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Review

Practical applications of vacuum impregnation in fruit and vegetable processing

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Vacuum impregnation (VI) is considered as a useful technique to quickly introduce external liquids in the porous structures of animal and plant tissues, in a controlled way. As consequence some mass transfer processes (as dewatering) are improved and also some changes in food composition may be produced. VI has broad applications in fruit and vegetable processing and provides many unique advantages. This review analyzes the main factors and responses of porous fruits and vegetables to VI processing, summarizes important developments related to VI applications in the fruit and vegetable industry, and discusses quality aspects of VI processed fruits and vegetables, as well as technical challenges and future research needs in this field.

Introduction

Osmotic treatment and vacuum impregnation

Increased interest in osmotic treatment stems primarily from the need to make improvements in the quality of food products. Osmotic treatment is applied with the goal of modifying the composition of food material through partial water removal and impregnation of solutes, without affecting the material's structural integrity. During the osmotic process, there are two major simultaneous counter-current flows due to water and the osmotic solute activity: flow of water from the food into the osmotic solution and flow of solutes from the solution into the food. In this multi-phase food system, mass transfer rates are attributed to the water and solute activity gradients across cell membranes as both solutes and water seek equilibrium. In addition, a third minor transfer process, leaching of product solutes (sugars, acids, coloring, minerals, and vitamins) into the solution occurs, but it is considered quantitatively negligible (Dixon & Jen, 1977). A wide range of applications of osmotic treatment is possible through appropriate choice and control of operating conditions, such as processing temperature, pressure, time, composition of solution, geometry of the food pieces, and contact between the food pieces and solution. Under these alternative process approaches, the entire range of osmotic process applications in fruits and vegetables can be classified in the categories described in Table 1.

Among developments in osmotic treatments of foods, vacuum impregnation (VI) may be the newest. VI of a porous product consists of exchanging the internal gas or liquid occluded in open pores for an external liquid phase due to the action of hydrodynamic mechanisms (HDM) promoted by pressure changes (Fito, 1994; Fito & Pastor, 1994). The operation is carried out in two steps after product immersion in a tank containing the liquid phase. In the first step, vacuum pressure ($p_1 \sim 50$–100 mbar) is imposed on the system for a short time (t_1) in the closed tank, thus promoting the expansion and outflow of internal gas in the product. Gas release takes the product pore native liquid with it. In the second step, atmospheric pressure (p_2) is restored in the tank for a time (t_2) with compression leading to a great reduction in volume in the gas remaining in the pores, and thus to the subsequent influx of external liquid into the porous structure (Fito, *et al.*, 2001a). In the VI processing, external liquid flows into a capillary tube because of the expansion or compression of the internal gas of a food. The volume fraction of a sample (X) impregnated by external liquid when mechanical equilibrium is achieved has been modeled as a function of compression ratio, sample effective porosity, and sample volume deformation at

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Table 1. Potential applications of osmotic processing in fruits and vegetables

Application categories	Specific examples
Partial water removal (solids concentration) followed by:	Pasteurization and cold storage Freezing Complimentary dehydration (air, vacuum, freeze, or microwave)
Solute impregnation with:	Sugars (candying) Salts (salting)
Product formulation aiming at:	Better organoleptic quality Texturization (enhancing texture characteristics by incorporation of selected texturizing agents, i.e. calcium ions, enzymes, etc.) Better nutrition (nutrition supplement) Microbial stability (anti-microbials) Combinations of the above aims
Combinations of the above three categories in successive processing steps	Development of minimally processed fruits and vegetables with extended shelf-life

the end of the process, and is described in Eq. (1) (Fito, Andres, Chiralt, & Pardo 1996):

$$\varepsilon_e = \frac{(X-\gamma)r+\gamma_1}{r-1} \quad (1)$$

where:

X = volumetric fraction of sample occupied by liquid as a result of HDM at the end of the process (m^3 of liquid/m^3 of sample at $t=0$)
ε_e = effective porosity (m^3 of gas inside the pores/m^3 of sample)
γ_1 = relative samples volume deformation at the end of the vacuum period (m^3 of sample deformation/m^3 of sample at $t=0$)
γ = final relative volume sample deformation (m^3 of sample deformation/m^3 of sample at $t=0$),
r = compression ratio (~atmospheric pressure/vacuum pressure).

The mass fraction of any component i (water or solutes) reached in a VI product is estimated from Eq. (2) (Chiralt *et al*., 1999; Fito *et al*., 1996):

$$x_i^{VI} = \frac{x_i^0 - x_{HDM}y_i}{1+x_{HDM}} \quad (2)$$

where:

x_i^{VI} = mass fraction of component i
x_i^0 = initial composition of a sample
x_{HDM} = mass fraction of impregnated solution
y_i = mass fraction of component i in the impregnation liquid.
x_{HDM} is calculated from Eq. (3)

$$x_{HDM} = X\frac{\rho^{IS}}{\rho^0} \quad (3)$$

where:

ρ^{IS} = density of VI solution (kg/m^3)
ρ^0 = density of initial product (kg/m^3).

Usually with very short values of t_2 the mechanical equilibrium is achieved and Eq. (1) gives the actual values of X. Nevertheless, when the equilibrium is not reached at the end of VI treatment, e.g. high viscous impregnation liquids, very long value of t_2 are needed, and a kinetic equation must be used. The kinetic equation for HDM has been described by Chiralt *et al*. (1999).

The possibility of introducing an external solution with specific and/or selected solutes into product pores makes VI a viable tool for the processing of highly porous fruit and vegetable products.

Unique functions of vacuum impregnation

Vacuum impregnation allows introduction of desired food ingredients directly into products throughout its pores, in a controlled way, according to the HDM model (Chiralt *et al*., 1999). VI has been widely used as a pretreatment before complementary processing steps, such as drying, freezing, canning and frying, and has an ability to modify the food formulation and to develop new products. The two unique functions of VI in food processing, especially in fruit and vegetable processing are quality improvement and energy saving. Quality improvement of porous structure of foods by VI pretreatment is largely due to the use of a gentle product treatment at a relatively low processing temperature, thus minimizing heat damage to plant tissues, and preserving color, natural flavor and aroma, and any heat-sensitive nutrient components. For example, use of sugar or syrup as VI solutions is known to prevent loss of fresh fruit volatile flavor components during ordinary air or vacuum drying methods (Escriche, Chiralt, Moreno, & Serra, 2000; Ponting, 1973; Ponting, Watters, Forrey, Jackson, & Stanley, 1966; Talens, Escriche, Martinez-Navarrete, & Chiralt, 2002; Wienjes, 1968). It was noticed that the concentration change of the volatile fraction through the VI process was lower than in osmotic dehydration (OD) processing as a result of expelling internal air during the vacuum period (Escriche *et al*., 2000; Talens *et al*., 2002). VI is effective in preventing discoloration of fruit pieces from enzymatic and oxidative browning without using antioxidants due to removal of oxygen from the pores (Alzamora *et al*., 2000; Barbosa-Canovas & Vega-Mercado, 1996; Contreras & Smyrl, 1981; Dixon, Jen, & Paynter, 1976; Ponting, 1973; Ponting *et al*., 1966). Another important factor contributing to quality improvement is

that functional food ingredients, such as firming agents, antioxidants, and antimicrobial ingredients penetrate into the pore structure of the product to effectively improve quality and extend shelf-life. For example, certain solutes impregnated into the pores were found to protect natural tissue structure, thus improving texture quality and lowering drip loss in subsequent drying, canning or freezing processes by limiting collapse and cellular disruption (Bolin & Huxsoll, 1993).

Energy saving may be achieved through VI pretreatment in two ways. First, water is removed in the liquid form without heating. Second, the partial removal of water requires less heating during the following processing steps (Barbosa-Canovas & Vega-Mercado, 1996; Girod, Collignan, Themelin, & Paoult-Wack, 1990; Jayaraman & Das Gupta, 1992; Lewicki & Lenart, 1992). However, actual energy consumption must also consider the energy needed to recycle the impregnation solutions.

Plant tissue has intercellular spaces that may contain a gas or liquid phase and are susceptible to impregnation with an external solution. Hence, the porous structure of fruits and vegetables make them amenable to VI processing for developing high quality products. This review considers the important processing factors contributing to the VI process in fruits and vegetables, recent advances of this technique in the fruit and vegetable industry, and future research needs.

Vacuum impregnation and other osmotic treatments

Three kinds of osmotic treatments have been defined, depending on the pressure applied on the system: OD (osmotic dehydration at atmospheric pressure), VOD (osmotic dehydration at vacuum pressure), and PVOD (pulsed vacuum osmotic dehydration) (Fito, Andres, Pastor, & Chiralt, 1994). In PVOD, VI with the osmotic solution takes place during the first 5–10 min of process by the action of a vacuum pulse, causes a fast compositional change in the product that will affect the osmotic driving force and mass transfer kinetics (Fito & Chiralt, 2000). The most common or familiar osmotic treatment is osmotic dehydration (OD). It is necessary to clarify this technology before moving to the discussion about VI.

