisture diffusivities.
- Increased concentrations give increased moisture and decreased solute diffusivities. Dehydration efficiency (water loss/solid gain) increases with concentration but decreases or remains constant with temperature.
- Process conditions have a dramatic impact on process "efficiency." Water loss/sugar gain ratios for different process conditions may differ by up to 120% or more.
- The larger the solute molecular size, the higher the water loss and the lower the sugar uptake under fixed process conditions. Using the right size of osmotic solute, satisfactory moisture diffusivities, with nearly zero net solute uptake, can be obtained.
- High molecular weight solutes are the most effective in forming a dense solute barrier layer at the surface of the product, thus enhancing the dewatering effect during soaking in the concentrated solution (Raoult-Wack *et al*., 1991). Formation of the barrier layer promoted by high molecular weight solutes and/or high solute content could also be useful in reducing loss of natural fruit solutes.
- By increasing the surface area in contact with the solution, water removal and solid gain are enhanced, as confirmed by Van Nieuwenhuijzen *et al*. (2001) on apple cylindrical slices.
- Agitation of the solution enhances the water loss/solid gain ratio, especially during the first hour of treatment; the intensity of motion does not have a marked effect on the rate of mass exchange. In any case, the movement should be gentle to avoid mechanical damage to the food.
- Mixing of sucrose and salt in different proportions may be used for both plant and animal tissue treatments to reduce impregnation and to obtain higher water loss/solid gain ratios than those obtainable using solutes in binary solution. The antagonistic effect between the two solutes on product dehydration and salt gain was confirmed on apple sticks by Sacchetti

et al. (2001) and on paprika disks by Ade-Omowaye *et al*. (2002a). A higher dependency of water and solid diffusion coefficients on the sodium chloride concentration could be explained by the osmotic pressure variation linked to the molecular weight of the osmotic agent. The presence of a high level of sugar in the osmotio-dehydrated product can reduce the saltiness threshold; the presence of salt also has an enhancing effect on sucrose sweetness. Gekas *et al*. (1998) analyzed mass transfer properties of solutions relevant for osmotic processing of foods, whereas Sereno *et al*. (2001) reviewed models to correlate and predict water activity in aqueous solutions of single and multiple solutes, including electrolytes.

B. NATURE OF PLANT MATERIAL

The nature of the plant material subjected to osmotic dehydration is the key point for both modeling and optimizing the osmosis in itself and as a pretreatment to further processing. The same osmotic medium, applied to different raw materials, under identical process conditions causes substantially different rates of dehydration and solute uptake. Data on these findings were reviewed previously (Lazarides *et al*., 1999; Torreggiani, 1995) and have been confirmed by recent research.

During osmotic dehydration of apple, pumpkin, and carrot in sugar solution at 30 °C, the rate of water loss was 5–10 times higher than the rate of solid gain and depended on advancement of the dewatering process (Kowalska and Lenart, 2001). Under the same dewatering conditions, pumpkin and carrot reached smaller water contents than apple (Figure 3).

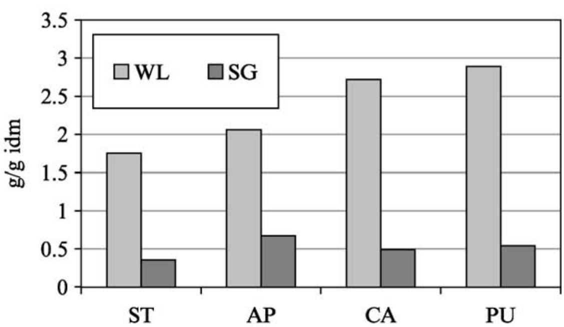

FIG. 3 Water loss (WL) and solid gain (SG) expressed on initial dry matter (idm) of strawberry (ST) slices (Brambilla *et al*., 2000) and apple (AP), carrot (CA), and pumpkin (PU) cubes (Kowalska and Lenart, 2001) after 60 min osmotic dehydration in a 60% (w/w) sucrose solution at 30 °C at atmospheric pressure.

Structural differences may explain the quantitatively different behavior; apple has a much more open structure, which facilitates the penetration of osmoactive substances. These data confirm previous results obtained for apple and potato (Lazarides *et al*., 1997) intracellular volume is bigger in potato than in apple, and a dramatically higher (by an order of magnitude) intercellular porosity (25% for apple and 2–5% or even less for potato) allows for the substantial transport of solutes into the intercellular spaces. Comparing different fruits (apple, strawberry, and mango) subjected to osmotic dehydration in sucrose, solute gain in apple is faster when the osmotic solution concentration increases and is faster in strawberry and mango when it decreases (Lazarides *et al*., 1997; Talens *et al*., 2000, 2001). Furthermore, highly concentrated sugar solutions seem to limit the leaching of strawberry internal solids (Talens *et al*., 2000).

Further evidence was provided by Mavroudis *et al*. (1998) on the importance of initial structural differences within apple parenchymatic flesh on mass transfer rates during osmotic processing. The shrinkage phenomena, encountered in the fruit tissue of apple undergoing osmotic processing, was also studied by the same authors. In both the apple varieties analyzed (Kim and Granny Smith), two structures were detected. The inner parenchymatic tissue has a higher bulk density than the outer; this fact is linked to differences in interconnectivity of intercellular spaces and cell morphology. The significance of the initial structure on the kinetics of osmotic processing has been demonstrated, at least between 5 and 40 °C processing temperature. In fact, solution penetration into the pores takes place more in the inner than in the outer parenchyma, thus lowering water loss and contributing to the higher solid gain rates in the inner specimens. Furthermore, a strong linear relationship between volume changes and water removal was found in osmotic dehydration, similar to findings in air drying. In osmotic processing, the bulk density depends on the initial structure, variety, and drying conditions in contrast with reported findings on air drying. The different bulk density behavior between osmotic and air drying could be attributed to solute uptake. Results obtained by Moreira and Sereno (2001) on apple cylinders treated with osmotic solutions suggest that volumetric shrinkage is essentially due to water removal/solid gain and offer a simple way to predict such changes during industrial processing.

The importance of the initial cellular structure is demonstrated when optimum processing conditions have to be located. For diced green peppers, while temperature, agitation, and tissue to solution ratio were not important factors, time, salt, and sorbitol concentrations were highly significant (Ozaslan *et al*., 1998). Temperature was also significant for water loss but only during early stages of the process. The importance of sorbitol is linked to its capability to hinder the entrance of excessive salt into the product.

Changing vegetable tissue changes the factors mainly influencing solid–liquid exchanges; for cauliflower the factors were temperature and salt concentration and for apple the factors were temperature and sugar concentration (Lazarides *et al*., 1995; Vijayanand *et al*., 1995). When pieces of mango were subjected to osmotic dehydration in sucrose solution, the influence of temperature on solid–liquid exchanges was maximum while shape factor was minimum; furthermore, the temperature and syrup concentration showed opposite trends in terms of their influence on distribution coefficients (Sablani and Rahman Shafiur, 2003). The effect of vacuum pulse on fruit and vegetable composition changes depends strongly on the tissue characteristics (Gras *et al*., 2001; Salvatori *et al*., 1998b). In kiwi tissue, for example, the effect of vacuum pulse was relatively slight (Talens *et al*., 2003) compared with other fruits, such as apple (Barat *et al*., 2001), probably due to the scarce porosity of the tissue (Salvatori *et al*., 1998b). Nevertheless, solute gain was greater than that observed in similar process conditions for strawberry halves (Talens *et al*., 2000).

C. RAW MATERIAL TREATMENTS PRIOR OR DURING OSMOSIS

As underlined previously, the rate of transfer during osmotic dehydration takes place through the semipermeable membranes present in biological materials, usually in the range of 5 to 8 nm thickness. Because the membrane offers dominant resistance to the osmotic treatment, among the numerous factors influencing the rate of diffusion during the process, treatments of the material prior to or during osmosis could play a very important role. It is worth remarking that all the variables studied can only be manipulated over a limited range, outside of which they affect quality adversely, even though the rate of transfer may be enhanced. Blanching, freeze-thawing, sulfating, acidification, and high process temperatures, all affecting the integrity of natural tissues, improve water and solute diffusivities within the product, resulting in faster equilibrium in favor of higher solute uptake (Lazarides *et al*., 1999). A number of techniques have been tried to improve the mass transfer rate with a minimal alteration in quality. Due to consumer demand for minimally processed food products with high sensory and nutritional qualities, most of the techniques under study are nonthermal processes and include the application of ultrahigh hydrostatic pressure or high-intensity electrical field pulse (PFE) to the material prior to osmotic treatment (Figure 4) and ultrasound or partial vacuum during treatment (Figure 5).

Looking more deeply into these ongoing studies, for example, the application of ultrahigh hydrostatic pressure, leads to significant changes in the tissue architecture. This resulted in increased mass transfer during the osmotic dehydration of pineapple and potato slices due to the combined effect

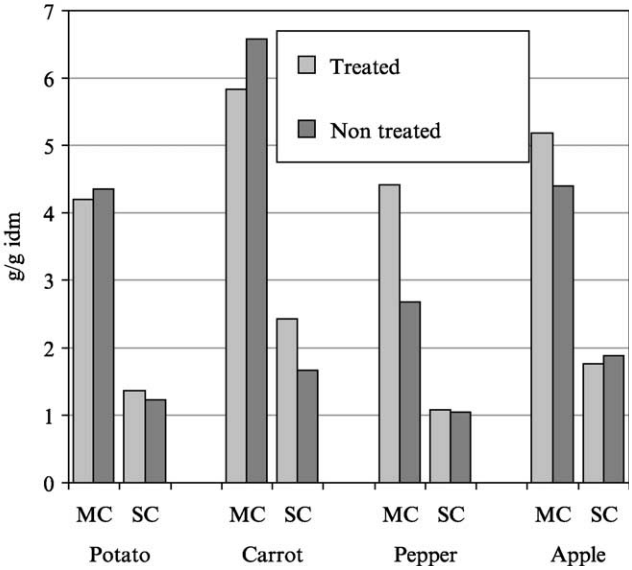

FIG. 4 Effects of varying raw material treatments prior to osmotic dehydration on moisture (MC) and solid (SC) content expressed on initial dry matter (idm). Potato slices, high hydrostatic pressure (Rastogi *et al.*, 2001); carrot slices, PFE (Rastogi *et al.*, 1999); bell pepper disks, PFE (Ade-Omowaye *et al.*, 2002b); and apple slices, edible coatings (Lenart and Dabrowska, 1998).

of cell permeabilization due to osmotic stress (as the dehydration proceeds) and high pressure induced permeabilization (Rastogi and Niranjian, 1998; Rastogi *et al.*, 2000b, 2001) (Figure 4). The increase in cell permeation index (Zp) values (or tissue softening or loss of texture) following high pressure treatment is due to the destruction of cell membranes and partial liberation of cell substances. Upon high pressure treatment, the polymethylesterase (PME) enzyme, which is bound to the cell wall, is liberated, not completely inactivated, and brought into close contact with its substrate, the methylated pectin. This causes deesterification not only during high pressure treatment, but also after the release of high pressure (standing time), which results in time-dependent softening of vegetable tissue (Basak and Ramaswamy, 1998).

Among the emerging nonthermal processes of interest as a pretreatment, pulsed electric field (PFE) could induce cell membrane permeabilization within a very short time (microsecond to millisecond range), leaving the product matrix largely unchanged, while positively affecting mass transfer rates in the subsequent processing of foods (Knorr *et al.*, 2002). Accelerated mass transfer rates during osmotic dehydration of PFE pretreated carrots, apples, and red bell peppers were reported by Rastogi *et al.* (1999), Taiwo

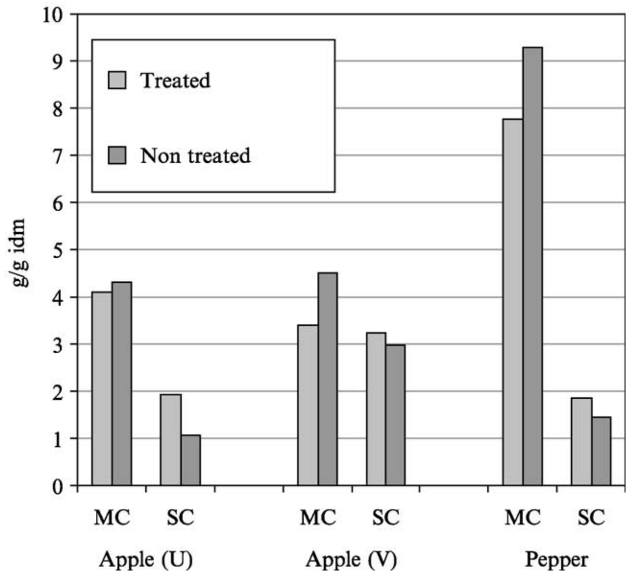

FIG. 5 Effects of varying raw material treatments during osmotic dehydration on moisture (MC) and solid (SC) content expressed on initial dry matter (idm). Apple cubes, ultrasound (U) (Simal *et al*., 1998); apple slices, vacuum (V) (Salvatori *et al*., 1998b); and bell pepper disks, high temperature (Ade-Omowaye *et al*., 2002b).

et al. (2001), and Ade-Omowaye *et al*. (2002b), respectively (Figures 4 and 5). Effective diffusion coefficients of water and solute, determined using the Fickian diffusion model, increased exponentially with electric field strength up to 1.0 kV/cm. During PFE processing of cellular foods, attention needs to be given to the degree of disintegration of the initial tissue structure because of its impact on food quality and functionality. Studies have demonstrated that formation of a conductive membrane after PFE treatment is not an instantaneous process, suggesting that the development of pores within the cell membrane, after PFE treatment, is a dynamic process, i.e., time dependent (Angersbach *et al*., 2002). A statement of the time interval after PFE pretreatment and the beginning of the subsequent process, such as osmotic dehydration, is important for meaningfully interpreting the contribution of PFE to mass transfer enhancement (Ade-Omowaye *et al*., 2003). Combined PFE and osmotic dehydration may have potential as a processing step in the production of intermediate moisture foods, where minimal solute uptake is desired.

Another promising technique is ultrasound application during osmotic dehydration. Used on porous fruit such as apple cubes, it affects mass transport, increasing both water losses and solute gain (Simal *et al*., 1998) (Figure 5). It would be necessary to maintain the solution temperature at 70 °C, when using agitation, to achieve a similar solute gain to that obtained at 40 °C with sonication. Ultrasonic osmotic dehydration technology uses lower solution temperatures to obtain higher water loss and solute gain rates while preserving the natural flavor, color, and heat-sensitive nutritive components.

