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ARTICLE *in* FOOD AND BIOPROCESS TECHNOLOGY · JANUARY 2010

Impact Factor: 2.69 · DOI: 10.1007/s11947-010-0358-9

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Food Bioprocess Technol (2012) 5:184–192
DOI 10.1007/s11947-010-0358-9

ORIGINAL PAPER

Modeling of Total Soluble Solid and NaCl Uptake during Osmotic Treatment of Bell Peppers under Different Infusion Pressures

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Received: 11 May 2009 / Accepted: 6 April 2010 / Published online: 28 April 2010

Abstract The uptake of sorbitol and sodium chloride in slabs of green bell pepper (10×10×2 mm) osmotically dehydrated at different concentrations of sodium chloride (30, 40, and 110 g/L) and sorbitol (7°Bx, 24°Bx, and 41°Bx) at different pressures (4.05, 44.66, and 85.33 kPa) with infusion times ranging from 6 to 60 min for sorbitol and up to 36 min for NaCl was evaluated. Models that describe the uptake of these solutes were developed under different experimental conditions. A completely randomized 3×3 factorial design was used to study the effect of the process variables on uptake of solutes for both sorbitol and NaCl. The uptake kinetic of solutes for both sorbitol and NaCl increased to an asymptotic level with both solution concentration and pressure. A negative exponential model adequately fitted the kinetics for both solutes with R^2=0.97 and 0.94. The best conditions for the highest increase in total soluble solids during sorbitol solution infusion were 4.05 kPa of pressure and 16 min of immersion. NaCl uptake in peppers followed an exponential trend without reaching the equilibrium conditions. The fitted models were found adequate to estimate that the increase in total soluble solids and NaCl in bell peppers during osmotic process can be used to establish pretreatment conditions in the drying process.

Keywords Pepper · Sorbitol · NaCl · Osmotic treatment · Mass transfer · Vacuum infusion · Models

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Introduction

Solute infusion in fruits and vegetables by osmotic means has been used to modify the functional properties and enhance the quality attributes of the final product. Chili peppers in both dried and fresh forms are used widely in many ethnic diets in different countries. Dehydrated bell pepper is used as an ingredient in cheese, sausage meat products, dressing, and for food appetizer formulations and delicatessen products. During the bell pepper dehydration process, some characteristics, such as color, texture, and flavor, are lost, affecting the product's final quality. This can be minimized by using osmotic dehydration (Torreggiani 1993) and has the additional advantage of extending shelf life. During osmotic dehydration, some of the water contained in fruits or vegetables is removed, and the tissue is impregnated by solutes when immersed in a hypertonic solution. This is due to the gradient of osmotic pressure between the tissue and the hypertonic medium (Biswal and Bozorgmehr 1992; Rastogi and Raghavarao 1996). The osmotic process is a function of several variables, such as solute concentration, temperature, composition of the osmotic solution, immersion time, and agitation. The structural characteristics and shape of food materials subjected to osmotic dehydration could be affected by either the uptake of solute or loss of water or both (Lerici et al. 1985; Rastogi and Raghavarao 2004a; Ispir and Toğrul 2009)

The uptake of different solutes in foods has been studied widely by different researchers (Pointing et al. 1966; Islam and Flink 1982; Torreggiani et al. 1995; Rastogi and Raghavarao 2004b; Shi et al. 2009). The most commonly used osmotic agents are sucrose and sodium chloride (NaCl) (Pointing et al. 1966; Dixon et al. 1976; Hawkes and Flink 1978; Rastogi and Raghavarao 1994; Azuara et al. 2009) either alone or in combination (Islam and Flink 1982; Lerici et al. 1985; Sacchetti et al. 2001). The properties of the osmotic agents used, such as molecular weight and ionic strength, affect the kinetics of water removal and solid gain. Ionic salts possess characteristics of ionic strength and molecular size that make them diffuse easily through the cell membrane, resulting in more gain of solids (Islam and Flink 1982). Another solute that has been used in osmotic dehydration processes is sorbitol due to its anti-browning and humectant properties (Torreggiani et al. 1995). A study reported by Ozen et al. (2002) has shown that blends of NaCl and sorbitol have a synergistic effect on both the uptake of solutes and the modification of physical properties in pepper tissue that are related to the quality of the product.