Osmotic dehydration

Osmotic dehydration was first documented in 1966 (Ponting *et al*., 1966). The technology involves the partial dehydration of a water-rich solid from foodstuffs, either whole or in pieces, through immersion in a hypertonic aqueous solution, i.e. a highly concentrated sugar or salt solutions with high osmotic pressure. OD removes substantial amounts of water from a product while adding minimal solids, and is the usual process to decrease product water activity in minimally processed fruits and vegetables or in some deeply processed fruits, such as candied fruits or jam. An effective and practical osmotic process depends on a high osmotic rate, which is mainly determined by the type, concentration, and temperature of osmotic solutions, and treatment time. OD in combination with a final drying step with conventional hot air or microwave has being studied extensively, and the technology has been applied to develop dried fruits and vegetables with unique quality (Alzamora *et al*., 2000; Barbosa-Canovas & Vega-Mercado, 1996; Le Maguer, 1988; Raoult-Wack, 1994; Shi, Fito, & Chiralt, 1995; Spiazzi & Mascheroni, 1997; Torreggiani, 1993). The technology of OD itself is beyond the scope of this review.

OD under vacuum (VOD) dramatically intensifies capillary flow and favors mass transfer rate. The role of vacuum in this process is hypothesized to be a reduction in interfacial fluid tension at the solid–solution interface, prevention of tissue collapse upon moisture migration, and removal of intercellular tissue gases which are replaced by the solution on vacuum release (Andres, Salvatori, Chiralt, & Fito, 2001; Fito, 1994; Fito & Chiralt, 1997; Fito, Chiralt, Barat, & Martinez-Monzo, 2000; Fito, *et al*., 2001a; Shi *et al*., 1996). Many applications of VOD have been recently reported (Biswal, Bozorgmehr, Tompkins, & Liu 1991; Bolin & Huxsoll, 1993; Fito *et al*., 1994; Fito, *et al*., 2001a,b; Maestrelli, Scalzo, Lupi, Bertolo, & Torreggiani, 2001; Martinez-Monzo, Martinez-Navarrete, Fito, & Chiralt, 1997; Roastogi & Raghavarao, 1996; Shi *et al*., 1996; Shi & Fito, 1993; Torreggiani, 1995; Torreggiani & Bertolo, 2001). According to Fito (1994), the main advantage of VOD over OD at atmospheric pressure lies in the increased mass transfer due to the HDM and to the corresponding increment produced in the solid–liquid interfacial surface, leading to a significant reduction in processing time. Fito investigated water loss (WL) and sugar gain (SG) in apple slices subjected to OD and VOD processes in a 65% sucrose solution at 50 °C, and reported that vacuum operation significantly increased the water loss rate compared to that obtained at atmospheric pressure at the same temperature. The solute gain did not seem to be affected by the pressure. The specific applications of VOD in the development of dehydrated fruits and vegetables are reviewed in the application section of this review.

Fito (1994) further noticed that the most important HDM effect is very rapid and occurs just when atmospheric pressure is restored. Thus a new procedure, called PVOD, was designed to carry VOD. In this procedure, a short period (5–15 min) of vacuum treatment is applied to the product that is immersed in the osmotic solution. Afterwards, the product undergoes normal OD at atmospheric pressure. In this way, filling of the food pores with the same osmotic solution is induced at the beginning of the treatment. PVOD processing has most of the advantages of VOD treatments, but involves a short exposure to vacuum and a length of holding period at atmospheric pressure. Fito *et al*. (1994) found that WL and SG obtained through the PVOD procedure (a 5 min pulse at 70 mbar followed by atmospheric pressure restoration) were only slightly inferior to those achieved by the VOD procedure, but superior to those obtained at OD. In the PVOD process, VI pretreatments

were carried out with the osmotic pressure at the beginning of the process.

While OD has traditionally been used for developing dehydrated fruits and vegetables, another similar technology, called infusion has attracted great attention recently and has been applied commercially. While osmotic dehydration removes substantial amounts of water from a product while adding minimal solids, infusion maximizes osmotic movement in both directions so solutes move into the food instead of merely causing water efflux. This yields a different set of characteristics in the finished product. While the end goal of OD is the removal of water to make the product stable, infusion focuses on the two counter-flows—removal of water from and infusion of solutes into the food. Infusion technology and its applications in dried fruits and vegetables have been reviewed extensively by Kuntz (1996).

Vacuum impregnation

The term impregnation means being filled, saturated, or the process of permeating. Impregnation sometimes is used interchangeably with infusion and infiltration. Hence, all terms need to be used when searching literature.

Vacuum impregnation leads to a faster osmotic process due to the coupled action of HDM and deformation relaxation phenomena (DRP) (Fito, 1994; Fito *et al*., 1996, 2000; Shi *et al*., 1995). In the VI processing, the gas–liquid exchange causes a rapid change of the overall sample composition that modifies the process driven force at the very beginning of the process, while pores remain full of liquid. It is desirable to obtain high quality dehydrated product while limiting the duration of the impregnation time as much as possible. The characteristics of VI, OD, and PVOD, including processing conditions, driving force, controlling mechanisms, and equilibrium are illustrated in Table 2. In VI, the penetration of external liquid is caused by the combined effect of capillary action and a pressure gradient (Fito & Pastor, 1994). The HDM plays an important role in all operations involving vacuum treatments of porous food. In addition to promoting diffusional mechanisms in the pores, VI causes structural changes in the tissue different than those caused by osmotic processing. Differences in the structural features observed in VI and non-VI samples have been explained in terms of the different pressure drop of fluid in the intercellular spaces flowing towards the volume generated by cell water loss, which is very different for gas or liquid phases in the intercellular space (Fito *et al*., 2000). When there is a liquid in the pores, the force balance on the double layer plasmalemma-cell wall leads to later separation while plasmalemma shrinks in line with water loss with little deformation of cell wall. When operation is under the atmospheric pressure, where a gas phase occupies the intercellular space, plasmalemma shrinks together with cell wall that deforms greatly when osmotic process progresses. Air–liquid exchange is only attributed to the action of capillary flow function. The difference in chemical potential across a semi-permeable membrane between food sample and osmotic solution is the driving force for mass transfer, which is related to water activity and temperature. The main resistance to mass transfer is the concentration differences with the plasma membrane. The osmotic dehydration proceeds until the water activity of both the sample and the solution reaches equilibrium. In the very long treatment, such as fruits candying, the driving force of mass transfer is based on the mechanism of gas releasing and pore filling.

Main processing factors contributing to VI process

As described in Eq. (1), three phenomena are coupled in VI: gas outflow, deformation-relaxation of the solid matrix, and liquid influx. The kinetics of these phenomena are significantly affected by the following material characters (Fito *et al*., 1996):

- tissue structure (pores and size distribution)
- relaxation time of the solid matrix, a function of the mechanical properties of the material
- transport rate of HDM, a function of the structure (size and shape of pores) and the viscosity of the solution
- size and shape of the sample.

Table 2. Characteristics of a practical definition for different gas–liquid exchange processes[a]

Process	Time scale	Driving force	Controlling mechanism	Equilibrium condition	Water loss rate	Solid gain
Vacuum impregnation	Minutes	Pressure gradients and capillary action	HDM	$\Delta P_{int-ext}=0$	High	Low
Osmotic dehydration	Hours	Capillary action and chemical potential of components (mainly water)	PDM and CMD	$\Delta a_W=0$	Middle	Middle
Candying or salting	Days/weeks	Mechanical forces and pressure gradients	Gas release and pore filling	$\Delta P_{DRP}=0$, $\Delta M=0$	Low	High

HDM, hydrodynamic mechanism; DRP, deformation relaxation phenomena; CMD, cell matrix deformation. $\Delta P_{int-ext}$, pressure difference between the exterior and interior of the product (N/m^2); Δa_W, water activity difference between the solution and product; ΔP_{DRP}, pressure difference associated with the DRP of the cell matrix (N/m^2); ΔM, weight loss referred to the initial mass sample (kg/kg).

[a] Summarized from Fito *et al*. (2000).

The VI process and the quality of finished products are also determined by processing conditions, including pre-treatment of the samples (Alvarez *et al*., 1995; Valle, Aranguiz, & Leon, 1998), temperature, composition, and concentration of the VI solution, pressure and immersion time under vacuum, time to restore atmospheric pressure, agitation, and solution/sample ratio. The influence of material characteristics on VI processing has been reviewed extensively, thus is not discussed in this review (Alzamora, Gerschenson, Vidales, & Nieto, 1997; Beristain, Azuara, Cortes, & Garcia, 1990; Gras, Vidal, Betoret, Chiralt, & Fito, 2003; Kaymak-Ertekin & Sultanoglu, 2000; Lerici, Pinnavaia, Dalla Rosa, & Bartolucci, 1985; Mavroudis, Gekas, & Sjoholm 1998a,b; Mújica-Paz, Valdez-Fragoso, López-Malo, Paloub, & Welti-Chanes, 2003; Ponting *et al*., 1966; Raoult-Wack, 1994; Raoult-Wack, Lenart, & Guilbert, 1992; Roastogi & Raghavarao, 1994, 1996, 1997; Torreggiani, 1993). The aim of this review is to consider the operating variables and ways to broaden applications of the VI technique.