Application of vacuum during osmotic dehydration deserves a broader discussion as, through the adequate control of the process parameters, it may be used as a tool not only to improve mass transfer, but also to develop engineered products (Fito *et al*., 2000, 2001a,b). This latter aspect is dealt with later on in Section III.E. The vacuum impregnation (VI) operation consists of immersing the porous product in the solution, applying vaccum pressure (p_1) for a short period (t_1) in order to promote the outflow of the internal gas, and then restoring the atmospheric pressure (p_2) for period t_2 in which the hydrodynamic inflow of the external solution in the pores is promoted. The amount of the external solution that has penetrated in the tissue, due to the action of the hydrodynamic mechanism (HDM), has been modeled as a function of the product effective porosity (ϵ_e), the applied compression ratio ($r \approx p_2/p_1$), and the sample volume deformations provoked by pressure changes (Fito, 1994; Fito *et al*., 1996; Rastogi and Raghavarao, 1996). It has been demonstrated that the VI of porous fruits is greatly effective in promoting mass transfer kinetics in the tissue (Salvatori *et al*., 1998b) (Figure 5). The greater the product porosity, the more effectively the action of hydrodynamic mechanisms promotes the desired composition changes in short time operations, without any temperature requirements (Chiralt *et al*., 1999). Although VI promotes solute gains by diffusion through the apple intercellular spaces, when the solution viscosity increases, a delay in this phenomenon was observed (Martìnez-Monzò *et al*., 1998a). In addition to promoting diffusional mechanisms in the pores, VI brings with it a different structural development of the tissue through the osmotic process, thus affecting the tissue response to mass transport (Barat *et al*., 1998a, 2001). Microstructure observation of osmodehydrated tissue, at different times of the osmotic equilibration process, shows that two main periods can be distinguished in terms of structural changes. In the first period (24–48 hr depending on osmotic conditions) the prevailing water loss leads to the shrinkage of plasmalemma together with the cell walls (in OD, osmotic dehydration at atmospheric pressure) or the separation of both cell elements (in PVOD, pulsed vacuum osmotic dehydration) in line with the cell cavity filling up with the external solution. In both cases the mechanical energy accumulated in the deformed cell wall matrix was released throughout the second period, producing the volume recovery of cell walls in both kinds of treatments. Mechanical relaxation promotes suction of the external osmotic solution. However, irreversible deformations in a practical timescale can be appreciated specially for a high osmotic syrup concentration without previous vacuum impregnation.

As well as the aforementioned pretreatments, another technique exists that has been developed to increase the low selectivity of cell membranes: the application of more selective barriers such as edible coatings. Edible coatings are applied to many food products for a variety of aesthetic and protective purposes (Krochta *et al*., 1997). Coating the food to be dehydrated with an artificial barrier on the surface may efficiently hinder the penetration of solute inside the food, not affecting the rate of water removal (Guilbert *et al*., 1995; Ishikawa and Nara, 1993). Water loss during osmotic dehydration of coated apple slices was found to be dependent on the type and thickness of polysaccharides coating, and solid gain was either reduced or remained similar for coated and uncoated apples (Lenart and Dabrowska, 1997) (Figure 4). A low methylated pectin solution of 2% concentration and a 10-min drying time were optimal for coating apple slices before osmotic dehydration considering the highest water loss and the lowest dry matter gain (Lenart and Dabrowska, 1998). The use of edible chitosan films has been proposed as a barrier for solid gain in papaya slabs subjected to osmotic dehydration (Jamet and Larios, 2001). Results indicated that chitosan covers reduced solid gain and increased water loss significantly, which led to products more like the fresh counterparts. The efficiency of the process can be increased up to 10 times through an increase of process temperature and a decrease of the number of chitosan covers. When fruits or vegetables have to retain their skin throughout processing, specific pretreatments have to be devised. A good example is when the osmotic treatment is applied to tomatoes. Physical skin-puncturing treatments, to be followed by osmotic dehydration of whole tomatoes, was proposed to produce high-quality intermediate moisture (IM) tomatoes (Shi *et al*., 1997). This type of IM tomatoes can be diced and used as an ingredient by the food service in preparing tomato-based convenient food items such as pizza and pita bread. Physical skin treatments led to higher water removal than chemical ones and did not create waste material. To obtain the best results, the number of pin holes must be more than 80 holes/cm^2.

D. MODELING

The lack of adequate predictive models is an obstacle to industrial applications. The poor understanding of the fundamentals of mass transfer in biological cellular structures—a problem common even to other areas of food processing dealing with transport phenomena—is the main hindrance of advance in this field. Existing engineering or mathematical models, reviewed by Le Maguer and Yao (1995), are not discussed here in detail, whereas structural or mechanistic ones are analyzed. The aforementioned authors classified the models according to two main approaches, i.e., macroscopic and microscopic. The first approach assumes that the tissue is homogeneous, and modeling is based on concepts of diffusion and irreversible thermodynamics. These models try to describe mass transport in mathematical terms, ignoring the mechanisms taking place at the cellular level, and are generally useful in the individual case. However, both driving force and cellular structure are today recognized as two of the major factors in the understanding and control of mass transfer phenomena occurring in food processing in general and in osmotic processing in particular (Gekas, 2001; Gekas *et al*., 2002; Le Maguer *et al*., 2002; Spiess *et al*., 2002). Details of the food structure at a cellular level determine the pathways of both water and nutrient transport, so affecting rates of mass transfer from or to the cells, and influencing the final quality of stored or processed foods.

The microscopic approach looks at heterogeneous properties of the tissue and has been developed for plant material on the basis of plant physiology studies on the effect of osmosis on water balance and transport in growing plants.

Plant tissues are complex systems consisting of a solid matrix, intercellular space, extracellular space, and occluded gas. There are three generally accepted pathways of mass transfer in plant material: apoplasmatic transport (outside the cell membrane), symplasmatic transport (through small channels between two neighboring cells in the intracellular space), and transmembrane transport (between the cell and the free space comprising the intercellular space and cell wall) (Le Maguer and Yao, 1995) (Figure 6).

During the process, the solute diffuses into the intercellular space and, depending on the characteristics of the solute, it may pass through the membrane and enter the intracellular space. Differences in chemical potentials of water and solutes in the system result in fluxes of several components of the material and solution; water drain and solute uptake are the two main simultaneous flows. Together with the changes in chemical composition of the food material, structural changes such as shrinkage, porosity reduction, and cell collapse take place and influence mass transfer behavior in the tissue.

Le Maguer and Yao (1995) presented a physical model of a plant storage tissue based on its cellular structure. The mathematical equivalent of this model was solved using a finite element-based computer method and incorporated shrinkage and different boundary conditions. The concept of volume average was used to express the concentration and absolute pressure in the intracellular volume, which is discontinuous in the tissue, as a

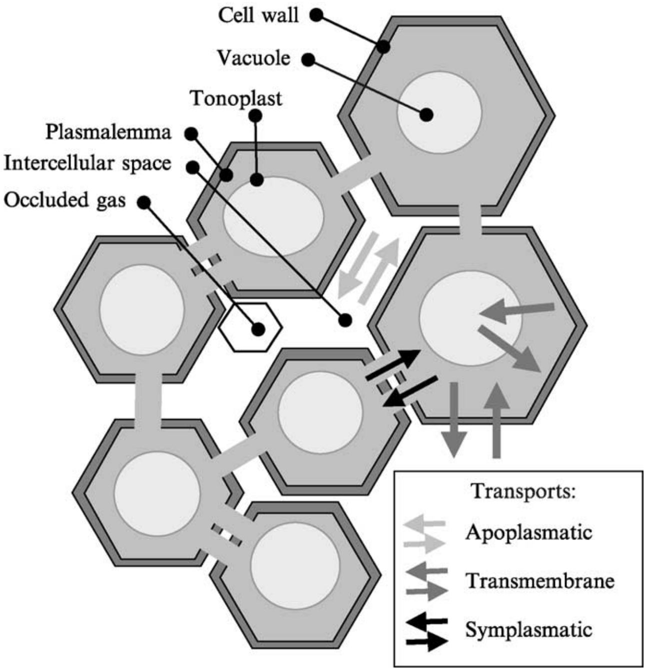

FIG. 6 Transport mechanisms inside plant tissues.

continuous function in the model. Simulations based on this model showed that the solute gradient is controlled mainly by the sharpening effect of the bulk flow on the concentration, with bulk flow removing about 90% of the water from the tissue and washing back about 60% of the solute that has diffused in.

However, many other tissue parameters, such as membrane permeability, porosity, and cell size, are required for the development of models regarding all the mechanisms acting on the various components (intercellular and extracellular spaces, vacuole, etc.). For most tissues subjected to osmotic treatment, lack of data required for this modeling approach represents a hindrance to progress.

The function, the mechanism of transport of the biological membrane, and its fate during various processing conditions are most important for the food process engineer. Within this frame, the impact of three disaccharides—sucrose, maltose, and trehalose—on cellular shrinkage and cell viability, which is undergone by onion epidermis and strawberry cortex tissue during osmotic treatment, was investigated using a fluorescence method through a confocal scanning laser microscope (CSLM) (Ferrando and Spiess, 2001). Differences in cellular response to osmotic stress were observed between these two plant tissues of distinct origin and morphology. The different sugars, used as osmotic agents, influenced the cellular shrinkage behavior of onion epidermis significantly, yet in strawberry cortex tissue, cellular shrinkage was not affected by the nature of the osmotic agent. The sugar concentration, however, had a significant effect on membrane integrity. Maltose and trehalose had a protective effect on the plasma membrane of the onion epidermis cell, maintaining its properties as a barrier, as indicated by these sugars significantly lower effective water diffusivity in comparison with sucrose. Trehalose played a main role during rehydration of the onion epidermis, leading to the highest swelling rate. However, parenchymatic cells of strawberry tissue were not susceptible to any protective effect, whatever the kind of disaccharides employed.

The proportion of intact, damaged, and ruptured (nonintact) cells (Zp) due to osmotic stress during the osmotic treatment of potato were monitored using electrophysical measurements based on electrical impedance analysis (Rastogi *et al.*, 2000a). Osmotic stress on potato cell culture made cell membranes shrink, thereby damaging the cells. The proportion of intact cells reduced rapidly at the beginning but the rate slowed down toward the end of the process. The equilibrium cell disintegration index (Zp_{eq}) value increased exponentially with the concentration of osmotic pressure. In the case of potato slices and tissue, there is a critical osmotic pressure above which the rate of water removal increases. As the dehydration front moves toward the center of the material, disintegration of cell membranes occurs, which results in diffusion through these types of material: diffusion of water from the intact core of material to the transition layer (dehydration front), diffusion of water at the transition layer, and diffusion of water through a layer where the cells have been damaged by the osmotic stress to the surrounding medium.

Analyzing vegetables at the cellular level, another important variable that must be considered, so as to understand solid–liquid exchanges during osmotic dehydration is cell viability. The way water is removed from the tissue affects strongly its respiratory activity (Lewicki *et al.*, 2001). Respiration of apple tissue decreases with increasing dry matter content. Freeze-drying affects less respiration pathways than convective drying, whereas osmotic dewatering affects respiration in a different way. The diffusion of sugars into tissue increases the pool of substrates for respiratory pathways, but, at the same time, by increasing the concentration of solutes, causes structural changes in membranes and cell organization, as well as reduced availability of water for biological reactions. At the beginning of osmotic dewatering, the first process prevails over the second.

Inside the plant tissue, under osmosis, different parenchimatic structures can be found together with a concentration profile, both of which should be taken into account in process modeling. Concentration profiles in apple tissue, during osmotic dehydration, were studied and compared with simultaneous structural changes (Albors *et al*., 1998; Salvatori *et al*., 1997, 1998a, 1999). Establishment of a fully developed concentration profile required a longer time than that usually employed in industrial processes. The occurrence of an ‘‘advancing disturbance front’’ (ADF) was proposed and can describe the kinetics of concentration changes in samples during osmotic dehydration. This model describes mass transfer in terms of a characteristic dimensionless parameter of the material (K), a zone of broken cells near the interface (z_0), a constant advancing rate of the ADF (V_f), and a quickly perturbed distance near the interface (d_f) describing the faster transport mechanisms occurring near the interface.

In order to model simultaneous mass transfer and structural changes, Barat *et al*. (1999, 2001) analyzed the sample volume changes of apple slices throughout the osmotic process both at atmospheric pressure and by applying a vacuum pulse at the beginning of the process. Sample volume changes in porous fruits can be explained in terms of the fruit liquid phase (LP) volume decrease, in line with fluxes of water and soluble solids, and of changes in the volume of sample gas phase (GP), associated with the cell matrix shrinkage, which can contribute greatly to the change in total volume. Even when a great part of the initial gas is removed by applying a vacuum pulse, the GP plays an important role in sample volume development, as pressure changes provoke gas and cell matrix compression, mainly from a critical value of the viscosity of the external solution. Magnetic resonance imaging (MRI) has been put forward as a useful tool in modeling mass transfer and structural changes, as it can uniquely reveal important parameters related to the environment of water molecules in the food. The specific aim of a study on strawberry tissue during drying by osmotic dehydration, air drying, and their combination was to measure one-dimensional maps of the magnetic resonance (MR) parameters T_2 and M_0 (Evans *et al*., 2002). The T_2 parameter (water proton spin–spin relaxation time) gives an indication of the molecular mobility of the water and generally increases with increased mobility; proton density (M_0) is determined from the magnitude of the MR signal and is a quantitative measure of water density. The one-dimensional MR method, described in this study, also enables the evaluation of tissue shrinkage with good temporal and spatial resolution. Results indicated that during a relatively short osmotic pretreatment (1–2 hr), water diffusivity was fast enough to replenish water lost at the surface, thereby maintaining molecular mobility throughout the slice. A classic Fickian modeling approach may be applicable for the osmotic dehydration of strawberry slices over short periods of time. Further studies are required to investigate the effects of longer osmotic dehydration protocols on T_2 values in strawberry tissues.