The characteristics of the final product are largely influenced by the extent of osmotic solute uptake, which can modify composition and taste (Pointing 1973). In a recent study by Ozdemir et al. (2008), the osmotic dehydration of diced green pepper was optimized using NaCl and sorbitol as osmotic agents, and it was found that the optimum infusion time was around 240 min: such long infusion times are a drawback for this process. The osmotic process can be accelerated either by increasing the temperature and concentration gradient or by applying vacuum. The effect on the pressure gradients obtained by applying vacuum promotes the outflow of internal gas or liquid and their substitution by external liquid, thus improving the gain of external solutes present in the liquid. Studies have demonstrated that by using, vacuum both the solute uptake and the water removal infusion times can be reduced; thus, the osmotic dehydration kinetics are faster than at atmospheric pressure (Hawkes and Flink 1978; Fito 1994; Shi et al. 1995; Fito et al. 1996; Rastogi and Raghavarao 1996; Chiralt et al. 2001).

Most of previous researches has evaluated water loss and solids uptake and correlated the results with the potential for the saving of energy during processing (Rastogi et al. 1997; Uddin et al. 2004; Rastogi and Raghavarao 2004a) as well as the impact on characteristics of the final product. Torreggiani (1993) described the specific role of the osmotic pre-step during fruit and vegetable processing as the enrichment in soluble solids rather than the removal of water and attributed this to the lowering of water activity, which is dependent on soluble solids concentration. Another fundamental aspect of solid uptake during process can be related with the yield of the final product when the osmotic process is used as pretreatment in the drying process, as well as with sensory characteristics of the final product (Eren and Kaymak-Ertekin 2007).

A number of recent publications have described kinetics and developed models for the prediction of mass transfer during osmotic dehydration (Rastogi et al. 1997; Kaymak-Ertekin and Sultanoğlu 2000; Chiralt et al. 2001; Rastogi and Raghavarao 2004a: Uddin et al. 2004; Jokić et al. 2007; Ispir and Toğrul 2009). In some of these researches, these fundamental and empirical mathematical models have been used to describe the transport of a given component from one phase to another. The fundamental models consider and explain the physical changes during the process, accounting for both the internal and external resistances. Fick's second law has been used to describe the mass transfer mechanism assuming that this is controlled by diffusion phenomena (Crank 1975). The empirical models present some advantages, such as the ability to model water losses, solid uptake, as well as the physical–chemical and sensory properties in the food material. These models ignore the internal resistances during mass transfer so they are limited to obtain a general expression of the mass transport phenomena experienced during the process. Shi and Le Maguer (2002) described some important aspects related to application of these models. The impregnation or solute uptake in tissues is described through logarithmic or exponential-type models (Fasina et al. 2002) at either atmospheric or reduced pressures. Equation 1 may describe the solute uptake in tissues by impregnation mechanisms.

$$Y_{es}(t) = \exp(-ct) \tag{1}$$

Where $Y_{es}(t)$ is the percent of the solute estimated at the impregnation time, t; c is a impregnated rate constant (min^{-1}); and t is the impregnation time (min). The modeling of the solid uptake in the osmotic process has been widely studied by several researchers (Palou et al. 1994; Chiralt et al. 2001; Shi and Le Maguer 2002; Park et al. 2002; Moreira and Xidieh 2004; Uddin et al. 2004; Ozdemir et al. 2008). However, some of these models have limitations regarding both included variables and the range of such variables. It is, therefore, necessary to generate models that include all the factors related to the osmotic process and that describe the typical asymptotic tendency of the mass transfer mechanism. The objectives of this study were to evaluate the infusion of sorbitol and NaCl in diced pepper tissue when immersed in osmotic solutions at different concentrations and at different pressures and to develop empirical models to describe the uptake of both solutes under different conditions.

Materials and Methods

Raw Materials

Green bell peppers (*Capsicum annum* L.) of the modified Verdel variety were used in this study. The peppers were harvested and stored at 2°C and 90% relative humidity for no more than 10 days before processing. Food-grade commercial sorbitol solutions (70%) and granular sodium chloride (97%) were used in this study. The batch was characterized by measuring moisture content (14.38 g H_2O/g dry basis), total soluble solids (4.0 g/100 g) and sodium chloride content (0.540 g/100 g), and titratable acidity (0.033 g citric acid/100 g).