Type of VI solutions

One of the key factors in any type of osmotic treatment is the selection of osmotic solution. Three types of solutions are usually used in osmotic operation: (1) isotonic, a solution containing the same solute concentration both outside and inside the cell membrane; (2) hypotonic, a solution containing less solute molecules outside of the cell membrane than inside of it; and (3) hypertonic, a solution containing more solute molecules outside of the cell membrane than inside. Plant tissue cells placed in different kinds of solutions react differently. In isotonic solutions, cells neither shrink nor swell. In hypotonic solutions, the cells will swell due to water entering the cell. When placed in hypertonic solutions, the cells will shrink or shrivel due to water leaving the cell. Hence, the selection of VI solutions depends on the purpose of osmotic treatment, i.e. the type of finished product, because the type of osmotic solution significantly affects mass transfer during the VI processing, consequently the deformation and shrinkage of product might encounter. Martinez-Monzo, Martinez-Navarrete, Chiralt, and Fito (1998) and Martinez-Monzo *et al*. (1997) showed that when isotonic solutions were used (cell turgor unaltered), no significant differences in the initial and asymptotic moduli between fresh and VI apples were found. Nevertheless, the relaxation rate and total relaxation level increased in the VI samples in relation to the degree of impregnation. These results led to changes in the viscoelastic behavior of the isotonic VI samples attributed to the replacement of gas with liquid in the pores. When hypertonic solutions are used for VI operation, osmotic dehydration of samples occurs simultaneously. This contributes to changes in the chemical and physical properties of a product, promoting turgor losses and complete loss of cell elasticity after plasmolysis. The apparent elastic modulus thus decreases sharply, increasing the viscous character. VI with hypotonic solutions only implies a greater level of stress relaxation, as can be explained by an outflow of the intracellular liquid corresponding to cell rupture promoted by excessive turgor (Pitt, 1992).

The selection of VI solution should also take into consideration of following factors: nontoxicity, good sensory characteristics, high solubility, and low cost. In general, any soluble solute or solvent that is miscible can be used as a VI solution. This includes starch syrup, glycerol, ethanol, polyols, lactose maltodextrin, trehalose, L-lysine, casein, monosodium glutamate, and combinations of these solutes, such as glucose with sucrose, glycerol with sucrose, and sucrose with salt (Argaiz, Lopez-Malo, Palou, & Welti 1994; Barbosa-Canovas & Vega-Mercado, 1996; Biswal & Maguer, 1989; Ferrando & Spiess, 2001; Garrote & Bertone, 1989; Giangiacomo, Torreggiani, & Abbo, 1987; Hawkes & Flink, 1978; Hoover & Miller, 1975; Lerici *et al*., 1985). In most cases, low molecular weight carbohydrates are used for VI processing of fruits and vegetables because low molecular weight solutes quickly penetrate the samples: the smaller the molecular weight, the faster the diffusion (Stockes–Einstein Law). For example, the diffusivity of sucrose is smaller than that of glucose because the molecular weight of glucose is about one-half that of sucrose (Garrote & Bertone, 1989). High fructose corn syrup (HFCS) solution had a diffusion coefficient 32% higher than that of a sucrose solution due to the smaller molecular dimension of the monosaccharide (Andreotti, Tomasicchio, & Macchiavelli, 1983; Bolin, Huxsoll, Jackson, & Ng, 1983; Chandrasekaran & King, 1972; Lerici *et al*., 1985; Ray, 1960). Thus, fruits impregnated by HFCS had lower water activity than those treated, at the same operation conditions, with a sucrose solution because of the faster penetration rate of HFCS (Bolin *et al*., 1983; Chandrasekaran & King, 1972). VI in HFCS also resulted in a lower WL and a higher SG than those in the maltodextrin syrup (Mastrocola, Serverini, Lerici, & Sensidoni, 1987).

While small molecular weight sugars result in faster diffusion than those of large molecular weight sugars, some of them may impact flavor of impregnated products. Corn syrups can impart their characteristic flavor to delicately flavored products. Sensory study indicated that HFCS dehydrated fruit is sweeter than that treated with a sucrose solution. While dextrose is a more effective osmotic agent than sucrose because of its high dehydration rate (Kaymak-Ertekin & Sultanoglu, 2000), a sucrose solution was found to be slightly better than a glucose solution with respect to discoloration and sugar gain in a strawberry product (Yang & Maguer, 1992). Sucrose, corn syrup, and concentrated fruit juices have been most commonly used in fruit VI (Fito *et al*., 2000).

Solubility is another important characteristic, as the chosen solute must dissolve in the systems used at the appropriate concentration and temperature. Solubility is usually determined by molecular weight, rate of transfer,

and permeability. Fructose is very soluble, and is a very good plasticizer or softening agent. Glycerol is half the molecular weight, and thus is more effective at reducing water activity.

The use of mixed solutions consisting of two or more solutes has been proposed to take advantage of the characteristics of each solution (Raoult-Wack, 1994). A mixture of dextrose and sucrose was found to provide the highest diffusivity of water as the dextrose concentration increased in the mixed solution. Thus, low molecular weight solutes favor the impregnation processing, whereas high molecular weight solute is helpful for the dewatering effect (Kaymak-Ertekin & Sultanoglu, 2000). Hawkes and Flink (1978) combined sucrose with lactose or maltodextrin to dehydrate apple rings, and reported that during air-drying and subsequent frozen storage, maltose provided a better protection than sucrose with respect to ascorbic acid retention and color stability. This was attributed to a reduction of enzyme activity by a low level of structural damage during drying (Forni, Sormani, Scalise, & Torreggiani, 1997).

Many studies have used blends of sucrose and salt in fruit and vegetable processing to obtain a maximum WL with low SG (Biswal & Bozorgmehr, 1992; Giangiacomo *et al*., 1987; Islam & Flink, 1982; Lenart & Flink, 1984; Lerici *et al*., 1985; Qi, Sharma, & Lemaguer, 1999; Sereno, Moreira, & Martinez, 2001). It was found that adding a small quantity of sodium chloride to a sucrose solution tremendously increased the dewatering rate in fruits (Biswal & Bozorgmehr, 1992; Lerici *et al*., 1985; Sereno *et al*., 2001). The interaction between sucrose and salt was also found to limit the salt residue in the fruit samples. Because of its lower molecular weight, a small incremental increase in the sodium chloride concentration leads to significant change in osmotic pressure, whereas the same incremental increase in the sucrose concentration (higher molecular weight) does not. This means that diffusion coefficients are more sensitive to changes in sodium chloride concentration than in sucrose concentration (Ade-Omowaye, Rastogi, Angersbach, & Knorr, 2002). A high level of sugar can reduce the taste threshold for salt. Conversely, salt can enhance the sweetness of sucrose (Ade-Omowaye *et al*., 2002; Sacchetti, Gianotti, & Dalla Rosa, 2001). In general, low salt concentrations should be used in fruit processing to avoid a significant decrease in organoleptic quality.

Other aspects of impregnation solutions

Concentration, temperature, solution to product ratio, and agitation of an impregnation solution plays significant roles in VI processing. Their effects on mass transfer rate and composition of final product have been studied in several fruits, including apple (Barat, Chiralt, & Fito, 1998; Kaymak-Ertekin & Sultanoglu, 2000; Lazarides & Mavroudis, 1995; Martinez-Monzo *et al*., 1998; Sereno *et al*., 2001), mango, kiwi (Leunda, Guerrero, & Alzamora, 2000), and banana (Sousa, Salvatori, Andres, & Fito 1998). Lazarides and Mavroudis (1995) observed a corresponding increase in dehydration rate with increased solution concentration due to an increased osmotic pressure difference. Lenart and Lewicki (1990) and Roastogi and Raghavarao (1996) found that the rate of mass transfer increased to a certain extent with an increase in concentration and temperature of the osmotic solution, above which undesirable changes in flavor, texture and color occurred. Yang and Maguer (1992) reported that the stabilization or decrease in mass transfer occurred when the solution concentration reached 50–60%. Garrote and Bertone (1989) studied the effects of solution concentration of glycerol, glucose, and sucrose on halved strawberries and found that the increase in solution viscosity along with increased solution concentration resulted in a decrease in solute transfer rate, which canceled out for the increase in the concentration gradient. The smallest exudate loss was achieved in fruit held in 50% glucose and 50% sucrose solutions. Hence, there is an optimum solution concentration based on the type of final products. Barat, Chiralt, and Fito (2001) observed different results in apple slices subjected to VI treatment with 25–65% sucrose at 30, 40 or 50 °C, where concentration of osmotic solution did not show a significant effect on the effective diffusivity. It was explained that diffusion appeared to be hindered by unspecified active transport. Moreira and Sereno (2003) further investigated the effects of temperature, concentration, and flow rate of solution on osmotic dehydration/impregnation rate during immersion of apple cylinders in sugar solutions at $\leq$25 °C, and suggested that the sample SG is controlled by diffusion inside the material while water loss is governed by mixed internal–external flow. Additionally, volume changes observed in samples correlated linearly with moisture content (dry basis) and the net change in sample weight. These results indicated that shrinkage is essentially due to water removal/solid gain and offers a simple way to predict such changes during industrial processing. Sablani and Shafiur Rahman (2003) recently studied the effect of initial sucrose concentration (30–70%) and solution temperature (22–90 °C) on equilibrium distribution coefficients for mango during osmotic dehydration processing. They reported that the distribution coefficient for water decreased with increasing temperature and syrup concentration, while the distribution coefficient for solids increased with temperature and decreased with increase in syrup concentration.