III. COMBINED PROCESSES

As mentioned previously, osmotic treatments have regained interest as a prestep to further processing and are applied as a tool to obtain intermediate and end products of improved quality by conventional and new processes (Torreggiani and Bertolo, 1999). Osmotically treated materials may be processed into finished products by applying varying stabilizing operations, such as mild heat treatment, drying, freezing, and other techniques. The optimal balance between water removal and solute uptake is determined in each case by the properties of the raw material, subsequent processing steps, and the expected improvement of the product. Knowledge of the changes occurring during the osmotic step should enable a better design of combined preservation procedures to maintain quality characteristics, such as color and texture, and nutritional properties. What must not be forgotten for a successful industrial implementation of combined processes is the need for specifically designed items of equipment, particularly where a high level of dehydration is necessary. A paper by two of the most active research groups in this area, the CIRAD, both in Montpellier and in Réunion, and the ENSIA in Montpellier, defined the functions required by users of osmotic dehydration equipment and presented 17 principles used to make foods come into contact with a concentrated solution (Marouzé *et al*., 2001). This wide range of technical solutions, based on a variety of different principles, is currently available for the industrial implementation of osmotic processes. These solutions can be chosen according to the type and shape of the food to be treated, the required method of treatment, and the nature of the concentrated solution.

A. MINIMALLY PROCESSED FRUITS AND VEGETABLES

Osmotic dehydration, both at atmospheric pressure or preceded by the application of subatmospheric pressure for a short time, has been proposed in the production of minimally processed fruits and vegetables, which are convenient, ready-to-eat, high-moisture but ambient stable foods. The consumer prefers minimally processed foods, as these foods have appealing fresh-like characteristics and thus superior sensory quality. However, at the same time, these foods must be microbiologically safe and stable. These somewhat conflicting goals are achievable by the application of advanced hurdle technology (Leistner, 2002). Application of the aforementioned technology in Latin America has created a new line of minimally processed, fresh-like fruits that, for several months, are microbiologically safe and stable at ambient temperature (Alzamora *et al.*, 1995; Lòpez-Malo *et al.*, 1994; Tapia *et al.*, 1996). The hurdles that proved suitable for this group of food products are a mild heat treatment (blanching), a slight reduction of water activity (a_w) and pH, and a moderate addition of preservatives (sorbate and sulfite) through an osmotic step. The blanching of fruits is important for microbial stability because even though vegetative microorganisms might survive this mild heat treatment, their number is reduced and thus only fewer and lower hurdles are essential. The number of surviving bacteria, yeasts, and molds decreases rapidly during ambient storage of the products, probably due to metabolic exhaustion, as they are not able to multiply in stable hurdle technology fruits. However, the added sulfite and sorbate deplete during storage of these fruits too, which is beneficial for the consumer but diminishes microbial stability. Therefore, a recontamination of the fruits during storage should be avoided (Leistner, 1995). Within this frame of risks, hazards, and consumer trends, predictive microbiology emerges as a powerful tool to quickly explore the microbiological impact of varying conditions within food formulation, processing, and/or distribution and retail conditions (Alzamora and Lòpez-Malo, 2002; Tapia and Welti-Chanes, 2002).

Moreno *et al.* (2000) analyzed the combined effect of two kinds of blanching (steam and microwave) and osmotic treatments (OD, atmospheric pressure, and PVOD, pulsed vacuum) treatments on some physical–chemical and quality parameters of minimally processed strawberries. Microstructural features, associated with treatments, as well as the microbial stability of the processed fruits, were also studied. Poliphenoloxidase (PPO), present in strawberry tissues, causes a loss of red color because of the deterioration of anthocyanin pigments (Markakis, 1974) and browning, linked to cellular disruption and access of oxygen (Cano *et al.*, 1997). Therefore, blanching treatments are recommended before minimally processing strawberries in order to preserve color during shelf life. The use of microwaves (MW) to reduce PPO activity in strawberry (Moreno *et al.*, 1998) and banana slices (Cano *et al.*, 1990) led to satisfactory results. Changes in the tissue, induced by steam or MW treatments, such as cell decompartmentation, led to a faster mass transfer rate, even by hydrodynamic mechanisms, in agreement with the results of Alzamora *et al.* (1997) on apple. Steam blanching promoted the highest texture reduction, especially in combined steam–OD and steam–PVOD treatments. OD and PVOD treatments alone only represent a 2–4% of force decay; the softness associated with loss of fruit turgor seems to be partially compensated with hardening due to the dehydration effect.

Steam-treated strawberries showed a degree of cell decompartmentation near the fruit skin, greater than MW-treated samples, at the same distance to the fruit surface. These observations agree with the major sucrose gain observed in steam–OD and steam–PVOD treatments. The steam–PVOD treatment was the most effective in a_w depression due to the highest sucrose gain during osmotic treatment. This also implied one of the highest losses of firmness and color changes, but these parameters maintained reasonable values. At the same time it induced the greatest microbial stability, probably by the reduction of the initial microbial count by thermal effect.

Not only is the mild heat treatment fundamental for microbial stability of minimally processed fruits, but the osmotic syrup concentration as well. In fact, concerning minimally processed kiwifruit slices, the concentration of the osmotic solution played a key role in the adhesion kinetic of *Metschnikowia pulcherrima* on the fruit surface (Gianotti *et al*., 2001). A high sucrose concentration prevented the formation of biofilms on the fruit surface, mainly due to a reduction of the mobility of the microorganisms, linked to the increase of solution viscosity. Furthermore, a high concentration of the osmotic medium slowed down the microbial growth during the storage of osmotically dehydrated kiwifruit slices.

Optimization of vacuum pulse osmotic treatment for minimally processed pineapple cylinders led to processed fruits, which exhibited a close likeness to fresh ones, without microbiological problems (Navarro and Corzo, 2001).

B. DRYING

Osmotic treatments have been studied mainly as a pretreatment to different drying operations, such as convection drying, freeze-drying, vacuum drying, and microwave drying. The combination osmosis–convective air drying is suggested frequently to produce fruit and vegetables with water activity values of 0.6–0.7, to reduce or even avoid sulfating, to stabilize plant pigments and flavor during processing and storage, and to reduce shrinkage (Torreggiani, 1995). The structural and functional properties of the osmotically treated product will depend on the changes in composition due to the impregnation and the impact of the process on the cell wall and middle lamella, as well as the degree of damage to the plasma membrane due to processing.

1. *Drying techniques*

a. Air. Early studies on the effect of osmotic dehydration and blanching, prior to conventional drying, on the rate of moisture transport have shown that the influence of these operations differs widely as the tissue properties change from one commodity to another (Alzamora and Chirife, 1980; Saravacos and Charm, 1962; Vaccarezza and Chirife, 1975). Mazza (1983) observed that as the concentration of sucrose, used for dipping carrot cubes, was increased from 5 to 60%, the rate of moisture transport during air drying decreased due to the depression of water vapor pressure in the product by the dissolved sugar. This decrease was also due to the impairment of heat transfer and lowering of the diffusivity of water vapor within the product linked to the crystallization of sucrose during the air-drying process. Pineapple that had been osmodehydrated was found to have lower drying rates than fresh pineapple due to a higher initial solid content and/or to the action of solute on the water sorption behavior (Rahman and Lamb, 1991). Effective diffusivity of moisture transport during air drying decreased with the increase of solid gain due to the osmotic pretreatment. Islam and Flink (1982) concluded that the uptake of sugar and/or salt increased internal resistance to moisture movement in potato slices, and Karathanos *et al.* (1995) found that the effective moisture diffusivity of water (D_{eff}) decreased significantly for apples pretreated in concentrated sugar solutions mainly due to the lower porosity. These results were confirmed by Sankat *et al.* (1996) on air drying of pretreated banana slabs. Strawberry and apple air-drying behavior, after blanching and/or sugar impregnation, was examined by Alvarez *et al.* (1995) and by Nieto *et al.* (1998), respectively. The strong decrease in the moisture transport rate during the first falling rate period of drying was attributed to glucose uptake as well as volume shrinkage. Furthermore, sugar distribution in the cellular tissue appears to have a role in drying behavior. In fact D_{eff} values for blanched impregnated apples are lower than those corresponding to nonblanched impregnated ones at the same water activity (0.95 or 0.93) (Nieto *et al.*, 1998). There could be an absorption of the sugar by cellulose, pectic substances, and other polysaccharides of the cell wall. Perhaps the blanching treatment exposed and/or produced some reactive groups available for hydrogen bonding, increasing glucose adsorption in cell walls and consequently increasing the cell wall resistance to water flux. However, for strawberry, blanching pretreatment increased the D_{eff} and glucose dipping after blanching caused no additional effect (Alvarez *et al.*, 1995). This fact was attributed partially to modifications of the strawberry cell structure: disruption of membrane and degradation of the middle lamella and hemicellulosic polysaccharides, present in the cell wall, by heating and a very severe ultrastructural damage of the cell walls, resulting from the sugar impregnation step. Blanching might enhance D_{eff} due to elimination of the cell membranes resistance to water diffusion and a decrease in the resistance of the cell walls to water flux. Glucose dipping caused no additional consequences due to two counterbalancing effects: solute uptake, which increased water transport resistance, and the significant reduction of cell wall resistance due to degradation. Thus, the effect of pretreatments on the drying rate depend very much on the kind of raw fruit, as confirmed by the results of Nieto *et al.* (2001) and Castañón *et al.* (2001a) on the kinetics of moisture transfer during air drying of blanched and/or osmotically dehydrated mango (Figure 7). Osmotic dehydration influenced the drying rate adversely; this effect increased as the glucose concentration of the impregnation solution increased and fruit water activity decreased (Nieto *et al.*, 2001). The air behavior of pretreated mango was ascribed, as for apple (Nieto *et al.*, 1998), to glucose uptake during the impregnation step, volume shrinking, low modification of the cell wall resistance to water flux, by pretreatments, and/or gelatinization of starch and denaturation of protein–carbohydrate mucilage. However, the drying time needed to reach a final moisture content of 0.5 g water/g dry matter was 50 to 75% lower in osmotically treated mango than the time needed for fresh mango (Castañòn *et al.*, 2001a). Sugar uptake and loss of water due to an osmotic pretreatment increase the internal resistance to moisture movement also in papaya slices, and the time needed to reach an equal water activity value was 50% lower as the initial a_w decreased from 0.99 to 0.97 (Castañòn *et al.*, 2001b). Even pineapple rings dehydrated osmotically needed a lower process time than fresh ones to reach the same final moisture content (Vélez-Ruiz *et al.*, 2001). The drying time was shortened by decreasing water activity of the fruits and by increasing air velocity and temperature.

Differences in behavior were observed by Tan *et al.* (2001) between pineapple and potato osmodehydrated for 3 hr in sucrose and in NaCl, respectively, at increasing concentrations (10, 20, and 30% NaCl and 30,

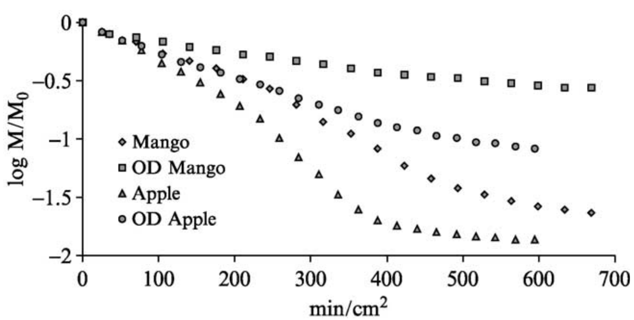

FIG. 7 Effect of 90-min osmotic dehydration (OD) in 40% (w/w) glucose solution at 25 °C at atmospheric pressure on drying rates (M/M_0: moisture content/initial moisture content) at 60 °C of infinite plate-shaped mango (Nieto *et al.*, 2001) and apple (Nieto *et al.*, 1998).

50, and 70% sucrose). The rate of drying of the osmodehydrated potato is consistently lower than that of the nonpretreated sample; this difference, at the beginning of the drying process, could be up to fourfold. However, for pineapple, the drying rates were rather similar in all cases, probably because of its natural high sugar content.

Campolongo (2002) found that 1-hr osmotic dipping in sucrose or sorbitol, instead of decreasing, enhanced moisture transfer during apricot cubes air drying, confirming once more the utmost importance of the raw material properties (Figure 8). The osmotic step, both in sucrose and in sorbitol, increased the initial drying rate of apricot cubes in the first (up to 2 kg water/kg dry solids) falling rate phase, probably due to the 60-min soaking loosening the surface cellular structure, which was already observed in strawberry tissue (Brambilla *et al*., 2000). Apricot cubes osmodehydrated in 60% (w/w) sucrose solution showed a drying rate reduction below 2 kg water/kg dry solids when compared to nonpretreated ones. This could be a result of the reduction of tissue porosity due to sugar infiltration (Karathanos *et al*., 1995) and/or the formation of a peripheral layer of sugar (Collignan *et al*., 1992a). Sorbitol intake though did not cause any drying rate reduction. Cubes pretreated in 14% (w/w) sucrose solution, isotonic with the fresh fruit, showed the highest drying rate throughout the drying process. This behavior could be related to surface cellular structure loosening caused by 60-min soaking and not counterbalanced by sugar infiltration. As for air drying of vegetables, tomatoes of two varieties were dried by convection at

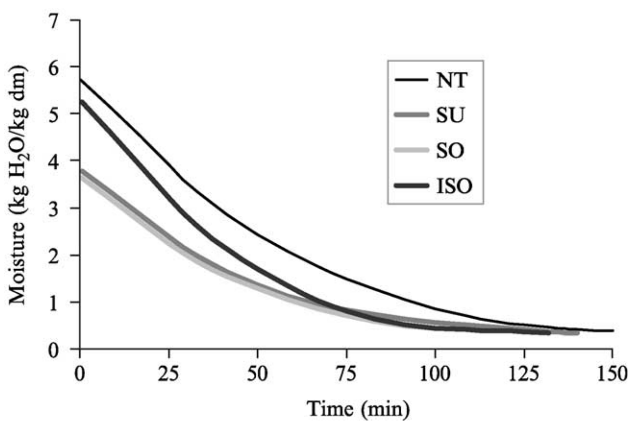

FIG. 8 Effect of 60-min osmotic dehydration at 25 °C at atmospheric pressure in 60% (w/w) sucrose (SU) or sorbitol (SO) solution or 14% (w/w) sucrose (ISO) solution added with 1% ascorbic acid and 0.5% citric acid on drying rates at 70 °C of apricot cubes (NT, not pretreated) (Campolongo, 2002).