Experimental Procedures

Green pepper batches were selected, sectioned, trimmed (eliminating seeds and placenta), and cut into pieces of 10×10×2 mm. Osmotic dehydration experiments were carried out in a vacuum chamber connected to a vacuum pump (Model Director 8915, Welch Vacuum Technology Inc, IL, USA) adapted with a paddle agitator (6×2 cm) operated at 250 rpm, for both sorbitol and sodium chloride trials at room temperature. Samples (100 g) in a mass sample/sorbitol solution ratio of 1:4 were infused in sorbitol solutions at different pressures with infusion times of 6, 16, 32, and 60 min. In another experimental block, lots of 100 g of pepper dices were infused in sodium chloride solutions at different concentrations in a mass sample/salt solution ratio of 1:4 at different pressures and with infusion times of 6, 12, 24, and 36 min. The conditions of infusion time were performed according to preliminary experiments. Immediately after the desired infusion time, pressure was restored to atmospheric conditions, and the samples were removed from the solutions, quickly rinsed, blotted dry with paper towel to remove adhered osmotic solution, and then weighed. The samples infused with sorbitol solution were analyzed to determine total soluble solids content and reported as weight percent. The samples infused with sodium chloride solution was analyzed as NaCl content and reported as weight percent.

Analytical Determinations

The content of total soluble solids was determined by refraction index, according to the method 22.024 of the AOAC (1984), using a refractometer (Atago, Abbe, Japan). Sodium chloride was determined according to method III 32.034–32.039 of AOAC (1984) by titration with 0.1 N silver nitrate and using potassium dichromate as an indicator. Each determination was done in triplicate, and the average value was calculated for each treatment.

Experimental Design

A completely randomized 3×3 factorial design for each solute with two replicate and four repeated measurements over time was used in this study. The experimental variables were sorbitol solution concentration (7°Bx, 24°Bx, and 41°Bx) at infusion time of 6, 16, 32, and 60 min. The salt solution-infused treatments were performed with NaCl solution concentrations of 30, 70, and 110 g/L at 6, 12, 24, and 36 min. The infusion of both solutes was performed at pressures of 4.05, 44.66, and 85.33 kPa. The response variable for the sorbitol infusion treatments was total soluble solid content and for salt infusion treatments was sodium chloride content in pepper tissue.

Modeling of Solute Uptake

In order to study mass transfer during the infusion process, Eq. 1 was used as a basis to develop the model. Data for each treatment with sorbitol and sodium chloride were analyzed using a negative exponential model (Ørskov and McDonald 1979).

$$Y_{es}(t) = a + b\{1 - \exp(-ct)\} \qquad (2)$$

Where $Y_{es}(t)$ is percent of the solute estimated at the impregnation time, t; t is impregnation time, min; a is the initial solute percent in the tissue at $t=0$; b is the impregnation potential percent of the solute in the infusion process; and c is the rate constant (min^{-1}) of the potential impregnation (b).

Afterward, the coefficients estimated (a, b, and c) were analyzed by linear regression to determine the effect of pressure and concentration for both sorbitol and sodium chloride treatments separately.

Additionally, a generalized model of Ørskov and McDonald (1979) was developed to include the process variables pressure (pr) and concentration of solute (con), taking into account the linear relations found in the coefficients estimated for both sorbitol and sodium chloride treatments separately.