In general, an increase in temperature increases the WL, while not causing a significant change in SG (Kaymak-Ertekin & Sultanoglu, 2000; Lazarides & Mavroudis, 1995; Lenart & Flink, 1984; Sereno *et al*., 2001; Yang & Maguer, 1992). The effects of temperature on mass transfer kinetics can be well predicted by the Arrhenius equation (Barat *et al*., 2001). High temperature also speeds up the osmotic process, but may cause negative effects on color, texture, and flavor of samples. Optimal temperature depends on

the type of the raw materials used, the type of finished product, and the speed of processing.

The ratio of VI solution to product is an important parameter. The optimum value is usually determined by two factors: stability of the solution during processing, and the economics of transport and recycling of the solution. A high solution to sample ratio ensures retention of a constant solution concentration during processing. However, the high ratio increases cost and necessitates solution recycling. Lenart and Flink (1984) suggested that a value of 4–6 might be optimal for the best osmotic effect.

The effect of agitating the solution on VI processing has been investigated (Bongirwar & Sreenivasan, 1977; Garrote, Silva, & Bertone, 1992; Mavroudis *et al*., 1998a; Ponting *et al*., 1966). It is clear that agitation affects WL and SG in impregnation processing (Peanagiotou, Karathanos, & Maroulis, 1998). WL is higher in the region of turbulent rather than laminar flow, i.e. VI processing can be hastened when the sample is agitated in solution. However, SG is not influenced significantly by agitation between the two regions (Mavroudis *et al*., 1998a). In some cases, the advantages of agitation do not justify the cost (Ponting *et al*., 1966).

Vacuum pressure and time

Studies have concluded that mass transfer in osmotic processing is much faster under vacuum due to the coupling of osmotic/diffusional mechanism and HDM (Fito, 1994; Fito *et al*., 1994; Fito & Pastor, 1994; Hawkes & Flink, 1978). Throughout the VI processing, vacuum pressure produces changes in the structure of the product, leading to the changes in dehydration kinetics. Effective porosity (ε_e) is an important parameter to describe sample behavior during VI processing because it determines the volume that can be occupied by the external liquid in the product tissue (Fito & Pastor, 1994). When the pressure is below 600 mbar, the experimental ε_e value is practically constant for most fruits and vegetables except for fruits like mango and peach, where ε_e increases with decrease in pressure because of the loss of native liquid during the expansion and release of the gas in the pores (Fito *et al*., 1996). A high WL rate can be obtained in low-pressure systems (Lerici *et al*., 1985; Shi & Fito, 1993), but SG differs only slightly between vacuum and atmospheric pressure treatments, as the main factor influencing the SG is the biological microstructural characteristics of plant tissue (Shi & Fito, 1993). It was concluded that vacuum treatment is effective in increasing diffusion of water and leads to a remarkable increase in WL, but not significant in the SG because of the difference between the diffusion coefficient of water and that of the solute in the product (Bolin *et al*., 1983; Spiazzi & Mascheroni, 1997). VI technology makes it possible to use a lower solution temperature or shorter impregnation time to gain a higher WL rate.

Andres *et al*. (2001) recently studied the effect of vacuum level on VI apples (*Granny Smith*) and found that only the volumetric fraction of sample occupied by liquid (X1) depends on the level of vacuum: the higher the vacuum, the more negative X1. By using a vacuum lower than 400 mbar it was possible to remove practically all the native liquid from the pore structure. Mújica-Paz, Valdez-Fragoso, Lopez-Malo, Palou, and Welti-Chanes (2002) evaluated the effect of vacuum pressure (135–674 mbar) and its application time (3–45 min) on the volume of isotonic solution impregnated in slices of mango, apple, papaya, banana, peach, melon, and mamey, and reported that vacuum pressure and time had a significant effect on the volume in all fruit slices. In general, the higher the vacuum, the greater the volume of impregnated solution. Mújica-Paz *et al*. (2003) further investigated the combined effects of vacuum level (135–674 mbar) and concentration of OS (41–60°Brix) on dehydration parameters of apple, mango, and melon. They found that the lowest final water activity level was achieved with a vacuum pressure of 674 mbar and 50°Brix syrup in apple, and 593 mbar and 57°Brix in melon.

The effect of impregnation time on sample deformation and on the amount of solutes impregnated into samples depends on the property of raw material, vacuum level, and other factors. Fito *et al*. (1996) and Salvatori, Andres, Chiralt, and Fito (1998) evaluated the X, ε_e, and γ values of apple, mushroom, banana, strawberry, mango, and apricot as a function of time under vacuum (5–20 min) and time after restoration of atmospheric pressure (5–15 min). Neither period was found to have a significant effect on ε_e values. However, different results were reported by Mújica-Paz *et al*. (2002) upon evaluating the effect of vacuum time (3–45 min) on the volume of isotonic solution impregnated into slices of mango, apple, papaya, banana, peach, and melon. It was showed that impregnation depends significantly on the VI time, except for apple. Table 3 summarizes commonly used processing parameters in VI processing of fruits and vegetables.

Table 3. Range of VI operation parameters commonly used in fruits and vegetables

Parameters	Conditions
Solution concentration	Isotonic solutions, has water activity equal to that of products, sucrose is most commonly used For minimally processed products, using 20 to <50°Brix For dehydrated foods, using 50–75°Brix
Solution temperature	Usually 20–50 °C
Vacuum level	For minimally processed products, using 5–50 mbar For dehydrated products, using 50–200 mbar
Vacuum time	Usually 10–30 min
Atmospheric restoration time	For minimally processed products, using 10–20 min For dehydrated products, using minutes to hours

Responses of fruits and vegetables to vacuum impregnation

The response of many fruits and vegetables to the VI processing with respect to deformation and impregnation has been characterized mathematically and experimentally. Impregnated sample volume fraction, sample relative volume of deformation, and effective porosity strongly depend on raw material characteristics (porosity, size, and shape), and VI conditions (type and concentration of solution, vacuum level, and time). In general, positive volume deformations (decrease in volume) at the end of the vacuum step were obtained due to deformation of the solid matrix associated with depression and gas expansion. At the end of the compression period, deformation was negative or positive depending on the nature of fruit. With reference to the liquid phase fluxes, most fruits received a net gain of liquid at the end of vacuum step due to loss of native liquid as pore volume initially occupied by native liquid is available for impregnation by the external solution. The expelled native liquid was then replaced by the external one throughout the compression step. Fito *et al*. (1996) and Salvatori *et al*. (1998) reported that the level of final impregnation is greatly affected by the coupling of penetration-deformation phenomena due to the viscoelastic response of plant tissue to pressure gradients. The compositional, mechanical, and structural changes in VI fruits have been reviewed (Fito & Chiralt, 2000; Salvatori *et al*., 1998). The focus of this review is to provide the most updated information in the responses of microstructural, thermal, and physicochemical properties of fruits and vegetables to VI process from the point of view in practical applications.

Microstructure of fruits and vegetables

The structural properties of osmotic treated plant materials are usually determined by the analysis of texture, mainly tissue failure or changes in bulk volume (Barat *et al*., 1998; Maltini, Torreggiani, Rondo Brovetto, & Bertolo, 1993). Few studies have reported on structural changes at the cellular level, which are only accessible through microscopic observations. Ferrando and Spiess (2001) analyzed the impact of three disaccharides (sucrose, maltose, and trehalose) on cellular shrinkage and cell viability in onion epidermis and strawberry cortex tissue during osmotic treatment using a confocal scanning laser microscope. Structural and functional characteristics of the VI treated sample depended on damage to the cell wall, the middle lamella, and to the plasma membrane. The choice of sugar employed significantly affected shrinkage behavior of onion epidermis, but not that of strawberry tissue. Maltose and trehalose were found to be protective towards the plasma membrane in onion epidermis (Ferrando & Spiess). Fito, *et al*. (2001a) conducted structural analysis on eggplant and orange peels impregnated with an isotonic solution containing iron and calcium salts by using Cryo-Scanning Electron Microscopy. They reported that the higher the porosity of the product, the wider the intercellular spaces. Torreggiani and Bertolo (2001) analyzed product microstructure by light and transmission electron microscopy. Their results showed that tissues subjected to vacuum had higher cellular tissue integrity. Mauro, Tavares, and Menegalli (2002) studied the effect of sucrose solutions on the cellular structure of potato tissue in equilibrium at 27 °C using a histological technique to photograph potato cells after osmotic treatment, and showed that extended exposure to osmotic solutions in equilibrium led to degradation of cell structure. Gras, Vidal-Brotons, Betoret, and Fito (2002) evaluated changes in the microstructure of different vegetables, including mushrooms (*Pleurotus* and *Agaricus* spp.), carrots, beetroots, aubergines, and courgettes by Cryo-Scanning Electron Microscopy observation, and found that VI could be used to fill intercellular spaces in the vegetable matrix, and was effective even for nonporous samples, such as carrots. Chafer, Gonzalez-Martinez, Chiralt, and Fito (2003) also used Cryo-Scanning Electron Microscopy technique to analyze citrus peel microstructure before and after VI process. The results reflected a high capacity of impregnation (45–70% of initial sample volume) and swelling (12–33% of initial sample volume) of the peels due to the great porosity of the albedo zone. In this zone, the large intercellular spaces can be flooded by an external solution, making the citrus peels highly suitable for VI processing to obtain new products with improved functionality and sensory acceptance. Previous studies have tried to explain the mechanisms of VI processing on the microstructure of samples. Nieto, Salvatori, Castro, and Alzamora (1998) reported that when impregnation is carried out under vacuum, cells became more rounded with retention of some intercellular spaces, but the distance between cells did not decrease. Fito *et al*. (2000) showed that the cell wall separated from the plasmalemma, and the liquid phase from the intercellular spaces flowed into the cell cavity through the cell wall, thus the cell wall did not shrink with plasmalemma, but did deform to some extent due to the total volume loss. Fito, *et al*. (2001b) further explained that the external solution filled the sample voids and the cross cell-sections were occupied in this area. Internal and external cell contents displayed similar dendritic aspect since liquid in both areas had the similar concentration.