60 °C (Lewicki *et al*., 2002). The skin was removed and tomato quarters were pretreated either by soaking in a $CaCl_2$ solution or by soaking in this solution followed by osmotic dewatering or by osmosis in a hypertonic solution containing sucrose and calcium chloride. Pretreatments of tomatoes with calcium chloride increased the rates of convective drying and osmotic dewatering as well. The convective drying time of pretreated tomatoes was 20% shorter than that of raw material. Pretreatment with $CaCl_2$ increased by 20% the amount of water removed during osmotic dehydration and facilitated the infiltration of sucrose. Treatment with $CaCl_2$, followed by osmotic dewatering, was more effective than osmotic treatment in sucrose solution containing calcium chloride, but rehydration properties of pretreated and dried tomatoes were poor. It was suggested that interactions of calcium with polymers stiffened the structure, which, on one hand, improved drying processes, but, on the other, restricted polymers hydration and swelling during rehydration.

As the transport rate in air-drying processes is affected greatly by tissue structure and composition, vacuum infusion pretreatments can lead to a different drying behavior of fruit and vegetables, as well as to different final properties of the product (Fito *et al*., 2001a). VI pretreatment with an isotonic solution slowed down the drying rate of apple slices (Martìn *et al*., 1998, 1999). The increased density of the product and the limitation of diffusion in the sample pores are the main factors that made the drying process rather slow. However, when combined air drying–microwave drying is applied, the drying rate of apple slices VI pretreated overtakes that of nonpretreated samples, probably due to the induced changes in dielectric properties (Martìn *et al*., 1998, 1999).

Artificial neural network (ANN) models were used for predicting quality changes during the osmoconvective drying of blueberries for process optimization (Chen *et al*., 2001). Osmotic dehydration, in fact, affects several associated quality factors, such as color, texture, and rehydration ratio, as well as the end drying time, which is dealt with in Section III.B.2. Ideally, an optimized condition should be aimed at resulting in the lowest drying time, highest rehydration ratio, lowest color difference, and minimal hardness. From the results reported by the aforementioned authors, significant differences exist between the optimal processing conditions for different optimization objectives, and ANN models could be used effectively for predictive modeling and optimization of osmotic processing conditions for the osmoconvective drying of blueberries. The same university department developed models, based on a central composite rotatable design (CCRD), to predict the product moisture content in the two-stage drying process of apple slices as a function of osmotic treatment conditions (Ramaswamy and van Nieuwenhuijzen, 2002).

b. Infrared and microwave. In addition to convective drying, osmotic dehydration can be combined with other drying techniques in order to improve drying efficiency and dried product quality further. Decreasing the drying time, without degradation of food quality, is the main concern for all dried agricultural food producers. One possible method of shortening the drying time of the combined osmoconvective process is the introduction of infrared sources, which are inexpensive, very reliable, have a long service life, and a rapid time response with low maintenance costs (Ratti and Mujumdar, 1995). A combination of intermittent infrared and continuous convective heating was proposed to dry osmotically pretreated potato and pineapple cubes and led to a significant reduction of drying time, without affecting the color of dried products (Tan *et al*., 2001).

Microwave energy can be applied successfully in several unit processes in the food industry because of the volumetric heating of the material. The combined use of microwave and convective drying not only could enhance the drying rate greatly, but also improve the final vegetable product quality (Torringa *et al*., 1996). Dried vegetables and fruits are an important sector in the ingredient market; in fact, in Europe the dehydrated vegetable market is estimated at around 8–9 $\times$ 10^8 kg with a value of 5–6 billion Euro (Torringa *et al*., 2001). Dehydrated vegetable products are suited to a broad range of food formulations (Tuley, 1996), but, unfortunately, they are often difficult to rehydrate because of case hardening and shrinkage during the drying process, resulting in not fulfilling the consumer expectancy for processed products that keep more of their original characteristics.

Combined microwave–hot air drying could improve the structure and bulk volume of dried mushrooms greatly (Nijhuis *et al*., 1998). However, the geometry and dielectric properties of mushrooms are such that overheating of the center hampers the application of this technology. Osmotic dehydration has proved to be an effective method used to improve mushroom suitability to microwave drying (Torringa *et al*., 1998, 2001). The increased salt concentration, due to osmotic pretreatment, has a strong effect on the loss factor so that the vegetable is heated more homogeneously, due to reduced center heating, has a slightly shorter drying time, shows improved rehydration properties, slightly reduced shrinkage, and higher open-pore porosity (Figure 9).

Microwave-assisted (0.1 or 0.2 Wg^{-1}) convection drying was also applied to osmotically dehydrated blueberries, leading to dried berries that were comparable to freeze-dried ones in much shorter time (Venkatachalapathy and Raghavan, 1998). Frozen blueberries were also dried in a microwave and spouted bed combined dryer (MWSB) after a pretreatment using ethyl oleate and a NaOH dipping solution followed by sucrose osmotic treatment (Feng *et al*., 1999). Osmotic dehydration prevented the blueberries from

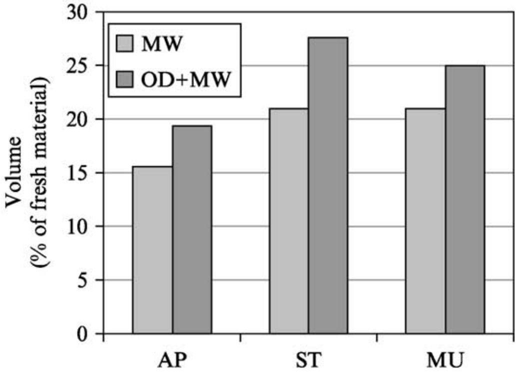

FIG. 9 Effect of osmotic dehydration [180 min, 60% (w/w) sucrose solution at 25 °C for apple and strawberry; 30 min, 10% NaCl at 20 °C for mushroom] on volume (percentage of fresh material) of apple (AP) and strawberry (ST) microwave–vacuum dehydrated up to $a_w < 0.5$ (Erle and Shubert, 2001) and mushroom (MU) microwave–hot air dehydrated up to a moisture content of 0.05 g/g dry matter (Torringa *et al*., 2001).

bursting, when microwaved, but resulted in a high bulk density and low rehydration ratio.

The combination of osmotic pretreatment in sucrose and microwave–vacuum dehydration of strawberry halves and apple slices was studied by Erle and Shubert (2001). The use of a microwave overcomes the usual problem of poor heat transfer in vacuum drying. In microwave–vacuum drying, the heat is not transferred to but is generated into the tissue. This allows for energy transfer rates much higher than in conventional drying operations, especially in the falling rate period (Roussy and Pearce, 1995). The application of an osmotic treatment prior to microwave–vacuum drying combines the advantages of both unit operations in an unique way: because no phase transition takes place in osmotic dehydration, energy consumption is especially low, even if the diluted solution needs to be reconcentrated by evaporation. Microwaves require electricity, an expensive form of energy, but they are employed in the final stages of drying, where they can be used more efficiently than hot air (Gunasekaran, 1999). Selecting the conditions during osmotic treatment offers the possibility of improving both the efficiency of microwave dehydration and the quality properties of the final product. Compared with solely microwave–vacuum-dried fruits, osmotic pretreatment improves volume retention from 20 to 50% for strawberries and from 20 to 60% for apples, based on the fresh fruit volume (Figure 9). Scanning electron microscope (SEM) pictures revealed that the cellular structure is also preserved better when osmotic pretreatment is used. Gel formation among pectins, sucrose, and, when used, calcium ions is believed to be the main cause of structure buildup.

c. Osmotic treatment after drying. Impregnation after partial dehydration instead of the more common osmoconvective drying, where the osmotic treatment precedes air drying, was proposed by Dalla Rosa *et al.* (2001) on strawberry halves and blueberries to obtain semimoist products to be used as ingredients in complex foods, such as dairy and bakery products. Combined convective air drying followed by osmotic dehydration resulted in a larger water loss compared with a single osmotic treatment for a given process time, confirming data of Robbers *et al.* (1997) on kiwifruit. Furthermore, the desired lowering of water activity needed to obtain the compatibility between the food basis and the ingredient is reached at a higher water content than in the stand-alone air-drying process.

2. *Quality characteristics improvement*

Although effective moisture diffusivity decreased normally in osmotically treated fruits, there are some quality characteristics that are always better in osmodehydrated-dried than in fresh-dried ones.

a. Color. An osmotic step could improve the stability of color and vitamin C during air drying and frozen storage of osmodehydrofrozen apricot cubes by the modification of sugar composition (Camacho *et al.*, 1998; Forni *et al.*, 1997). The higher the sugar enrichment, the higher the protective effect on vitamin C during air drying, with maltose being the most effective carbohydrate. Also, browning, expressed as the browning index, calculated from the color coordinates L^*, a^*, and b^* ($[(L_f^* \bullet b_f^*)//(70 \bullet a_f^*)] - [(L^* \bullet b^*)/(70 \bullet a^*)]$; index f refers to fresh fruit values), was significantly lower in cubes pretreated in concentrated solutions of both sucrose and maltose (Figure 10).

Apricot cubes pretreated in the sucrose solution isotonic with fresh fruit have, before drying, the same vitamin C content as cubes pretreated in concentrated solutions, but a lower sugar concentration. The same browning effect was observed in nonpretreated apricot cubes, confirming the protective effect of sugar concentration. The lower ascorbic acid degradation observed in apricot cubes treated in sucrose and maltose could also be related to the fact that these fruits have Tg' values higher than those of untreated ones, hence lower T-Tg' values. As a consequence, they could have lower structural collapse during drying (Levi and Karel, 1995; Roos and Karel, 1993; Slade and Levine, 1991), which may also affect diffusion-controlled deteriorative changes such as nonenzymatic browning (Karmas *et al.*, 1992),

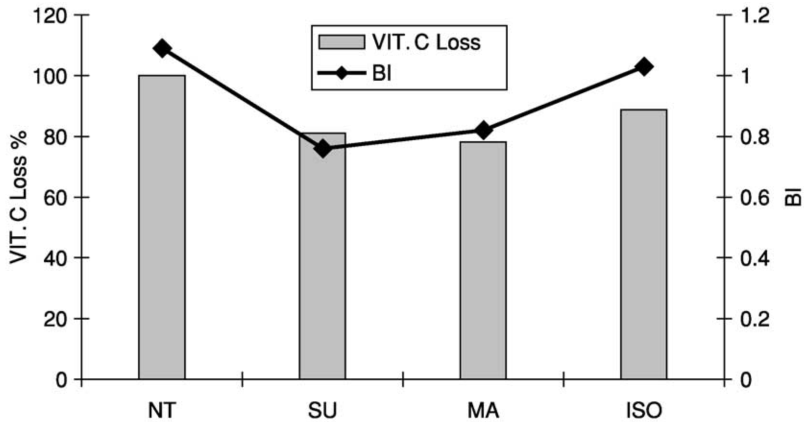

FIG. 10 Vitamin C loss (percentage of apricot content before drying) and browning index (BI) of apricot cubes air dried (NT) or air dried following 60-min osmotic dehydration at 25 °C at atmospheric pressure in 60% (w/w) sucrose (SU) or maltose (MA) or 13% (w/w) sucrose (ISO) solution added with 1% ascorbic acid and 0.5% NaCl (Camacho *et al.*, 1998). All samples were dried at 60 °C up to $a_w = 0.80$.

phenolase activity, and thus the ascorbic acid degradation rate. Further research has underlined the influence of different sugars on the level of structural collapse during air drying of both apricot and clingstone peach cubes (Riva *et al.*, 2001, 2002) and is discussed in Section III.B.2.b.

Color parameters of osmotically treated apple and banana cylinders and potato and pineapple slices showed a remarkable stability over the whole duration of subsequent air drying, whereas untreated samples experienced an extensive browning, proved by a significant higher color difference ($\Delta E = \Delta\ L^{*2} + \Delta\ a^{*2} + \Delta b^{*2}$) values when compared with fresh ones (Krokida *et al.*, 2000a; Tan *et al.*, 2001) (Figure 11). The suggested explanation is that sugars act superficially by increasing the osmotic pressure of the surface layers of fruits and vegetables, reducing enzymatic-browning reactions.

As for vegetable dehydration, by incorporating sorbitol into red pepper cubes, a lower color degradation could be obtained when they are subjected to air drying to produce reduced moisture red pepper ingredients (Torreggiani *et al.*, 1995a). As already observed in frozen strawberries during storage (Torreggiani *et al.*, 1995b), even in vegetables and during air drying at 65 °C, sorbitol showed a significant protection of the red color and thus of the anthocyanin pigments. Red pepper cubes, osmodehydrated in a new type of syrup (HLS, hydrolyzed lactose syrup from cheese whey ultrafiltration permeate), added with sorbitol, showed the lowest color differences when

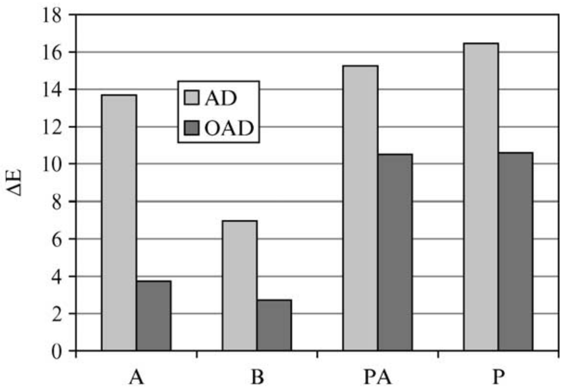

FIG. 11 Color changes (ΔE) of apple (A) and banana (B) cylinders (Krokida *et al*., 2000a) and pineapple (PA) and potato slices (P) (Tan *et al*., 2001) air dried (AD) or air dried following 300-min osmotic dehydration (OAD) at atmospheric pressure in 50% (w/w) sucrose solution at 30 °C for apple and banana, 30% (w/w) sucrose solution at 25 °C for pineapple, or 10% (w/w) NaCl solution at 25 °C for potato.

compared with fresh ones. Results also suggested that for red pepper at low water activities, the combination of osmo- with air-dehydration could even be detrimental to color characteristics if a "nonprotective" sugar other than sorbitol is utilized as the osmotic medium.

As for tomatoes, conservation of lycopene during the processing of tomato products is of commercial significance. The degradation of lycopene affects not only the attractive color of tomato products but also their nutritive value and flavor. Four dehydration methods (air drying, vacuum drying, vacuum drying following osmotic pretreatment, and osmotic treatment) produced slight differences in the total lycopene content but resulted in quite a different distribution of the isomer composition (Shi *et al*., 1999). Osmotic treatments reduced lycopene losses through a higher retention of total lycopene and induced only slight changes in the distribution of all-*trans* and *cis* isomers and in color attributes (Figure 12). The osmotic-vacuum treatment had less effect on lycopene loss and isomerization than vacuum drying and conventional air drying. In air drying, isomerization and oxidation (autoxidation) affected simultaneously the decrease of total lycopene content, distribution of *trans* and *cis* isomers, and biological strength. A possible explanation of this result is that sugar enters the tomato matrix and strengthens the binding force of lycopene. Furthermore, osmotic solution (sugar) remaining on the surface layer of the tomato prevents oxygen from penetrating and oxidizing lycopene.