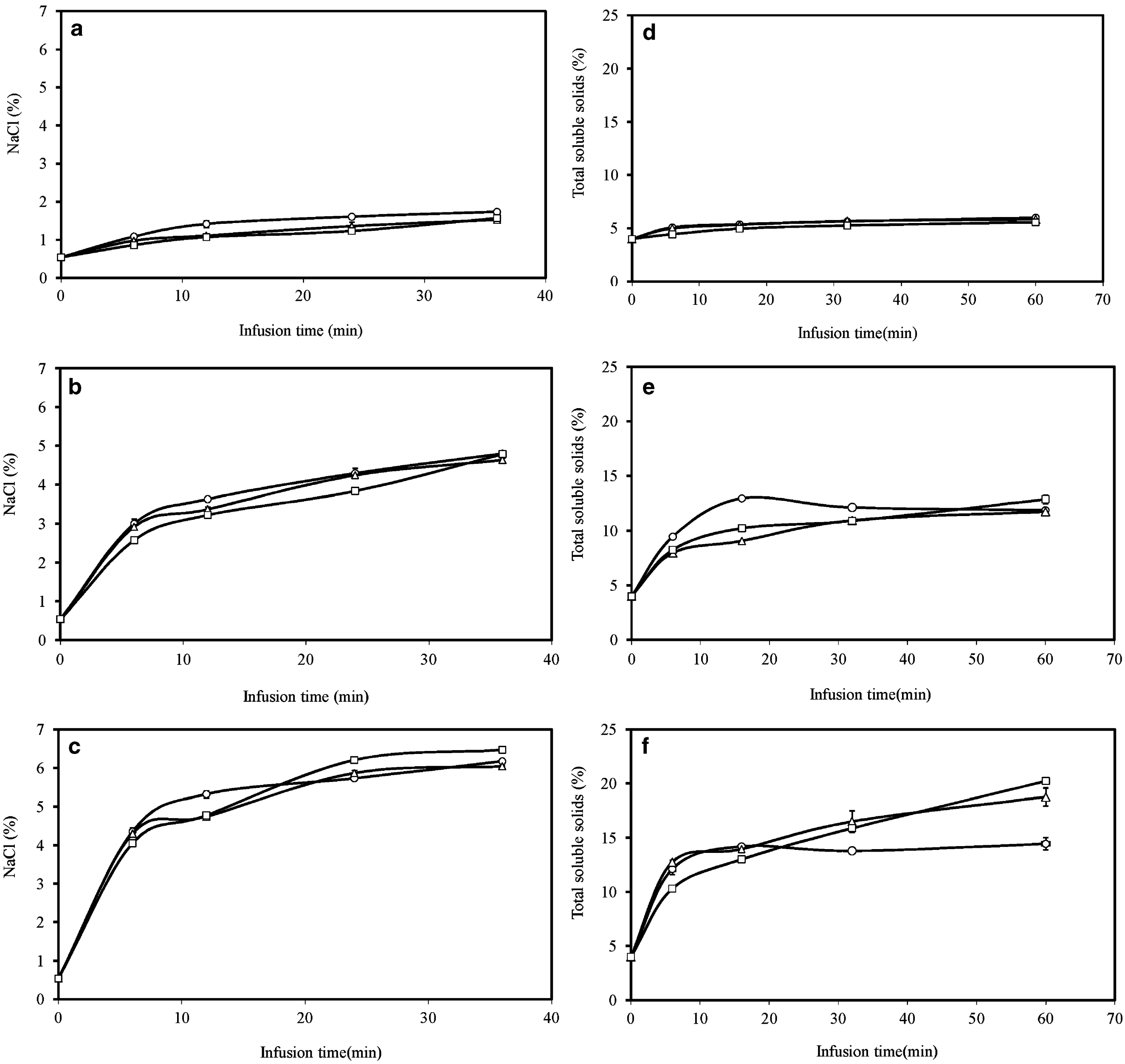

Fig. 1 Kinetics of sodium chloride and soluble solids content in slab bell pepper infused in NaCl and sorbitol solution under different pressures. **a** 30 g/L NaCl; **b** 70 g/L NaCl; **c** 110 g/L NaCl; **d** 7°Bx sorbitol; **e** 24°Bx sorbitol; **f** 41°Bx sorbitol (*circles within a line* 4.05 kPa; *triangles within a line* 44.66 kPa; *squares within a line* 85.33 kPa)

Statistical Analysis

SAS (2001) was used to carry out an analysis of variance to evaluate the effects of pressure, concentration, infusion time, and their interaction on the NaCl and sorbitol uptake. Also, it was used to fit linear and nonlinear regression models. Average relative error was used as a criterion to evaluate the best fit for impregnation of both solutes in the tissue (Moreira and Xidieh 2004).

$$\mathrm{RE} = \frac{100}{n} \sum_{i=1}^{n} \frac{\left|Y_{\mathrm{exp}} - Y_{\mathrm{es}}\right|}{Y_{\mathrm{exp}}} \qquad (3)$$

Where RE(%) is the average relative error; n is the number of experimental data points; Y_{exp} is the percentage of sodium chloride or total soluble solids percent measured; and Y_{es} is the percent estimated of the sodium chloride or total soluble solids.