The type of VI solution plays different roles in the microstructure of VI samples (Martinez-Monzo *et al*., 1998). VI with isotonic solution generated a new appearance of intercellular spaces that are completely flooded by the solution, and displayed a similar dendritic appearance to the intracellular volume. There are no apparent disturbances in the cell following the VI treatment (Martinez-Monzo *et al*, 1997). Shrinkage of the plasmalemma due to water loss was observed, but no significant shrinkage of the cellular wall was found. In infused tissue without vacuum

treatment, the space between the plasmalemma and the cell wall was completely filled with solution indicating that the external liquid entered the cell cavity through the permeable cell wall replacing intracellular water, thus avoiding the cell wall deformation (Albors, Salvatori, Andres, Chiralt, & Fito, 1996). Another considerable difference observed in VI samples is the more compact aspect of the dendritic surface compared with fresh sample. Microscopic observation revealed that atmospheric impregnation caused contraction of cell membranes, degradation of cell walls and a decrease in cell–cell contact. In contrast, microscopic analysis of VI tissues showed that they were similar to fresh tissues (Muntada, Gerschenson, Alzamora, & Castro, 1998).

For VI in hypertonic treatments, dehydration of the tissue lead to plasmolysis, but much less cell shrinkage of the cellular wall was observed as compared to that occurs in osmosed tissue at normal pressure. Moreover, cell wall observations of osmoses tissue by transmission electron microscopy showed a much better preserved cell wall ultrastructure, which is similar to fresh fruit texture when VI was used to decrease water activity in the minimal processing of fruits (Alzamora & Gerschenson, 1997). Roastogi, Angersbach, and Knorr (2000) indicated that the most possible cause of cell damage could be contributed to the reduction in size caused by WL during VI, which results in the loss of contact between cell membrane and call wall. In addition, the type of sugars used as VI solution also has different effects on the microstructure of fruit and vegetable. For example, when sucrose is used, cell shrinking increases and otherwise cell remains its original form with the use of glucose (Monsalve Gonzalez, Barbosa-Canovas, & Cavalieri, 1993; Muntada *et al*., 1998).

Physicochemical properties

Texture, total acids, and color are among those physicochemical properties most affected by VI as a result of change in product density, especially in highly porous samples. The texture quality of VI processed products is significantly related to the type of VI solutions used. VI with hypotonic or isotonic solutions does not change the firmness of fresh apples (Martinez-Monzo *et al*., 1998; Xie & Zhao, 2003a), but the firmness is strongly reduced when VI with hypertonic solution, and sample dehydration occurs simultaneously. The dehydration further promoted the losses of cell turgor and elasticity, the alteration of cell resistance, the increase in viscous character, the changes in air and liquid volume fractions in the product, and the changes in sample size and shape (Chiralt *et al*., 2001; Fito *et al*., 2000; Pitt, 1992). The loss of turgor pressure is either due to plasmolysis or disruption of the tonoplast and plasmalemma. The loss in elasticity is owing to the air–liquid exchange during the vacuum operation (Alzamora *et al*., 1997, 2000). Chiralt *et al*. (2001) studied the effects of VI pretreatment (5 min at 50 mbar) on the mechanical

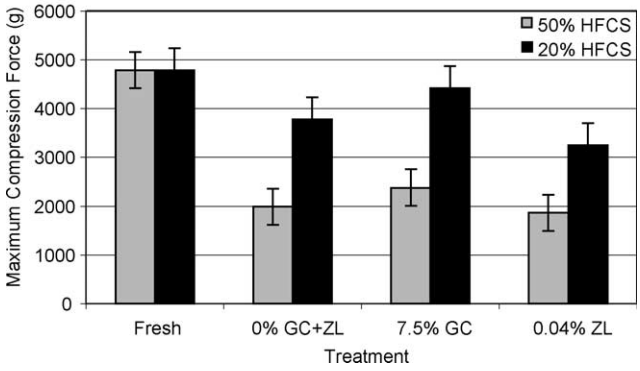

Fig. 1. Firmness of fresh cut apples (*Royal Gala*) subjected to VI treatment under different conditions (HFCS, high fructose corn syrup; GC, Gluconal® Cal; ZL, zinc lactate). (Xie & Zhao, 2003a).

properties of kiwifruits, mangoes, and strawberries subjected to osmotic treatment with 35–65°Brix sucrose solutions at 30 °C, and found that VI decrease retention of mechanical properties in kiwifruit and mangoes, but not on strawberries. Xie and Zhao (2003a) evaluated the firmness of fresh apple slices impregnated with 20 or 50% diluted high fructose corn syrup (HFCS), and found that the 50% HFCS solution significantly reduced the fruit firmness, but 20% HFCS solution containing calcium avoided the loss of firmness (Fig. 1). In contrast, Alzamora *et al*. (1997,2000) and Muntada *et al*. (1998) reported that VI treated minimally processed fruits perceive as notoriously more juicy even than fresh fruits and vegetables, and in general exhibit better textural quality.

The effect of VI treatment on product acidity depends on the nature of raw material and type and concentration of VI solution. Torreggiani (1993) reported that pH value of the fruit before and after VI processing did not change significantly. Xie and Zhao (2003a,b) showed that a 3% HMP (high methoxyl pectin) and a 50% HFCS solution increased pH and decreased total acidity of VI processed strawberries and Marionberries. The effect of 20% HFCS solution was significantly lower than those of 50% HFCS solution in fresh-cut apples (Table 4). Partial removal of the native soluble acids in the fruits may occur during VI processing, leading to a noticeable decrease in the total titratable acidity when the high concentration of VI solution was used. Table 4 shows the changes of some physicochemical properties of the fruits after VI treatment.

VI processing may change the color of fruits and vegetables. The gas–liquid exchange in fruit and vegetable implies a more homogeneous refraction index through a sample. When color is measured by diffuse reflection, a decrease in the reflection coefficients was obtained for VI samples as compared with fresh ones, thus implying lower values of the clarity and chrome color coordinates and small changes in hue (Martinez-Monzo *et al*., 1997). These changes caused a lightening and less color saturation of the samples (Torreggiani, Forni, & Rizzolo, 1987). Fito and Chiralt (2000) reported that VI treatment causes bigger

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Table 4. Physicochemical properties of vacuum impregnated fruits at different conditions