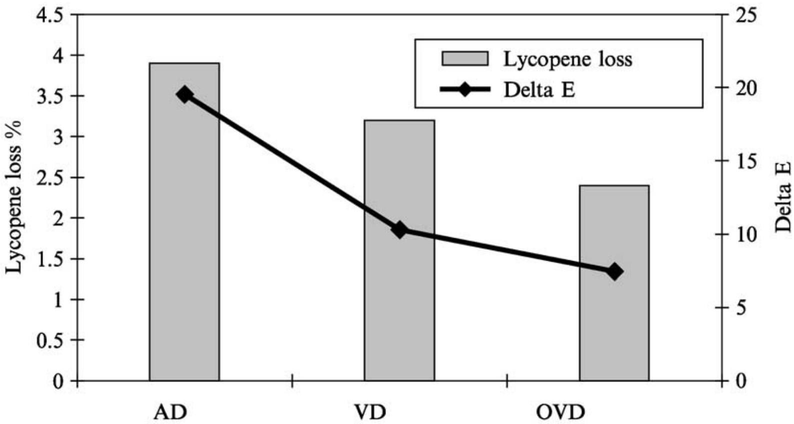

FIG. 12 Lycopene loss (percentage of raw tomato content) and color changes (ΔE) of whole tomatoes air dried at 95 °C (AD), vacuum dried at 55 °C (VD), or vacuum dried at 55 °C following 240-min osmotic dehydration (OVD) in 65% (w/w) sucrose solution at 25 °C (Shi *et al.*, 1999). All samples were dried up to 3–4% moisture content.

b. Shrinkage. The incorporation of sugars has been demonstrated to improve not only color, but also the structure stability of dried fruits in general. Pretreated and air dried apples were more tender and retained their shape better than untreated air-dried ones (Collignan *et al.*, 1992; Lewicki and Lukaszuk, 2000). Color and structure characteristics of both clingstone peach and apricot cubes were preserved better during air drying when fruits were pretreated in different sugar solutions (Campolongo, 2002; Riva *et al.*, 2001, 2002) (Figure 13). In this work, color attributes and geometric features were evaluated by image analysis after acquisition of a significant number of images per sample (Papadakis *et al.*, 2000). Mathematical transformations were applied to the image parameters to also estimate volume reduction, related to absolute moisture content. During subsequent air drying, sugars added during the osmotic step helped decrease structural collapse, with the improvement being reflected by 25–30% and 10–15% increases in the final volume of pretreated clingstone peach and apricot cubes, respectively, confirming the results reported by Lozano *et al.* (1983), del Valle *et al.* (1998), and Reppa *et al.* (1998) on apple cylinders. Both clingstone peach and apricot pretreated in sorbitol showed the lowest structure collapse, retaining a better surface smoothness. Protective effects of the osmotic step in sorbitol on geometric features appear to be linked to the lower heat damage (testified by the lower shift of the color attributes) during the air-drying step and could be related to the higher replacement of air in intercellular spaces by the sorbitol solution that penetrates via capillarity (del Valle *et al.*, 1998).

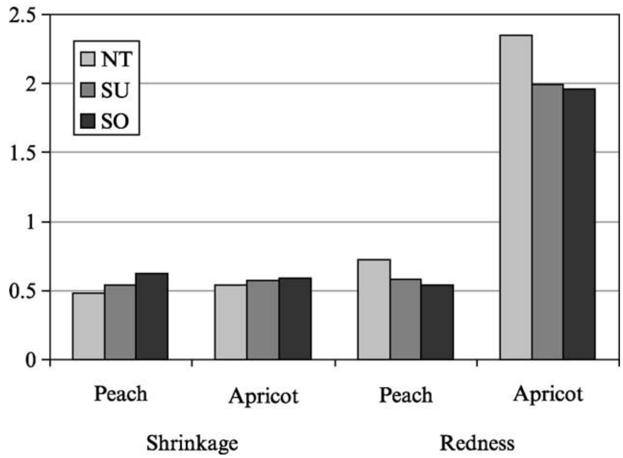

FIG. 13 Shrinkage coefficient (volume/initial volume) and redness (a*/10) of peach and apricot cubes air dried at 70 °C up to 35% weight reduction without (NT) or following 60-min osmotic dehydration at 25 °C at atmospheric pressure in 60% (w/w) sucrose (SU) or sorbitol (SO) solutions, added with 1% ascorbic acid and 0.5% citric acid (Campolongo, 2002; Riva *et al.*, 2001, 2002).

A simple relationship was not found between shrinkage and "glass"–"rubber" transitions of both peach and apricot tissue (Campolongo, 2002; Riva *et al.*, 2001, 2002). Even when sorbitol use increased ΔT (= $T - T$g') values, both the color and the structure showed the highest stability. The fact that sorbitol performed better than sucrose indicates that the chemical nature of the infused solute is more important than its glass transition temperature in preventing structural collapse, in accordance with the results reported by del Valle *et al.* (1998).

As for the mechanism explaining the protective effect of sugar, the protection of almost completely dried (below 2% of water content) plant material against cell death has been linked to the presence of disaccharides, which play a significant role in preserving the membrane functionality in the dry state. Among the disaccharides, trehalose was found to be the most efficient in the preservation of the cell membrane (Crowe *et al.*, 1993). The presence of trehalose during drying prevents, therefore, lipid-phase transitions between the dry and the next rehydration state. This hypothesis was partially confirmed by results reported by Ferrando and Spiess (2001), which have already been referred to in Section II.D. Maltose and trehalose had a protective effect on the plasma membrane of onion epidermis cells subjected to osmotic stress, maintaining its properties as a barrier, as indicated by their significant lower effective water diffusivity in comparison with sucrose. Trehalose played a main role during the rehydration of the onion epidermis, leading to the highest swelling rate. However, parenchymatic cells of strawberry tissue were not susceptible to any protection effect regarding the kind of disaccharides employed, thus underlining the utmost importance of the species (Ferrando and Spiess, 2001).

c. Aroma compound retention. Aroma is one of the major determinants of fruit quality, and the retention or loss during osmotic dehydration and air dehydration of strawberry has been analyzed (Di Cesare *et al*., 1999). The concentration of strawberry slices obtained through osmotic treatment in concentrated sucrose solutions improved the volatile retention during air drying at 60 °C of the fruits. During the osmotic step, furanones, pyranones, and, to a lesser extent, esters remain in the fruit tissue, while alcohols and carbonyl compounds move from the fruit to the syrup, probably due to the different solubility of these compounds in water. Furthermore, the concentration of strawberry slices, through osmotic dehydration, improves the volatile retention during air drying in such a way that previously osmodehydrated strawberry slices could be dried up to higher drying levels when compared to non pretreated fruit.

d. Rehydration. While the osmotic step significantly improves color, structure stability, and aroma, it could be detrimental when the product has to be rehydrated.

Knowledge of sorption characteristics of fruit and vegetable, after osmotic dehydration, has important practical effects, especially in dry product rehydration and rehydrated product stability, and is essential in designing combined dehydration processes. Despite the massive volume of literature on osmotic pretreatments, publications on sorption characteristics of osmotically dehydrated products are rather limited (Krokida *et al*., 2000a,b; Lenart, 1991; Tan *et al*., 2001). Osmotic treatment resulted in lowering of the sorption isotherms for both apple and banana (Krokida *et al*., 2000a) and for potato slices, whereas the shift for pineapple slices occurred only at a higher level of moisture content (Tan *et al*., 2001). In terms of rehydration behavior, the observed isotherm shift indicated higher rehydration characteristics for air-dried samples compared to osmotically pretreated ones. This sorption shift may be due to sugar content changes causing differences in binding site availability and bond energies for different structures (Van den Berg and Bruin, 1981). At low moisture levels, water is bound strongly to active sites and does not enhance solution or plastering processes. At higher levels, a combination of actions occurs, resulting in a sharp increase in adsorptive capacity. Such actions include solution, new site creation, plastering, and water–water adsorption. Minor sugars and other soluble constituents probably dissolve before the main sugars.

C. FREEZING

Freezing damages the tissues of fruit and vegetables both physically and chemically. During this process, a part of the aqueous fraction freezes out and forms ice crystals that damage the integrity of the cellular compartments. The cellular membranes lose their osmotic status and their semipermeability (Tregunno and Goff, 1996). The metabolic system of the plant tissue is interrupted, dislocation of the enzymatic system occurs, and the cell loses its turgor. In addition to a dramatic change in texture of the tissue, biochemical deterioration reactions are highly probable. Dehydration prefreeze treatments can aid in reducing or even preventing this problem (Huxsoll, 1982). The process of freezing primarily dehydrated foods is known as dehydrofreezing.

If water is removed partially from the food prior to the freezing process, the cytoplasmatic components within the cells are concentrated and the freezing point is depressed, with a consequent increase of supercooling and microcrystallization. There is a lower ratio of ice crystals to unfrozen phase, with a consequent reduction of structural and sensory modifications. Convective air dehydration is usually used for partial dehydration, but some fruits are affected negatively by any air-drying technique, with kiwifruit being a good example (Forni *et al.*, 1990). For these fruit, air drying must be replaced or combined with osmotic dehydration, which is effective at room temperature and which operates away from oxygen.

1. Texture

Even though osmotic treatments have been proven to be a useful tool in fruit and vegetable cryoprotection, the changes in mechanical properties, caused by the process itself, have to be taken into account.

Different factors contribute to the mechanical properties of plant tissue: cell turgor, which is one of the most important ones, cell bonding force through middle lamella, cell wall resistance to compression or tensile forces, density of cell packaging, which defines the free spaces with gas or liquid, and some factors, also common to other products, such as sample size and shape, temperature, and strain rate (Vincent, 1994). Depending on the sample properties (mainly turgor and resistance of middle lamella), two failure modes have been described (Pitt, 1992): cell debonding and cell rupture.

The main changes induced by an osmotic treatment affecting the mechanical behavior of plant tissues are loss of cellular turgor, alteration of middle lamella (Alzamora *et al.*, 1997), alteration of cell wall resistance, establishment of water and solute concentration profiles (Salvatori *et al.*, 1997, 1998a, 1999), changes in air and liquid volume fractions in the sample (Fito *et al*., 2002), and changes in sample size and shape.

Chiralt *et al*. (2001b) evaluated the effect of process variables in osmodehydrated kiwi, mango, and strawberry brought to the same soluble solid concentration by applying different processing conditions. All the fruit analyzed were softer than fresh ones, and relaxation measurements showed that infusion (atmospheric or vacuum) decreased the elastic component of reological behavior sharply, confirming the results obtained by Muntada *et al*. (1998) on kiwifruit and by Sormani *et al*. (1999) and Brambilla *et al*. (2000) on strawberry slices.

To define the influence of osmotic dehydration on fruit tissues, the changes, produced at the structural level, were studied, through texture and microscopic analysis, on strawberry slices subjected to osmotic dehydration at atmospheric pressure for different lengths of time (Brambilla *et al*., 2000). A good agreement was obtained between structural and texture changes. Light photomicrographs of osmodehydrated strawberry tissues revealed that there is a deterioration in the cell links and that the cell walls already lose their shape after 4 hr of osmotic treatment, with a consequent texture decrease (Figure 14). Furthermore, comparing dehydration methods, air-dried strawberry slices appeared tougher than osmotically dried samples at the same water content (O2/D4, O4/D5) (Brambilla *et al*., 2000; Chiralt *et al*., 2001b) (Figure 14). Similar results were obtained by other authors on kiwifruit (Robbers *et al*., 1997). This could be due to the different sample concentration profiles developed in each treatment, as the driving force is very different in each case, or to a greater degree of alteration of middle lamellae through the osmotic process. Not only the analysis of how differently soluble pectin fractions are modified, but also the analysis into the enzymatic activity during processing could help better understand the phenomenon. These results also suggest, for strawberry, osmotic pretreatments shorter than 2 hr. Also, for kiwifruit, a long immersion time in the osmotic solution did not seem to favor textural properties of the final product (Chiralt *et al*., 2001b; Muntada *et al*., 1998). Microscopic observations showed that atmospheric solute infusion of kiwifruit halves for 6 days to attain a_w equilibrium caused a contraction of cellular membranes, degradation of cell walls, and intercellular contact decrease, while a much shorter vacuum pulse infusion led to cell wall optical density similar to fresh cells (Muntada *et al*., 1998). Calcium lactate infiltration increased failure forces due to enhanced cell cohesion and increased cell wall integrity.