Result and Discussion

The kinetics for solute uptake under different impregnation conditions are shown in Fig. 1. As infusion proceeds, at all pressure levels and salt concentrations, infiltration of solutes increased. Pressure and salt concentration had a significant effect ($p<0.05$) on the NaCl content in linear and interaction effects (Table 1). Even though great differences in NaCl uptake were not obtained during infusion, the results showed that the NaCl uptake increased slightly at low pressure levels. The large influence of salt concentration is shown in Fig. 1a–c. At a concentration of 30 g/L NaCl (Fig. 1a), a little increase in the salt content was reached at a pressure of 4.05 kPa. The major part of NaCl increase content was observed in the first 12 min of impregnation time. Further increase in time did not increase significantly the NaCl content. At 70 and 110 g/L NaCl, a significant increase of NaCl content on the peppers can be observed (Fig. 1b, c). In both cases, the increase in NaCl content followed an exponential trend, with the rate of solute uptake decreasing at large impregnation times. However, it can be seen that at higher concentrations (70 and 100 g/L), salt gain is at least threefold with respect to 30 g/L. This trend was observed due to the coupling of hydrodynamic mechanisms and relaxation–deformation phenomena with diffusion (Fito et al. 1996; Chiralt et al. 2001) promoted by concentration gradients produced between the food material and salt solution. It was more noticeable at higher salt concentration and was attributed to the large osmotic driving force between cell tissue and the hypertonic medium, provoking strong alterations in cell permeability (Islam and Flink 1982; Lenart and Flink 1984; Torreggiani 1993).

Table 1 Variance analysis of NaCl and sorbitol uptake at different pressures, concentrations, and times

Source of variation	*df*	NaCl $p>F$	Sorbitol $p>F$
t	4	<0.0001	<0.0001
pr	2	0.0050	0.6401
con	2	<0.0001	<0.0001
pr×con	4	0.0898	<0.0001
t×pr	8	<0.0001	<0.0001
t×con	8	<0.0001	<0.0001
t×pr×con	16	<0.0001	<0.0001

t time, *pr* pressure, *con* concentration

Regarding sorbitol infiltration into the vegetable tissue at different pressures and sorbitol solution concentrations, there was a significant effect ($p<0.05$) on total soluble solids content of the peppers, showing an interactive significant effect between both variables (Table 1). Figure 1d shows that the sorbitol solution at 7°Bx generated a minimal uptake of sorbitol at the different combinations of sorbitol concentration and pressure with no differences among them. An increase of soluble solids content of peppers was observed for 24°Bx and 41°Bx sorbitol solutions at the different pressures, as shown in Fig. 1e, f. It can be observed that in both solutions, the highest increases of soluble solids occurred at a pressure of 4.05 kPa, and equilibrium was reached at 16 min of infusion time. At 24°Bx, after 60 min of impregnation, all pressure conditions showed the same soluble solids content while that for 41°Bx at higher impregnation times (32 and 60 min), the gain of sorbitol was higher at 44.66 and 85.33 kPa. For both 24°Bx and 41°Bx of sorbitol solution, the increase in total soluble solids followed an exponential trend. The fact that soluble solid increases tends to equilibrium in the first minutes during the infusion at the lowest pressure can be attributed to fast release of water from the tissue and simultaneous impregnation of the soluble solid into the intercellular space tissue, limiting soluble solid increase at higher infusion times (Ferrando and Spiess 2003; Rastogi and Raghavarao 2004a). Furthermore, properties such as viscosity of sorbitol solution at higher sorbitol concentrations can limit the pressure effect on mass transfer. The higher increases in total soluble solid obtained at higher pressures (44.66 and 85.33 kPa) can be attributed to the diffusion mechanisms due at higher concentration gradient between hypertonic solution and bell pepper tissue.