VI	MC (%)		Soluble solids (%)		a_w		pH		Total acids (%)	
	50% HFCS	3% HMP	50% HFCS	3% HMP	50% HFCS	3% HMP	50% HFCS	3% HMP	50% HFCS	3% HMP
Marionberry										
Fresh	84.51^{a} (0.60)	84.51^{a} (0.60)	12.12^{a} (1.62)	12.12^{a} (1.62)	0.981^{a} (0.001)	0.981^{a} (0.001)	3.20^{a} (0.02)	3.20^{a} (0.02)	1.62^{a} (0.02)	1.62^{a} (0.02)
12% GC	81.79^{b} (0.30)	84.31^{a} (0.50)	15.78^{b} (1.16)	12.02^{a} (1.76)	0.972^{b} (0.001)	0.982^{a} (0.001)	3.59^{b} (0.08)	3.66^{b} (0.02)	1.14^{b} (0.02)	1.37^{c} (0.04)
0.04% ZL	81.87^{b} (0.25)	84.56^{a} (0.30)	16.02^{b} (1.08)	12.08^{a} (1.65)	0.973^{b} (0.001)	0.982^{a} (0.001)	3.53^{b} (0.08)	3.71^{b} (0.03)	1.13^{b} (0.02)	1.42^{b} (0.04)
Strawberry (Totem)										
Fresh	88.58^{a} (0.35)	88.58^{a} (0.35)	9.90^{a} (0.59)	9.90^{a} (0.59)	0.996^{a} (0.001)	0.996^{a} (0.001)	3.51^{a} (0.04)	3.51^{a} (0.04)	1.09^{a} (0.03)	1.09^{a} (0.03)
12% GC	85.73^{b} (0.28)	87.96^{a} (0.49)	13.93^{b} (0.43)	8.90^{ab} (0.36)	0.992^{b} (0.001)	0.996^{a} (0.001)	3.75^{b} (0.02)	3.66^{b} (0.02)	0.74^{b} (0.01)	0.75^{b} (0.02)
0.04% ZL	85.65^{b} (0.42)	88.33^{a} (0.85)	14.42^{b} (0.73)	8.88^{ab} (0.34)	0.992^{b} (0.001)	0.996^{a} (0.120)	3.71^{c} (0.01)	3.71^{c} (0.03)	0.75^{b} (0.02)	0.74^{b} (0.01)
	50% HFCS	20% HFCS	50% HFCS	20% HFCS	50% HFCS	20% HFCS	50% HFCS	20% HFCS	50% HFCS	20% HFCS
Apple (Royal Gala)										
Fresh	86.04^{a} (0.36)	86.04^{a} (0.36)	14.8^{d} (0.89)	14.8^{b} (0.89)	0.980^{a} (0.002)	0.980^{a} (0.002)	3.87^{d} (0.05)	3.87^{c} (0.05)	0.34^{a} (0.01)	0.34^{a} (0.01)
VI alone	80.43^{bc} (0.52)	84.41^{c} (0.43)	20.7^{a} (0.61)	16.2^{a} (0.56)	0.975^{b} (0.001)	0.978^{b} (0.001)	4.35^{a} (0.05)	4.19^{a} (0.07)	0.28^{c} (0.01)	0.32^{c} (0.01)
7.50% GC	80.24^{c} (0.50)	84.44^{c} (0.33)	19.8^{bc} (0.93)	15.8^{a} (0.55)	0.975^{b} (0.001)	0.978^{b} (0.001)	4.33^{a} (0.03)	4.21^{a} (0.05)	0.29^{b} (0.01)	0.32^{c} (0.01)
0.04% ZL	80.36^{bc} (0.42)	84.46^{c} (0.30)	20.3^{ab} (0.93)	16.2^{a} (0.54)	0.974^{b} (0.001)	0.979^{b} (0.001)	4.27^{b} (0.03)	4.18^{a} (0.03)	0.28^{c} (0.01)	0.32^{c} (0.01)

HFCS, high fructose corn syrup; HMP, high methoxyl pectin; GC, Gluconal Cal®; ZL, zinc lactate. Values in parenthesis are standard deviations. Means within a column with the same superscript are not significantly different at $P=0.05$. The VI processing consisted of a 15 min vacuum at 50 mmHg and 30 min restoration at atmospheric pressure.

olor changes in apple, strawberry, and papaya than those in apricot, banana, and kiwifruit. Alzamora *et al*. (2000) indicated that for light colored fruits sensitive to enzymatic browning discoloration, air leaves the pores of the fruits during vacuum treatment, reduces the oxygen concentration in the sample tissues, hence the oxidative reaction rates are slowed down and lead to the final product with a good natural color. Leunda *et al*. (2000) and Xie and Zhao (2003a) confirmed these results in fresh-cut kiwifruits and apples subjected to VI treatment, where its color was stable and similar to fresh samples during refrigeration storage. In addition, it was found that the color of the VI solution has impacts on the color of VI products due to the filling of the pores with the solution, especially for light colored products (Xie & Zhao, 2003a).

Thermal properties

Thermal conductivity and diffusivity are greatly dependent on product composition and structure. VI processing promotes changes in product composition and structure, hence leading to modification in thermal properties, especially thermal conductivity of highly porous matrices. Porosity, pore size, and distribution in relation with the direction of heat flow, impregnating solution composition, and operation parameters strongly affect the changes of thermal properties (Fito, *et al*., 2001b; Fito, Pinaga, & Aranda, 1984; Martinez-Monzo, Barat, Gonzalez-Martinez, Chiralt, & Fito, 2000; Njie, Rusmsey, & Singh, 1998). Fito *et al*. (2000) reported that VI with isotonic solutions increases thermal conductivity because of the gas replacement, but only causes slight changes in thermal diffusivity due to the simultaneous density increase. Martinez-Monzo *et al*. (2000) also showed that VI results in a 15–24% increase in thermal conductivity of apples submitted to VI processing, whereas the thermal diffusivity only changed 2–4%. Njie *et al*. (1998) proposed a mathematical model to predict the effect of impregnation on thermal properties, and reported that the greater the porosity and more perpendicular the pore orientation, the higher the thermal properties increase due to VI. A linear relationship between thermal properties and moisture content was also observed. Martinez-Monzo *et al*. (2000) indicated that thermal conductivity, diffusivity, and specific heat decrease linearly with increased VI solution concentration. Fito, *et al*. (2001b) further indicated that specific heat does not change if no changes in sample composition were induced in VI process.

Practical applications of VI in fruit and vegetable processing

Food industry has growing interests in fruit and vegetable-based products, especially in value-added and minimally processed market because of their significant health benefit and favorable flavor and color. VI technique has both functions of dewatering and formulation, thus providing broad applications in fruit and vegetable

processing. Some of the potential applications include pretreatment before drying or freezing for improving final product quality, and development of compositionally formulated product by introducing functional food ingredients (Chiralt *et al*., 1999; Fito, *et al*., 2001a,b; Fito *et al*., 2000; Hoover & Miller, 1975; Javeri, Toledo, & Wicker, 1991; Ponappa, Scheerens, & Miller, 1993; Torreggiani, 1995; Xie & Zhao, 2003b). Anti-browning agent, pH reducer, firming agent, and anti-microbial agent may be incorporated into the product for extending shelf-life and enhancing microbial safety, or nutraceuticals may be impregnated into the porous structure of the plant tissues for developing nutritionally fortified fruit and vegetable products (Betoret *et al*., 2003; Fito, *et al*., 2001a; Gras *et al*., 2003; Xie & Zhao, 2003a). Some potential applications of VI in fruit and vegetable processing are illustrated in Fig. 2.

Pre-dehydration of fruits and vegetables

Dehydration, by partial removal of water to reduce water activity, has been widely used to extend shelf-life of fruits and vegetables. Dehydrated fruits and vegetables can be used as a food ingredient in many products, have also been added to cereals, granola bars, baked goods and mixes, and can even be eaten out of hand. Traditional air-drying method consumes intensively high energy and causes significant loss of flavor and nutrients because of the high heat exposure. VI has been proposed as a pretreatment before the final drying step to mainly achieve two goals: decreasing moisture content before final drying to save energy and incorporating functional solutes, such as anti-microbial, antioxidant, and anti-browning agents to improve product quality (Barat *et al*., 2001; Fito *et al*., 1994; Fito *et al*., 2001b; Sapers, Garzarella, & Pilizota, 1990; Torreggiani, 1995).

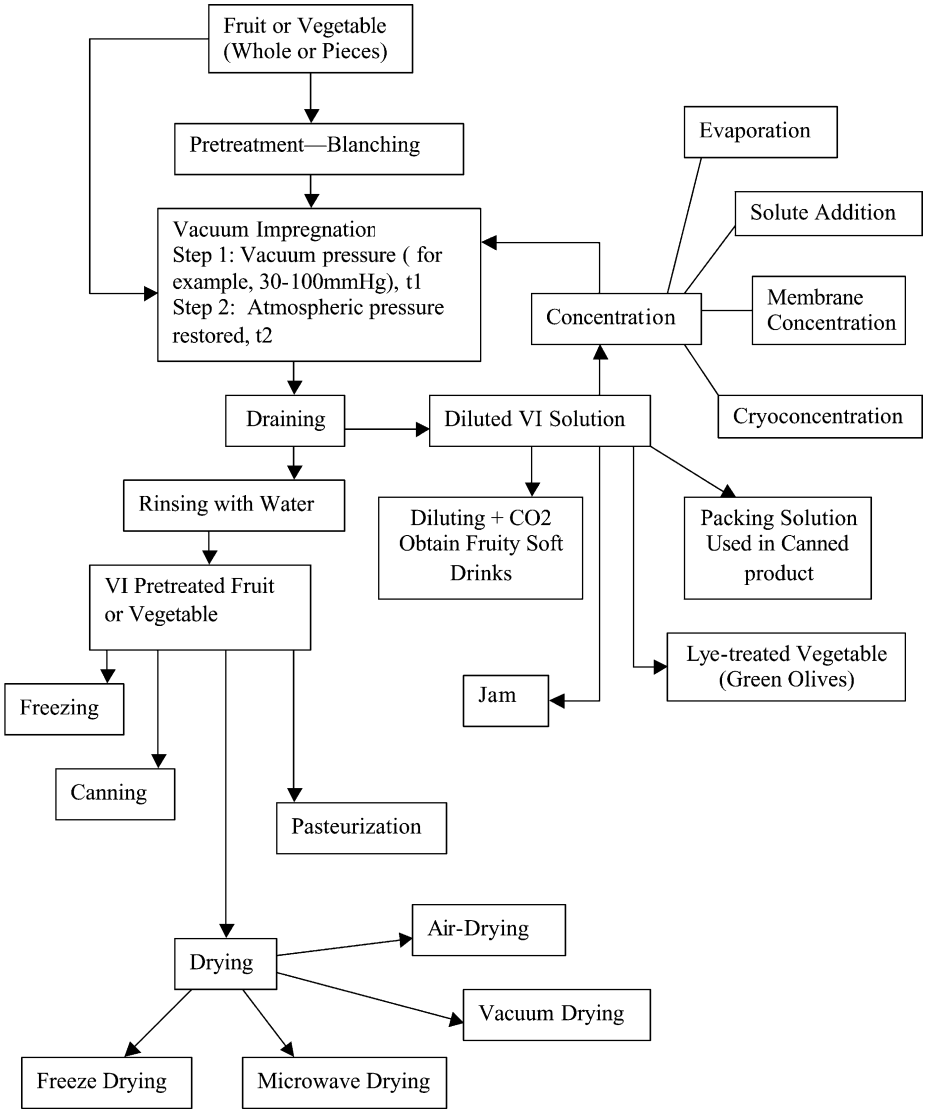

Fig. 2. Some potential applications of VI in fruit and vegetable processing.