A decrease in firmness, linked to osmodehydration in both glucose and sucrose, was also observed in apple cylinders (Reppa *et al*., 1998). This could be due to loss of turgor pressure, which makes the cells of plant tissues less rigid, i.e., fracturability disappears while deformability increases (Aguilera

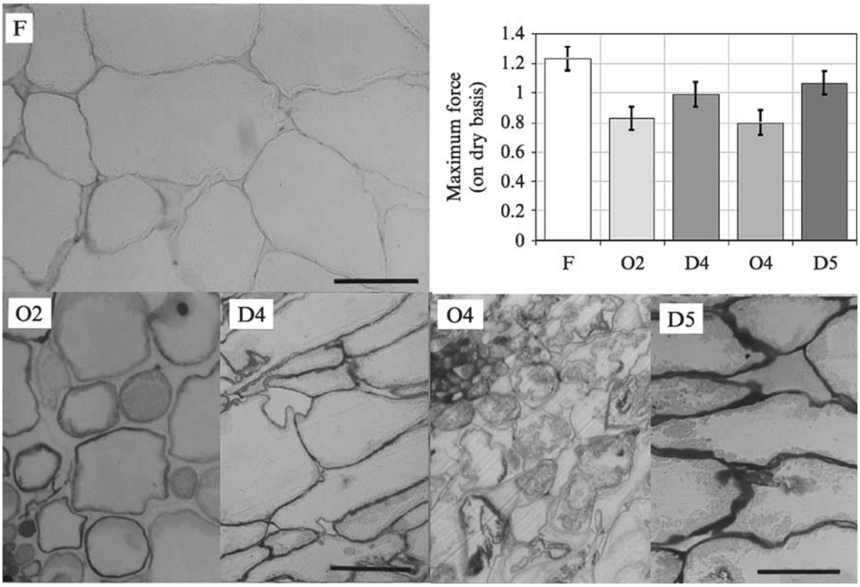

FIG. 14 Photomicrographs and texture values expressed as maximum force (kg) on dry basis of strawberry slices before (F) and after osmotic dehydration for 60 (O2) and 240 (O4) min in 60% (w/w) sucrose solution, at 25 °C at atmospheric pressure, and after air dehydration at 60 °C up to 40% (D4) and 50% (D5) weight reduction. Bars: 100 μm (Brambilla *et al.*, 2000).

and Stanley, 1990). Softening may be also caused by the formation of soluble pectins, which is promoted by low turgor, by calcium leaching from the cell wall, and by degradation of the middle lamellae (Poovaiah, 1986). Osmotically dehydrated apples had a semichewy consistency. As textural properties of fruits are closely linked to cellular structure and pectic composition (Ilker and Szczesniak, 1990), three cultivar of strawberry and a cultivar of kiwifruit at three ripening stages were studied for the influence of osmotic treatment on the modification of texture and of water-soluble, oxalate-soluble and residual insoluble pectin fractions (Forni *et al.*, 1998; Torreggiani *et al.*, 1998a,b). For strawberry, the cultivar influenced solid–liquid exchanges during osmotic dehydration applied for 1 hr in a 70% (w/w) fructose syrup, showing the great importance of the tissue structure and the size and architecture of the intercellular spaces. Osmotic dehydration caused a slight decrease of texture values of strawberry, correlated with a decrease in the oxalate-soluble and residual pectin (protopectin) fractions, considered as determining fruit firmness. As for texture, and thus ripening stage of kiwifruit, the lower the texture level, the lower the solid gain, while water loss was higher in firm (unripe) fruit. No relationships were found between texture changes and pectic composition of kiwifruit during osmotic treatment applied for 2 hr in a 70% (w/w) sucrose syrup, confirming the utmost importance of species. Knowledge of the changes in mechanical properties, linked to osmotic dehydration conditions and to fruit and vegetable characteristics, will be of essential importance in the optimization of the combined process of dehydrofreezing.

Vast literature indicates the usefulness of partial water removal prior to freezing, referring to numerous species of fruits (Torreggiani, 1995), which has also been confirmed for muskmelon and guava. Muskmelon spheres, predehydrated by osmotic dehydration, were significantly more acceptable than those preair dehydrated, confirming the suitability of osmotic dipping as a pretreatment in the production of innovative high-quality frozen products (Maestrelli *et al.*, 2001). Blanching and osmotic treatments improved texture and color retention and also reduced drip losses of freeze-thawed guava halves (Aguilar-Bernal *et al.*, 2001).

The combined technique of dehydrofreezing has proven to be useful even in improving the quality of a delicate tissue such as that of strawberry. The structural collapse, after thawing–rehydration of strawberry slices, was reduced by adopting partial removal of water through air dehydration, osmotic dehydration, or their combination (Maestrelli *et al.*, 1997). A reduction in moisture content of at least 60% is needed to improve the texture characteristics of thawed–rehydrated fruit, irrespective of the dehydration method used. These data were confirmed by Martìnez-Navarrete *et al.* (2001) on strawberry halves; changes, promoted by freezing on mechanical and color attributes of the fruit, were smaller in samples osmodehydrated previously, thus having a lower water content.

Microscopic analysis on predehydrated and freeze-thawed strawberry slices confirmed these findings, showing that the reduction of freezing damage is due to the decrease in moisture content (Sormani *et al.*, 1999). Predehydrated strawberry slices retain the tissue organization after thawing, whereas untreated ones show a definite continuity loss and thinning of the cell wall. Osmotic dehydration, applied for 4 hr, even if it causes structural damage by itself, has been proven to improve tissue organization of the thawed fruit; the protective effect, due to the reduction of water content, overcomes the tissue damage induced by the process. Although the processing time is longer, application of an osmotic step alone or in combination with air dehydration could, through the incorporation of sugars, improve color, flavor, and vitamin retention during frozen storage, as described further in Section III.C.2.C.

The analysis of how differently soluble pectin fractions of strawberry slices are modified by air dehydration, combined osmotic–air dehydration, applied before freezing, and freezing itself indicated that protopectin (residual insoluble pectin fraction) content decreases significantly during air dehydration, with the osmotic step reducing the loss (Brimar, 2002) (Figure 15). Freezing causes a significant reduction of protopectin content, with the biggest effect occurring in strawberries not predehydrated before freezing. The different losses of protopectins in differently predehydrated fruits could explain the differences in texture observed in freeze-thawed fruits (Figure 15). Osmotic treatments using selective solutes can also allow cryoprotection of the cell during freeze-thawing (Burke *et al*., 1976; Tregunno and Goff, 1996; Wolfe and Bryant, 1992).

Another interesting treatment is vacuum infusion with cryoprotectants (sugars from concentrated grape must) and cryostabilizers (HM pectin), which was applied to reduce ice crystal damage in frozen apple cylinders and to improve the fruit resistance to freezing damage through a notable reduction of freezable water (Martìnez-Monzò *et al*., 1998a,b).

The addition of cryoprotectants and cryostabilizers in the formulation changed the glass transition temperature (Tg') of the maximally cryoconcentrated food liquid phase and the freezable water content of strawberry impregnated, under vacuum or at atmospheric pressure, with sucrose and sorbitol acqueous solutions, added or not with ascorbic acid (Vidales *et al*., 2001). The analysis of the product microstructure by light and transmission electron microscopy showed that tissues subjected to vacuum had higher cellular tissue integrity and that the ascorbic acid addition preserved the cellular tissue better in all the samples.

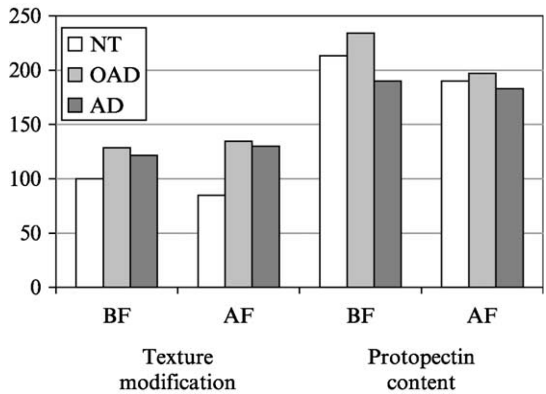

FIG. 15 Texture modification (percentage of raw fruit texture) and protopectin content (mg/100 g wet weight) before (BF) and after (AF) freezing of strawberry slices not pretreated (NT) or air dried at 80 °C up to 60% weight reduction without (AD) or following 60-min osmotic dehydration (OAD) in 60% (w/w) sucrose solution at 25 °C at atmospheric pressure (Brimar, 2002).

Partial dehydration before freezing could even enhance the resistance of texture of frozen strawberry slices and apricot cubes to a thermal treatment (Torreggiani *et al*., 1999b,d). For fruit to be incorporated as a food ingredient, e.g., in yogurt, a heat treatment has to be applied, but this causes texture damage, as does freezing. To reach a texture improvement after the proposed heat treatment, a moisture reduction, before freezing, of at least 50% is needed for both strawberry and apricot, irrespective of the dehydration method used. This percentage of moisture reduction is what is required to reduce the freezing damage of the fruits at thawing (Maestrelli *et al*., 1997), making it evident that the freezing step is the most crucial point in the production process of thermally stabilized strawberry and apricot ingredients. If the freezing damage is limited, then the fruit texture can be improved even after heat treatment.

2. *Pigments and vitamins*

Together with a texture improvement, the penetration of solutes, combined with a dehydration effect, could modify the fruit composition and improve pigment, color, and vitamin retention during frozen storage.

According to the kinetic interpretation based on the glass transition concept, physical and chemical stability is related to the viscosity and molecular mobility of the unfrozen phase, which, in turn, depends on the glass transition temperature (Champion *et al*., 1997; Karel *et al*., 1993; Slade and Levine, 1991). When the temperature is at or below *T*g', diffusion-limited changes occur at very slow rates, i.e., stability, if based on diffusion-limited events, is excellent. However, it must be kept in mind that many chemical changes are not diffusion limited. The rates of presumed diffusion-controlled reactions are considered proportional to the difference between the *T*g', also called mobility temperature (Reid, 1999), and the temperature of study. Manipulation of mobility temperatures, through composition, could therefore influence reaction rates. So, if through osmotic dehydration the fruit formulation can be modified and thereby an increase in the glass transition temperature could be obtained, then there could also be an increase in storage stability.

While the kinetic interpretation, based on the glass transition temperature, holds for chlorophyll and vitamin C stabilization in kiwifruit, for the anthocyanin pigments in strawberry, a simple relationship does not exist between the pigment loss and the amplitude of the difference between the storage temperature and the glass transition temperature of the maximally freeze-concentrated phase. Incorporation of an osmotic step of different sugars into kiwifruit slices modified their low temperature phase transitions and increased chlorophyll and vitamin C stability significantly during frozen storage at $-10\,^{\circ}C$ (Torreggiani and Bertolo, 2001; Torreggiani *et al*., 1994).

Kiwifruit pretreated in maltose, and thus having the highest *T*g' values, showed the highest chlorophyll and vitamin C retention.

The osmodehydrated strawberry halves showed pigment retention significantly higher than that observed in fruit frozen without a concentration pretreatment, but no differences were observed among fruit osmodehydrated in the different sugars, thus having different glass transition temperatures (Torreggiani *et al*., 1995b). The sorbitol-treated strawberry slices, which had the lowest glass transition temperature, showed the same anthocyanin retention as sucrose- and maltose-treated fruits, confirming the results obtained on strawberry juices added with different sugars (Torreggiani *et al*., 1999a). Other factors, such as the pH of the unfrozen phase and the specific chemical nature of sorbitol, could have influenced the anthocyanin degradation. Osmotic treatments carried out before strawberry freezing increased the ascorbic acid degradation rate during storage at −4 °C, while ascorbic acid retention was observed at −24 °C (Rubiolo and Amer, 2001).

3. *Aroma compounds*

Aroma is one of the major determinants of fruit quality, and the retention or loss during osmosis and air dehydration, applied before freezing, was investigated on muskmelon spheres in order to obtain high-quality innovative frozen products (Maestrelli *et al*., 2001). Results ascertained the crucial importance of the cultivar, which had a great influence on the quality characteristics of the end products. Among the pretreatments, air dehydration caused a significant increase of alcohols, while these "negative" aroma compounds, responsible for the fermented note, were stable in osmo-treated fruit (Lo Scalzo *et al*., 2001) (Figure 16). Furthermore, osmosis prevented the increase of alcohols during the freezing process. This finding could explain the higher sensory acceptability of the fruit pre-osmo when compared with those pre-air dehydrated.

The effect of osmotic process conditions on the volatile fraction of strawberries was analyzed by Talens *et al*. (2002), as well as the effect of freezing and frozen storage. Treatments with 65% (w/w) sucrose solutions showed the same behavior as observed by Di Cesare *et al*. (1999) and Escriche *et al*. (2000, 2001a): there was an increase in some ethyl esters and furaneol but a decrease in isobutyl ester and hexanal, with the changes being slightly lower in pulsed vacuum osmotic treatments (PVOD). Different changes in the volatile profile can be expected, depending on osmotic process conditions and duration. Freezing and frozen storage implied losses in all components, although in predehydrated strawberries the concentration of some esters (and furaneol) remained greater than in fresh ones due to the formation promoted during the osmotic step.

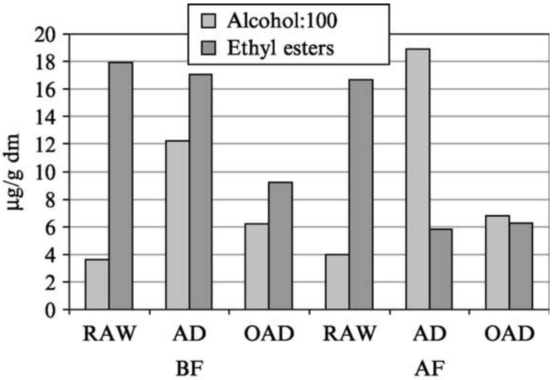

FIG. 16 Alcohol and ethyl esters content before (BF) and after (AF) freezing of melon spheres cv. Rony not pretreated (RAW) or air dried at 80 °C up to 50% weight reduction without (AD) or following 60-min osmotic dehydration (OAD) in 60% (w/w) sucrose solution at 25 °C at atmospheric pressure (Lo Scalzo *et al.*, 2001).

Osmotic dehydration also caused changes in the volatile profile of kiwifruit, depending on the treatment conditions applied (Talens *et al.*, 2003). The concentration of the ester fraction increased, whereas aldehydes and alcohols decreased. The behavior of the volatile profile was similar to that described for kiwifruit ripening (Young and Paterson, 1985). This suggests that osmotic stress might imply an acceleration of the maturation process at the cellular level, in line with an enhanced enzyme action (Escriche *et al.*, 2000, 2001a; Zabetakis and Holden, 1997), which results in volatile compound concentration. Migration of some compounds into the osmotic solution could also contribute to the observed decrease in hydrosoluble components. Vacuum pulse application and process time promoted ester formation. Nevertheless, the decrease in aldehydes and alcohols was greater in treatments carried out at atmospheric pressure. After 1 month of frozen storage of kiwifruit slices, a severe reduction of all compounds (esters, aldehydes and alcohols) occurred, which resulted in very small differences in the volatile profile of fruit directly frozen and previously dehydrated in different conditions. The sensory impact of these differences needs to be analyzed.

D. FORMULATION

Soluble solids uptake due to osmotic dehydration, in addition to improving color, aroma, and vitamin stability during both air drying and frozen storage, could also play a very important role in the preparation of new types of ingredients at reduced water activity (Torreggiani *et al.*, 1988). Due to the soluble solid intake, the overall effect of osmotic dehydration is a decrease in water activity, with only a limited increase in consistency. Consistency is actually associated with the plasticizing and swelling effect of water on the pectic and cellulosic matrix of the fruit tissues. Hence, it depends primarily on the insoluble matter and water content rather than on the soluble solids and water activity. In this way, low water activities may be achieved while maintaining an acceptable consistency.

A general representation of the extent to which physical changes can be induced, and functional properties can be controlled in practical processing, can be obtained by developing, according to Maltini *et al*. (1993), a "functional compatibility map." These maps illustrate that functional properties, gained by using single or combined steps, are related to the water activity, which is the main parameter making the ingredients compatible with the food. In the maps, a relationship is reported among the phase composition (i.e., the relative amount of insoluble solids, soluble solids, and water), the texture index, and the water activity of the fruits after processing. The two sets of data, referring to partial dehydration of raw fruit and partial dehydration of osmotically treated fruit, are presented in the same diagram and give a pair of curves for phase composition and for texture.

The difference between the upper and the lower curves for phase composition and texture, at equal water activity, is the result of the solid gain after osmotic treatment. The higher the solid uptake, the higher the difference in texture. Compared to simple air dehydration, the combination of osmotic dehydration and air dehydration can produce a softer product at low water activity, which is more pleasant to eat by hand, or to incorporate into pastry, ice cream, cheese, yogurt (Giangiacomo *et al*., 1994), and so on.

The choice of the osmotic syrup plays a very important role and the specific effect of the solution has to be taken into account. The choice depends mainly on taste, cost, and a_w-lowering capacity together with the possible kinetic hindering of the diffusion-controlled reaction during frozen storage. Fruit juice concentrates have similar osmotic properties to high fructose syrups (Maltini *et al*., 1990), and resulting products are of total fruit origin. If a concentrated fruit juice is used as osmotic solution, an even softer product could be obtained because of the higher content of monosaccharides in the fruit juice compared to the amount contained in syrup from starch hydrolysis and because of the higher relative water content at a determined water activity (Torreggiani *et al*., 1988). If a fructose syrup contains sorbitol, softer osmodehydrated apricot, clingstone peach cubes, and sweet cherry halves can be obtained when compared with the same fruit osmodehydrated in fructose alone (Erba *et al*., 1994; Torreggiani *et al*., 1997). The presence of sorbitol in HLS also leads to a lower texture in osmodehydrated red pepper cubes (Torreggiani *et al*., 1995a). Moreover, as reported previously, sorbitol has a specific protective effect on color during the air-drying step.

E. FUNCTIONAL FOODS

A functional food is defined as "any food or food ingredient that may provide a health benefit beyond the traditional nutrients it contains" (Mazza, 1998). Vacuum infusion allows the introduction of controlled quantities of a solution into the porous structure of fruit and vegetables (matrix) and can be used in the development of products fortified with physiologically active compounds (PAC) (Betoret *et al.*, 2001; Fito *et al.*, 2001b). Porosity of the solid matrix is the most crucial factor, which is involved in VI effectiveness; in plant tissues, porosity may be very high (20–30%) such as in apple, eggplant, or orange peel, meaning VI can be highly effective (Gras *et al.*, 2001; Salvatori *et al.*, 1998a) (Table I). From structural properties of food matrices and physicochemical characteristics of PAC solutions, the PAC concentration required in the impregnation solution to achieve an established percentage of PAC recommended daily intake (RDI) in a serving of the final product can be calculated through a mathematical model. The model has been validated with experimental data obtained with calcium-enriched eggplant, zucchini, and carrot using calcium lactate (Betoret *et al.*, 2001). If ferric citrate is used, structural and physicochemical limitations make the process nonfeasible.

The effectiveness of VI can be evaluated through cryo-SEM observations comparing fresh and impregnated tissues (Fito *et al.*, 2001b). Different tissues behave differently. The particular cellular arrangement in citrus peel albedo gives sponge-like properties to the peel with a great impregnating and swelling capacity. The eggplant parenchyma shows a similar structure to albedo in as far as the cell-bonding zones are enlarged or tubular, although cell sizes are greater.

The vacuum impregnation technique also represents a good choice for developing high-quality peel products alone or as ingredients, taking advantages of their interesting structure and composition. There has been a large increase in the amount of processed citrus fruits on the market in industrialized nations, which, however, has generated large amounts of by-products derived from peel. Citrus peel components provide many health benefits, among which the following should be pointed out: the effect of pectin on glycemic control, serum cholesterol concentration, cancer prevention, and control of mineral balance (Larrauri *et al.*, 1995) and the effect of limonene on cancer prevention and the vitamin activity of carotenoids (Girard and Mazza, 1998). The development of new processing methods that preserve or increase the nutritional quality of peels is necessary in order to develop new

TABLE I
PHYSICAL–CHEMICAL PROPERTIES AND VACUUM IMPREGNATION RESPONSE OF FRUITS AND VEGETABLES

Product	Geometry	ρ_a[a]	$\gamma 1$[b]	γ[b]	ϵ_e[c]
Apple, *Granny Smith* (Salvatori *et al.*, 1998b)	Cylinder ($d = 20$ mm, $h = 20$ mm)	802 ± 10	1.7 ± 0.3	−0.6 ± 1.2	21 ± 0.9
Apple, *Golden* (Salvatori, 1998b)	Cylinder ($d = 20$ mm, $h = 20$ mm)	787 ± 14	2.58 ± 0.2	−6 ± 0.5	17.4 ± 0.8
Mango, *Tommy Atkins* (Salvatori *et al.*, 1998b)	Slices ($t = 10$ mm)	1022 ± 5	5.4 ± 0.5	8.9 ± 0.4	5.9 ± 0.4
Strawberry, *Chandler* (Salvatori *et al.*, 1998b)	Pieces ($d = 50$ mm)	984 ± 9	2.9 ± 0.4	−4 ± 0.6	6.4 ± 0.3
Kiwi, *Hayward* (Salvatori *et al.*, 1998b)	Cubes ($l = 50$ mm)	1051 ± 6	6.8 ± 0.6	0.8 ± 0.5	0.7 ± 0.5
Pineapple, *Española Roja* (Salvatori *et al.*, 1998b)	Cross slices ($t = 10$ mm)	1030 ± 2	1.8 ± 0.4	2.3 ± 0.4	3.7 ± 1.3
Orange peel, *Valencia Late* (Cháfer *et al.*, 2001b)	Rectangles (2×7) ($t = 5$ mm)	770 ± 2	2 ± 0.02	14 ± 0.03	21 ± 0.04
Mandarin peel, *Satsuma* (Cháfer *et al.*, 2001b)	Rectangles (2 × 7) ($t = 4.5$ mm)	849 ± 3	−3 ± 0.02	12 ± 0.13	25 ± 0.11
Eggplant, *Soraya* (Gras *et al.*, 2001)	Cubes ($l = 25$ mm)	417 ± 5	−1.8 ± 0.7	−37 ± 5	64.1 ± 2
Carrot, *Nantesa* (Gras *et al.*, 2001)	Slices ($t = 10$ mm)	1036 ± 8	1 ± 1.1	3 ± 0.6	13.7 ± 2
Zucchini, *Blanco Griser* (Gras *et al.*, 2001)	Cross slices ($t = 10$ mm)	841 ± 17	3 ± 8	4 ± 1.6	4.4 ± 0.9

[a]Apparent density (kg/m^3 of sample).
[b]Relative volume deformations of initial sample at the end of the vacuum step and at the end of the atmosferic step, respectively.
[c]Effective porosity.

peel products. In this sense, VI could represent a very interesting tool to be used to introduce sugars (Chàfer *et al*., 2001a), preservatives, nutraceuticals, and so on into their highly porous structure (Spiegel-Roy and Goldschimdt, 1996). The peel porosity (gas volume fraction) is located in the albedo zone, the white and spongy part of the peel, which consists of enlarged parenchymatous cells with great intercellular spaces (Spiegel-Roy and Goldschimdt, 1996), while the flavedo zone shows a very compact cellular structure, which is covered with a layer of natural wax, and contains oil glands (Storey and Treeby, 1994). The impregnation and swelling capability of orange peel, subjected to osmotic dehydration, was shown through the great uptake of osmotic solution in the product, especially when vacuum pulse was applied at the beginning of the osmotic process, thereby promoting the peel vacuum impregnation (Chàfer *et al*., 2001b,c). The great intercellular spaces in the albedo part were completely flooded by osmotic solution, as could be observed by cryo-SEM (Chàfer *et al*., 2001c). The VI impregnation response of orange, mandarin, grapefruit, and lemon peels was characterized by using different kinds of isotonic solutions, and the response was correlated with the peel microstructure (Chàfer *et al*., 2003). The particular cell arrangement of albedo explains the ability of the samples to swell in line with both the out flow of internal gas (during the vacuum step) and the impregnation of the pores with external liquid. Because cells are nonturgid and wide open in their packaging, they do not offer great resistance to structure swelling. Additionally, the great amount of water-soluble and compatible polysaccharides in the extracellular volume contributes to the retention of a great amount of water (from the external solution). Even in the case of compounds with very low water solubility, the required amount may be introduced because of the great amount of solution that can be impregnated into the samples.

F. JAM MANUFACTURING

Osmotic pretreatments of frozen strawberries have been proposed in the production of high-quality strawberry jams (Viberg *et al*., 1998). Density changes in the fruits when they are immersed in different osmotic solutions and volume changes of osmotically processed strawberries were studied. The reduction in density differences between the syrup and the berries reduced floating of berries, which may otherwise cause problems both during thermal treatment and after packaging. Thermal processing of the osmotically processed berries did not cause a notable change in their volume. Furthermore, when an osmotic medium is selected for the processing of strawberries or other fruit, which contain an active invertase, it should be noted that the composition can change in the course of processing (Viberg and Sjöholm, 1998).

Osmotic concentration kinetics were also studied for the purpose of manufacturing carrot preserves (Singh *et al*., 1999). The preserve quality was assessed as a function of sugar solution concentration and sample-to-syrup ratio, and the kinetics of preserve manufacture were described using an empirical equation.

G. FRYING

In recent years, the consumer's interest for low-fat snack products has increased substantially. The effect of prefry drying on frying kinetics and quality of French fries has been examined by Gupta *et al*. (2000) and Krokida *et al*. (2001a). They both indicated that prefry drying decreased the fat content of French fries and affected their color and structure properties significantly. Osmotic dehydration can be an effective pretreatment to produce low-fat French fries (Krokida *et al*., 2001b). The mass transfer phenomena (both water loss and oil uptake) that take place during the frying of French fries get less intense. Color darkening takes place during osmotic dehydration, as observed in other vegetables, and browning reactions during frying are promoted, resulting in more dark and red-colored fried products. Salt-treated samples have the most acceptable color. The osmotic pretreatment increases total porosity for both maltodextrine and salt solutions, with the exception of the sugar solution, which decreases the total porosity due to the higher solid gain. The specific volume of osmotically pretreated samples decreases for sugar while it increases for maltodextrine solutions in comparison with that of untreated samples during frying.

H. FOOD SALTING PROCESSES

Despite a wide range of possible applications (Figure 17), only a few studies have been carried out since 1992 to assess the osmotic treatment of fish and meat products in concentrated solutions. An exhaustive review of these processes has been presented by the leading research group in this field, belonging to CIRAD (Collignan *et al*., 2001). The first part of the review focuses on the study of mass transfer that occurs when an animal protein structure is placed in contact with a concentrated solution, and this study is aimed at clarifying the mechanisms involved and evaluating the potential of this technique as an alternative to conventional processes. The second part assesses the process on the basis of product quality development during processing and storage. The third part investigates possible pilot applications of the process, while the fourth part presents successful technological applications. Several pilot development applications have been transferred

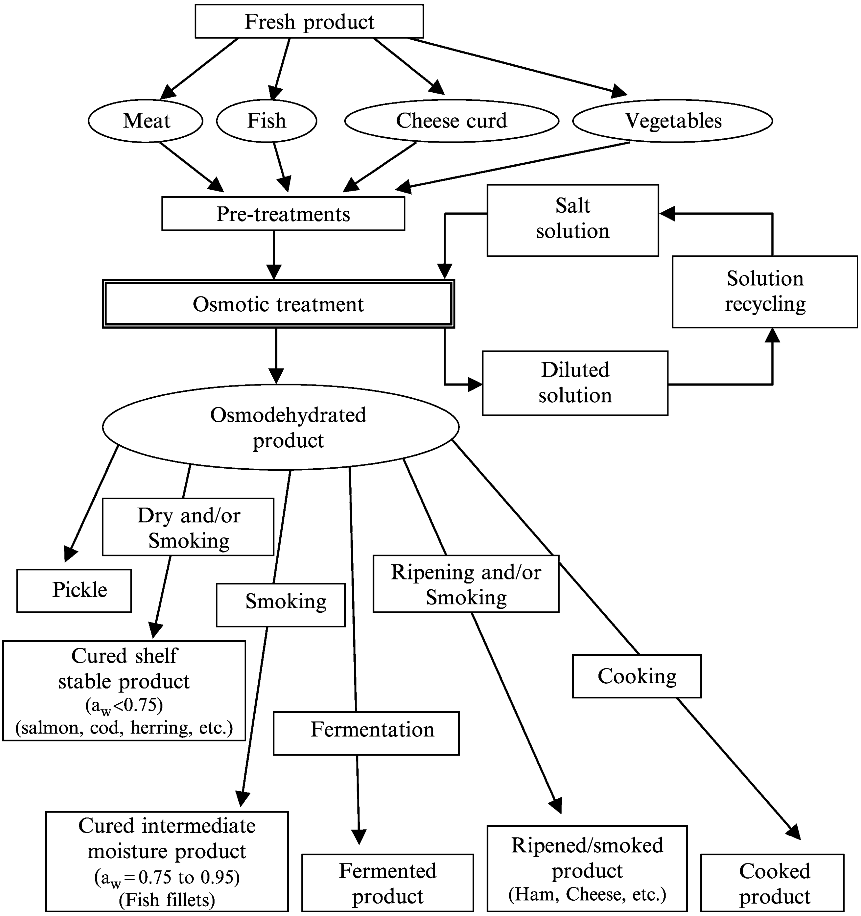

FIG. 17 Application range of salting osmotic treatment in specific fresh products.

to an industrial setting. Two patents were obtained for and extended to five EU countries for the processing of animal products. One involves a new salting, drying, and smoking process system that combines an immersion salting and drying process with electrostatic smoking (Collignan *et al.*, 1992b). The other patent was taken out for a dehydration and impregnation by drenching (DID) process system for marinating fish fillets (Marouzé *et al.*, 1996). Furthermore, a prototype for salting, drying, and cold smoking of fish has been developed for small-scale applications and validated under Réunion (French tropical island) production conditions (Collignan *et al.*, 2001). Processing in aqueous solutions also enables decontamination of a product surface; an interesting avenue was explored in a study on stabilizing seafood products by quick treatment in an acid solution (Poligné and Collignan, 2000).