Fito *et al*. (2001b) reviewed the effectiveness of VI at forming porous structures in fruits and vegetables to improve their drying behavior. The effects of VI processing on food structure, physical properties, drying rate, and the cell network relaxation mechanism of fruits and vegetables were discussed. This review focused on the quality aspects of dried fruits affected by VI pretreatment.

Maltini *et al*. (1993) reported that compared to simple air dehydration, the combination of VI pretreatment and final air drying produced softer product at a low water activity. The higher the solid gain of the product, the more the improvement in its texture quality. Kim (1990), Maltini, Pizzocaro, Torreggiani, and Bertolo (1991), and Torreggiani (1995) indicated that VI pretreatment increased the stability of pigments during the further drying and subsequent storage without the use of sulfur dioxide, a common chemical preservative for color preservation of fruits and vegetables. Alvarez *et al*. (1995) and Prothon *et al*. (2001) revealed that VI pretreatment increased moisture diffusivity of samples in comparison with un-VI treated ones due to the fact that solute uptake increased the water transport resistance. Hence, impregnated solutes concentrated inside the tissue, causing crystallization in some parts of the outer layers during the following drying step (Nieto *et al*., 1998; Prothon *et al*., 2001; Rahman & Lamb, 1991; Sankat, Castaigne, & Maharaj, 1996). Nieto *et al*. (1998) showed that moisture transport and volume shrinkage during the air-drying of apples strongly decreased by glucose uptake during impregnation, where sugar distribution in the cellular tissue affects the drying behavior. Barat *et al*. (2001) confirmed that VI had a significant influence on the changes in weight and solute concentration of apples slices by VI treatment at 180 mbar for 5 min.

It was also reported that VI pretreatment before drying affects the rehydration capacity of samples. The rehydration capacity in water of VI pretreated samples is lower than that of non-treated ones (Prothon *et al*., 2001). This phenomenon could be explained by the fact that VI resulted in fewer pores that are available for solutes impregnating into the intercellular spaces and along cell walls. Thus the cell wall is less permeable to water. Prothon *et al*. (2001) observed that the cell wall become thicker after impregnation and less rupture after microwave drying with impregnated process than that without VI pretreatment.

Pretreatment before freezing

Freezing is a traditional processing method for fruit and vegetable preservation. It better retains nutrients in the final product than those of other means of preservation. However, the phase change of water in the product disrupts cell integrity and compartmentation, thereby increasing undesirable physicochemical changes. Partial removal of water before freezing process might reduce the freezable water content and make the frozen product stable as a result of increasing the glass transition temperature of the maximally cryoconcentrated food liquid phase (Martinez-Monzo *et al*., 1998). VI pretreatment has been studied to improve quality of frozen fruits and vegetables by mainly reducing drip loss and improving texture quality, as well as saving energy consumption during freezing (Bengtsson & Fernquist, 1971; Biswal *et al*., 1991; Bolin & Huxsoll, 1993; Garrote & Bertone, 1989; Lenart & Flink, 1984; Maestrelli *et al*., 2001; Martinez-Monzo *et al*., 1998; Sormani, Maffi, Bertolo, & Torreggiani, 1999; Torreggiani, 1995; Torreggiani & Bertolo, 2001; Xie & Zhao, 2003b).

VI with cryoprotectants (usually hypertonic sugar solution) or cryostabilizers (ex, high methoxyl pectin and glycerol) has been suggested to reduce the quantity of freezable water and to lower the ice crystal damage in frozen plants (Levine & Slade, 1990; Martinez-Monzo *et al*., 1998). It was showed that the higher the concentration of the osmotic solution implied, the less the amount of freezable water is available during freezing process, thus less drip loss during thawing (Martinez-Monzo *et al*, 1998). When a hypertonic solution is used for VI treatment, sample osmotic dehydration occurred simultaneously due to combined effect of pressure gradients and capillary action (Fito & Pastor, 1994). Martinez-Monzo *et al*. (1998) tested the use of VI to introduce concentrated grape musts and pectin solutions as cryopreseratives to apple before freezing, and found that the mechanical property of the apples was improved as a result of reduced amount of freezable water by VI pretreatment with concentrated grape musts solution, while VI with pectin improved frozen product stability by increasing the glass transition temperature of liquid phase. Pectin could also reinforce the structure of cellular matrix by means of intercellular 'bridge' formed from polysaccharide gels. Sormani *et al*. (1999) confirmed that VI treatment improves tissue organization of thawed products as the protective effect resulted from the reduction of water content overcame the tissue damage induced by the freezing process. However, similar results did not found in mango, kiwi, and strawberry subjected to VI with sucrose solution at 30 °C (Chiralt *et al*., 2001). Xie and Zhao (2003b) further evaluated the use of HFCS and high methyl pectin (HMP) as cryoprotectants with incorporation of 7.5% calcium gluconal in VI solution for strawberries and Marionberries. It was reported that VI with cryoprotectants and calcium tremendously improved the texture quality and reduced drip loss of frozen-thawed berries (Fig. 3), the maximum compression force increased about 50–100% and the drip loss reduced about 20–50% in comparison with untreated samples. The significant decrease of drip loss after thawing demonstrated that reduction in moisture content during VI using HFCS protected the tissues from freezing damage by reducing the amount of freezable water.

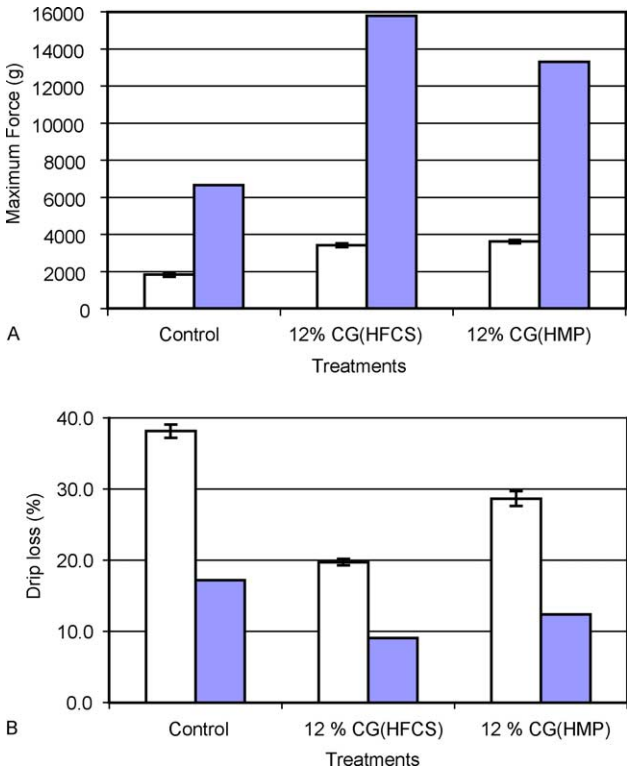

Fig. 3. Firmness (A) and drip loss (B) of impregnated strawberry (*Totem*) slices (white) and whole Marionberry (grey) after freeze-thawing process (HFCS, 50% w/w diluted high fructose corn syrup solution; HMP, 3% w/w high methyl pectin; GC, Gluconal Cal®).

Energy resources have become more limited, thus the need to improve overall operation efficiency becomes more important. Freezing process uses extensive energy. A reduction of product moisture content using VI treatment prior to freezing could reduce the refrigeration load notably (Huxsoll, 1982).

Development of nutritionally fortified fruits and vegetables

Increased consumer interests in the health benefits of foods have led to the significant development of nutraceuticals and functional foods. The global functional foods market is estimated to be $47.6 billion in 2001 in comparison with $30 billion in 1995 (Anon, 2001), and continuously leads food product development today (Burrington, 2000; Sloan, 2002).