The use of brine vacuum impregnation (BVI), instead of dry salting or brine immersion (BI) at atmospheric pressure, was reviewed by Chiralt *et al.* (2001a). The influence of different process variables (length of vacuum pressure period, temperature, sample structure, and dimension) is analyzed in terms of kinetic data and process yields for meat (ham and tasajo), fish (salmon and cod), and cheese (Machego type cheese). VI can be highly effective in plant tissues, as porosity, the most crucial factor involved in the process effectiveness, may be very high (20–30%) such as in apple, eggplant, or orange peel (Gras *et al.*, 2001; Salvatori *et al.*, 1998b). Nevertheless, curd, meat, and fish are much less porous, and an important part of the matrix is occupied by the free liquid phase that may be released from the matrix by pressure changes. One consequence of the important role of food microstructure in BVI operations is a greater variability in the final salt content of the product than that obtained in conventional brining. This is due to the coupling of different phenomena throughout the salting process, all of which are affected by food structure: pore impregnation or partial collapse and diffusion in the fluid liquid phase, whose volume fraction is affected by the impregnation level. When characteristic times of deformation and impregnation of the solid matrix are very similar, each one can occur to different degrees with a notable repercussion on the salt transport behavior. Likewise, in products where porosity can be affected greatly by process conditions, such as pressed curd, a careful control of these variables is necessary to assure a constant value of porosity that implies homogeneous behaviour in BVI (Gonzàlez-Martìnez *et al.*, 1999). In general, the salt content, required in the product liquid phase to assure further product stability, is reached in BVI at higher moisture levels, which may imply a juicier product. In cured products such as cheese or Spanish ham, the different concentration profiles in the first ripening period may suppose small changes in the ripening patterns, texture (Pavia *et al.*, 1999), and volatile profiles (Escriche *et al.*, 2001b). Nevertheless, in practical terms, differences between production batches may be greater than those induced by salting methods. In conclusion, BVI techniques, if applied to porous foods, lead to a notable reduction of salting time, increasing the process yields in line with the greater values of the ratio salt gain to water loss. Likewise, samples lose natural gas or liquid phases entrapped in their structure and reach a flatter salt concentration profile than that obtained in conventional salting methods (Barat *et al.*, 1998b). Nevertheless, careful control should be taken with process variables, especially with those affecting the sample impregnation level, in order to ensure a homogeneous salting level.

IV. SOLUTION MANAGEMENT

The response to environmental and economic questions for the management of osmotic solutions has been recognized as one of the "technical hurdles" to the industrial outbreak of the process itself (Dalla Rosa, 1999). A very comprehensive review has been made by the participants of the "solution management subgroup" within the frame of the concerted action FAIR CT96-1118 and has been summarized by Dalla Rosa and Giroux (2001). This review takes into account items related to the solution changes during the process, the possibility to restore or reuse the solution itself, and the relationship between the food subjected to dehydration and the solution properties (Figure 18).

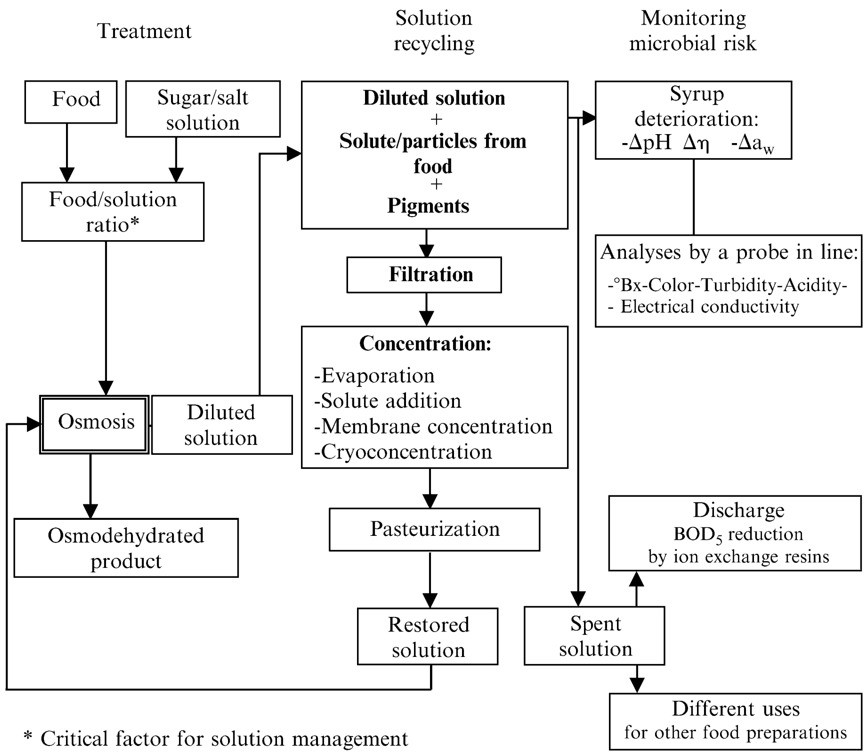

FIG. 18 Idealized flowchart of solution management and control system during direct osmotic treatments of plant or animal materials.

A. SOLUTION MASS AND DILUTION

As for the solution mass and dilution, a ratio food/solution 1:5 or lower, and thus a great amount of solution, has always been proposed in order to assure a constant rate of solid/liquid exchanges. The dilution rate can be modeled, and the dewatering capacity of the diluting solution can also be described and previewed easily in terms of reduction of chemical potential or difference of osmotic pressure between hypertonic solution and food. The dilution rate also depends dramatically on the type of food processed and reduces the osmotic capacity of the solution. Techniques have been developed to avoid large amounts of solution quantity, placing the food in equipment where the solution is sprayed onto the food; with this technology the food/solution ratio can be increased up to 1:2 (Marouze *et al*., 1996). This reduction of volume is also necessary to limit environmental impact, vis-à-vis a more demanding legislation.

B. SOLUTION RECYCLING

The most promising way to reduce environmental impact would be to reuse the concentrated solution for as long as possible. However, loss of solutes and particles from food into the solution were reported by many authors, leading to chemical, chemical–physical, and sensory changes of the osmotic solution itself. Specific research on the influence of the repeated use of a sugar solution has been carried out on treatments of papaya, pineapple, and peach (Argaiz *et al*., 1996), of apple (Valdez-Fragoso *et al*., 1998), of sour cherries (Szymczak *et al*., 1998), and of apple and stoned cherries (Giroux *et al*., 2001). It was shown that it was possible to reuse the solution between 5 and 20 times, depending on the treated fruit, without any impact on the main mass transfers in the products and with good microbial quality of the solution. The use of activated carbon or polyvinylpolypyrrolidone (PVPP) for decoloration of used syrup has been proposed by Szymczak *et al*. (1998) and has led, especially for the activated carbon, to nonsignificant differences on dehydrated fruit color between fresh and recycled syrups.

C. SOLUTION CONCENTRATION RESTORING

When reusing the osmotic solution, the first main problem is to restore the solute concentration. The technological answers that could be suggested include both phase and nonphase changing processes:

- evaporation (atmospheric at high temperature; under vacuum at moderate temperature)

- solute addition (no phase change)
- membrane concentration (no phase change)
- cryoconcentration

Evaporative restoring is probably the most popular technique to be implemented industrially for a medium/large production plant, as the cost of evaporators is relatively low. However, it is necessary to study the engineering and energetic aspects of the applied method of water removal, mainly the knowledge of the energy consumption in the osmotic process and the comparison between a per-unit energy consumption in this technique with that of other methods of water removal. The only research on this aspect related to fruit processing is still that of Lenart and Lewicki (1988) and Collignan *et al.* (1992a). Results indicated that per-unit energy consumption during convection drying of fruit and vegetables was two to three times higher than that of osmotic dehydration and syrup reconcentration through an evaporator. More recent data can be found for meat and fish osmotic treatment, mainly for processes already patented (Collignan *et al.*, 2001; Giroux *et al.*, 2001).

Restoring the solution concentration by adding dry solute or mixing with concentrated solution can save energy costs as it avoids heat of evaporation and the need for expensive plants. The method can be suggested successfully for small-scale production, at a low-technological level process, where the initial solution mass is small. Indeed, the main hurdle of this technique is the increase of the solution mass, even if a constant loss in volume of syrup (9–14%) is due to adherence to the food pieces (Bolin *et al.*, 1983).

Salt solution recycling is often a necessity in other food processing industries, such as in the cheese and table olive industry, where the reuse of salting brine is very common and the brines are worked for several cycles without any fresh brine addition. For this reason, great attention has focused on innovative technological solutions applied in these sectors, which could also be utilized for syrup recycling during osmotic treatments, e.g., the use of membrane concentration, which can reach different goals other than solution restoring. This technique could be useful because it combines filtration and reconcentration without any energy cost other than the energy required for pumping. Actually, membrane processing has to take into account the fouling phenomena at the membrane interface and the difficulty of working with relatively high viscosity fluids such as the osmotic solution (40–60 Pa * s in case of 60% of solids). The use of membranes has been applied successfully for remediation and/or recycling of dairy effluents (Horton, 1997) and for brine recycling in the table olive industry (Barranco *et al.*, 2001; Garrido-Fernàndez *et al.*, 2001). An innovative model system based on the use of membranes for osmotic solution management has been proposed by

Proimaki and Gekas (2000), where mass transfer among three concentric parts of an osmotic reactor is carried out.

D. MICROBIAL CONTAMINATION

When reusing the osmotic solution, the problem of microbial contamination also has to be faced. Different sources of contamination can affect the microbial stability of the used solutions, although the water activity values, ranging around $a_w = 0.90–0.95$, should be able to limit the growth of nonosmotolerant bacteria and yeast (Valdez-Fragoso *et al.*, 1998). During processing of fruit and vegetables with a pH $\leq$ 4.5, yeast, molds, and lactic bacteria are the most frequent microorganisms released from the product into the solution, but in this situation, pathogenic bacteria are not able to grow. During processing of animal products or low acid vegetables, such as potatoes, bacteria, even potentially pathogenic, are able to grow when the dilution of the initial solution leads to an increase of water activity. Individualization of critical control point and implementation of HACCP methodology for process control become a must when osmotic treatments are carried out in order to produce minimally processed shelf-stable foods (Leistner, 1995).

If the process is carried out in a nonsterile environment and the concentration restoring takes place by evaporation at low temperature or by nonevaporative processes, the sanitation of the solution comes out as a priority to maintain the microbial load at low level. Plate heat exchangers can be used despite the high viscosity of the solution (Dalla Rosa *et al.*, 1995), taking into account the protection demonstrated by concentrated sugar solutions on the heat inactivation of microorganisms (Torreggiani and Toledo, 1986). A big problem occurring as a consequence of heat treatment is nonenzymatic browning such as caramelization and Maillard reactions, as some amino acids or proteins have been extracted from the food. The susceptibility to thermal degradation depends mainly on the presence of reducing sugars and on the pH solution; the use of corn syrup instead of mono- or disaccharides can be useful.

E. POSSIBLE USES OF THE SPENT SOLUTION

When the end point of the solution recycling is reached and the suggested methods of purification are not applicable any more, the spent solution can be directed to different uses, even though there is a lack of specific literature. Solutions coming out from fruit treatment could be used as

- Syrup for fruit canning
- Jams

- Mixing with fruit juices
- Diluting with water and addition of carbon dioxide to obtain fruity soft drinks
- Production of natural flavoring
- Bee or animal feeding, after increasing the protein content

No further uses of spent brines have been suggested.

F. DISCHARGE OF THE SPENT SOLUTION

Spent solutions that cannot be used have to be discharged as wastewater. The main problem is related to the high biochemical oxygen demand in 5 days (BOD_5) of the concentrated solution, which in addition to containing carbohydrates is now also rich in organic materials, such as protein, pectin, and acids. Ion-exchange resins have been proposed to reduce the nitrate content in spinach blanching water (Kristani *et al*., 1999) and can be suggested, together with membrane processes (Horton, 1997), also for syrup sanitation. An alternative is a biological treatment, which has proven to be successful for the treatment of black olive wastewater (Borja *et al*., 1993; Brenes *et al*., 2000).

V. SUMMARY

The complexity and vastness of the scientific field that has been reviewed in this chapter bring forth, as a natural consequence, the parallel need for further in-depth studies into some key research areas. Knowledge of the process, as a unit operation, has jumped forward due to the fruitful work of the EU-FAIR Concerted Action CT96-1118 "improvement of overall food quality by application of osmotic treatments in conventional and new processes" and could already support the application of the technique at the industrial level as a prestep in innovative combined processes. The decisive challenge for a completely successful process control and optimization has to be focused on the following problematic aspects.

- Analysis of mass transfer in ternary media, until now, has mainly involved experimental studies of model and real food. Phenomenological models could be applied to obtain a more detailed description of the mechanisms involved. However, this would require an understanding of factors such as mass transport properties and transfer dynamics of different active compounds in concentrated solutions, which have yet to be characterized.
- In pulsed vacuum immersion, a phenomenological model would be difficult to develop as solution filtration and solute diffusion mechanisms have to be considered. The main problem to be solved concerning this aspect

is the measurement of some specific properties of processed products such as effective permeability, porosity, and specific surface.

- Up until now, product quality has mainly been evaluated through analyses of end products after processing and thus the results often remain factual. Kinetic analysis of mechanisms during processing is required to gain a broader understanding of quality development while focusing on close interactions between mass transfer and reaction mechanisms.
- Widespread research has to be focused on the potential of animal product surface decontamination, which is an additional feature of processing in concentrated aqueous solutions.
- As for the management of concentrated solutions, systems have been validated for relatively simple conditions of salting and drying products in a water–salt–sugar solution to obtain low product dehydration levels. When formulating products in more complex solutions (addition of liquid-flavoring agents, combinations of several different acids, etc.), the problem arises of measuring and sustaining optimal solute concentrations (development of specific sensors) and recycling the solution for further use (reconcentration, filtration, decontamination). The analysis of systems requiring a series of separate processing operations should be recommended.
- Predictive microbiology using growth models should be implemented in order to follow the microbial behavior in fruit osmotically dehydrated/impregnated and to compute their shelf life as a function of process variables, such as concentration of osmotic medium, initial contamination of the solution, and fruit storage temperature.
- Last but not least is the question of equipment. The study and development of equipment that can simultaneously perform osmotic dehydration and solution management are essential requirements for industry in the years ahead.

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