VI has been considered as a useful way to introduce desirable solutes into the porous structure of foods, conveniently modify their original composition as an implement for development of new products (Chiralt *et al*., 1999, 2001; Fito, 1994; Fito *et al*., 1996; Martinez-Monzo *et al*., 2000, 1998). Nutraceuticals may be introduced into fruit and vegetable products using VI technique without modifying their integrity. This so-called 'direct-formulation' distinguishes it from other processing methods (Mavroudis *et al*., 1998a,b; Torreggiani, 1993). The usage of VI to develop nutritionally enriched products is relatively new in comparison with its other applications. Fito, *et al*. (2001a) first evaluated the feasibility of using VI for mineral fortification of fruits and vegetables from an engineering point of view. Mathematical models were developed to determine the concentration of different minerals in VI solutions required to achieve a 20–25% dietary reference intake (DRI) fortification in 200 g of samples. Following the modeling prediction, experimental validation confirmed that VI could be an effective method for the enrichment of fruits and vegetables with minerals, vitamins or other physiologically active components. Betoret *et al*. (2003) studied probiotic-enriched dried fruits using VI technique by applying VI process either with commercial apple juice containing *Saccharomyces cerevisiae*, or with whole milk or apple juice containing 10^7 or 10^8 cfu/ml of *Lactobacillus casei* (spp. *rhamnosus*). It was reported that dried apple samples could contain about 10^6 cfu/g *Lactobacillus casei* (spp. *rhamnosus*), a similar level to that in commercial dairy products. Gras *et al*. (2003) evaluated calcium fortification of eggplants, carrots, and oyster mushroom using VI with sucrose solutions, and found that raw material variability induces significant differences in the final impregnation level, where eggplants and mushrooms reached the greatest impregnation level because of their great effective intercellular porosity, thus are highly suitable for obtaining fortified products by using small concentration of calcium in the impregnation solution. Microanalysis on calcium distribution in plant tissues showed that calcium impregnation occurs in the intercellular spaces of eggplants and oyster mushrooms, but in xylem of carrots. Xie and Zhao (2003a,b) studied calcium and zinc fortification of fruits using VI processing of HFCS solution containing calcium and/or zinc in fresh-cut apples, strawberry slices, and whole Marionberry. Results showed that a 15–20% DRI of calcium and above 40% DRI of zinc could be fortified in 200 g of fresh-cut apples, and about 11 and 23% DRI of calcium and zinc can be obtained in 200 g of berries, respectively, without affecting the physicochemical property of the fruits (Table 5).

VI for developing minimally processed fruits and vegetables

Minimally processed fruits and vegetables are products that maintain their quality attributes similar to those of fresh products. In some cases, a minimally processed product is a 'raw' food, and the tissue cells are alive. VI could be appropriate in the development of minimally processed fruit and vegetable products as a proper formulation of the impregnation solution allows expeditious compositional modifications of the solid matrix that may result in quality and stability enhancement of final product without submitting the food structure to the eventual stress. By partial removal of water, impregnating organic acids to reduce pH, and anti-microbial and antioxidant agents to inhibit

Table 5. Nutritional fortification of fruits using VI process

Fruit	VI solution	% DRI of calcium	% DRI of zinc
Apple (*Royal Gala*)	Control (raw)	0.82	2.02
	20% HFCS+5.24% GC	11.20	
	50% HFCS+5.24% GC	15.41	
	20% HFCS+7.50% GC	15.93	
	50% HFCS+7.50% GC	20.24	
	20% HFCS+0.02% ZL		32.40
	20% HFCS+0.04% ZL		40.71
	50% HFCS+0.04% ZL		42.58
Strawberry (*Totem*)	Control (raw)	3.26	1.77
	50% HFCS+12.00% CG	25.31	
	3% HMP++12.00% CG	30.53	
	50% HFCS+0.04% CG		17.3
	3% HMP+0.04% CG		19.8
Marionberry	Control (raw)	7.10	3.95
	50% HFCS+12.00 %CG	16.36	
	3% HMP++12.00% CG	18.02	
	50% HFCS+0.04% CG		64.72
	3% HMP+0.04% CG		42.63

HFCS, high fructose corn syrup solution; HMP, high methyl pectin; GC, Gluconal Cal®; ZL, zinc lactate. The VI processing consisted of a 15 min vacuum at 50 mmHg and 30 min restoration at atmospheric pressure.

microbial growth and oxidation in combination with low temperature storage, product shelf-life can be significantly improved. Tapia, Lopez-Malo, Consuegra, Corte, and Welti-Chanes (1995) evaluated the possibility to develop minimally processed papaya by VOD technique. The combination of using VOD to reduce water activity, to impregnate citric acid for reducing pH and potassium sorbate as a preservative was applied based on the hurdle technology. The papaya pieces showed a good overall acceptance even after 1 month of storage at 15 °C. Tapia, Ranirez, Castanon, and Lopez-Malo (1999) and Vergara-Balderas, Santacrus, Lopez-Malo, and Tapia (1998) investigated vacuum impregnated high moisture melon by submitting melon cylinders to PVOD in a 40°Brix sucrose solution containing 0.6% w/w phosphoric acid, 1000 ppm potassium sorbate, and 0.2% w/w calcium lactate to depress product water activity to 0.98 and pH to 4.3. Microbial analysis, tests on color and texture, and sensory study showed that products packed in the glass jars covered with syrup are well accepted after 15 days storage at 25 °C. Welti-Chanes, Santacruz, Lopez-Malo, and Wesche- Ebeling (1998) studied the stability of minimally processed orange segments by using VI in a 55°Brix sucrose solution containing organic acid and potassium sorbate to decrease water activity to 0.98. It was found that the product was microbiologically stable and well accepted on color, texture and sensory evaluation at up to 50 days when packaged in glass jars with cover syrup and stored at <25 °C. Leunda *et al*. (2000) further reported that VI treatment in combination with blanching and zinc chloride added into VI solution significantly improved color stability of minimally processed kiwifruits during storage.

Technical challenges and future research needs in VI technique

Technical challenges of VI technique

VI technique has been considered to improve product quality, modify product formulation, and save energy in some of the fruit and vegetable processing. By selecting appropriate process conditions, the specific application of VI can be controlled and optimized. However, extensive studies are still required in order to fully taking advantage of its unique features and applying in large-scale industrial operations. Followings are some of the technical challenges and future research needs.

Control of mass transfer rate

Although numerous studies have been undertaken to investigate mass transfer in VI processing, the mechanisms involved in this simultaneous interacting counter-current flows, and its impacts on the physicochemical and sensory properties of foods is still not fully understood. Control of different types of VI solutions (isotonic, hypertonic, and hypotonic) on mass transfer rate is important, especially when VI is used to develop compositionally formulated or minimally processed fruit and vegetable products. An optimal mass transfer to ensure sufficient solutes getting into the products without negative impacts on the physicochemical and sensory properties is the key for its successful application.

Other techniques may be used to accelerate mass transfer in VI treatment. For example, high electrical field pulse (Roastogi, Eshtiaghi, & Knorr, 1999) and ultrasounds (Simal, Benedito, Sanchez, & Rossello, 1998) were suggested to increase diffusion coefficients by increasing cell wall permeability in VI processing. However, more studied are needed to develop better understanding of their effects.

Reuse of VI solutions

One major issue in the large-scale industrial application of VI and any other osmotic processing is the management

of the remained solution at the end of the process. Potential applications of concentrated solutions include reusing as table syrups, fruit fillings, beverage bases, or syrups in canning process. From the engineering standpoint, it is possible to reuse the solution at least 20 cycles of the same recycled solutions (Rosa & Giroux, 2001; Valdez-Fragoso, Mujica-Paz, Giroux, & Welti-Chanes, 2002). Valdez-Fragoso *et al*. (2002) found that water loss, solids gain, and color of dehydrated apple cubes obtained in osmotic dehydration process with reused osmotic solution are similar to those obtained with fresh osmotic solution. Unfortunately, the recycle of osmotic solution is still one of the main shortcomings and challenges. One reason is that some of the characteristics of the solutions has changed at the end of process due to simultaneous leaching of color, acids, and fragments from the product and the solutes in the solutions penetrating into the product. To make the process feasible, the solutions are usually re-concentrated before reuse by heating or filtrating. However, the reconstruction process may change the properties of the solutions. For example, heating may darken or brown the color of the solutions, as well as generating off-flavor volatiles. The reuse becomes even more complicated in the case of mixed solutes: the proportion of each solute has to be tested and adjusted. In addition, VI solution is not environment friendly because of the organic acids and other ingredients leached from the product. Techniques to treat the waste concentrated solutions, especially for the mixture solution, are very important and need more studies.

Microbial safety of VI solutions

Lack of knowledge relevant to the microbial safety of VI solutions and processed product is another critical aspect need to be investigated and probably also hinders the application of VI technique. Product contamination could begin from the farm. If raw materials are contaminated, it may contaminate VI solutions during VI processing. Further contamination would occur if contaminated solutions are to be reused. Very little study was reported in this aspect, thus requiring a substantial research effort.

Complete immersion of samples in VI solutions

Maintaining a good contact between food samples and the VI solution is another challenging technique in VI and other osmotic processes. The density of fruits and vegetables is about 800–900 kg/m^3 (Rahman, 1995), lower than those of solutions (ex, 1300 kg/m^3 for a 60% sucrose solution at 20 °C). Hence, product tends to float on the solutions. Completely immersing the products under the solution and keeping good contact throughout the process are essential for a VI processing. Current industry operation has used stirring or compressing for this purpose, but it adds more cost and may also damage the products. Other approaches need to be considered.

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