Kinetics Modeling

The model parameters obtained from the nonlinear regression analysis (Eq. 2) are shown in Tables 2 and 3. The a parameter did not show significant changes ($p>0.05$) for the different concentrations and pressures for NaCl uptake showing similar values to the NaCl initial content in pepper tissue before infusion. The b parameter showed an increasing trend with respect to NaCl solution concentration and showed no important effect for the different impregnation pressures. This behavior could be due to the fact that the higher osmotic pressure produced by the NaCl solution results in a higher driving force and, therefore, a higher salt gain, thus increasing the b parameter. Parameter c, that describes the rate constant of impregnation, was signifi-

Table 2 Estimated parameters of the negative exponential model for the infusion of sodium chloride in the tissue of bell pepper at different NaCl solution concentration and pressure

NaCl conc, (g/L)	Pressure (kPa)														
	4.05					44.66					85.33				
	a (%)	*b* (%)	*c* (min^{-1})	R^2	RE (%)	*a* (%)	*b* (%)	*c* (min^{-1})	R^2	RE (%)	*a* (%)	*b* (%)	*c* (min^{-1})	R^2	RE (%)
30	0.5402	1.2032	0.1025	0.970	3.8	0.5826	1.0053	0.0675	0.910	7.1	0.6019	1.4857	0.0274	0.960	5.3
70	0.6391	4.0056	0.1295	0.975	6.3	0.6704	3.8774	0.1195	0.973	7.4	0.7395	3.9819	0.0844	0.956	10.1
110	0.5701	5.3892	0.1925	0.990	3.1	0.6551	5.2530	0.1665	0.970	6.9	0.6898	5.7636	0.1241	0.980	7.1

Table 3 Estimated parameters of the negative exponential model for the infusion of sorbitol in the tissue of bell pepper at different sorbitol solution concentrations and pressures

Sorbitol conc (°Bx)	Pressure (kPa)														
	4.05					44.66					85.33				
	a (%)	*b* (%)	*c* (min^{-1})	R^2	RE (%)	*a* (%)	*b* (%)	*c* (min^{-1})	R^2	RE (%)	*a* (%)	*b* (%)	*c* (min^{-1})	R^2	RE (%)
7	4.1234	1.7281	0.1007	0.936	2.7	4.0835	1.6857	0.1026	0.960	1.8	4.0058	1.618	0.0520	0.980	1.2
24	3.8332	8.5232	0.1866	0.957	4.0	4.5544	6.9975	0.0809	0.956	5.6	4.4972	7.7175	0.0888	0.940	6.3
41	3.9931	10.187	0.2670	0.981	2.7	4.9547	12.5436	0.1162	0.890	10.7	5.6169	15.4783	0.0406	0.960	9.5

Table 4 Estimated coefficients of fitted regression model during the infusion of NaCl solution and sorbitol in the tissue of diced bell pepper

Parameters[a]	NaCl Coefficients ± SE	Sorbitol Coefficients ± SE
a	0.5483±0.1082	4.1115±0.2569
b_0	−0.6806±0.1685	ns
b_1	0.0592±0.0016	0.2789±0.0110
b_2	ns	0.0246±0.0067
c_0	0.1655±0.0140	0.1113±0.0286
c_1	ns	0.00240±0.0004
c_2	−0.00043±0.0002	−0.00138±0.0003
R^2	0.97	0.94

$p \leq 0.05$

ns nonsignificant; SE standard error

[a] In the parameters model, the subscript 1 is related with the solute concentration and subscript 2 is related with pressure

cantly affected ($p<0.05$) by both NaCl solution concentration and impregnation pressure, and a maximum value was obtained at a high concentration and low pressure.

The parameters obtained for increased in total soluble solids for sorbitol solutions infused are shown in Table 3. It can be seen that the a parameter did not change with different conditions of pressure and sorbitol solution concentration, showing a similar value to the initial percent of total soluble solids in the pepper tissue before infusion. The b parameter increased with an increasing sorbitol solution concentration but was not affected ($p>0.05$) by impregnation pressure. On the other hand, it can be seen that the c parameter did not show a clear trend with respect to infusion pressure and sorbitol solution concentration except at 4.05 kPa, where the rate constant (c) increased as the sorbitol solution concentration increased. This could be attributed to the low pressure effect and to the sorbitol molecule characteristics: larger molecules significantly influence mass transfer since they accumulate on the tissue, limiting diffusion into intracellular space. Furthermore,

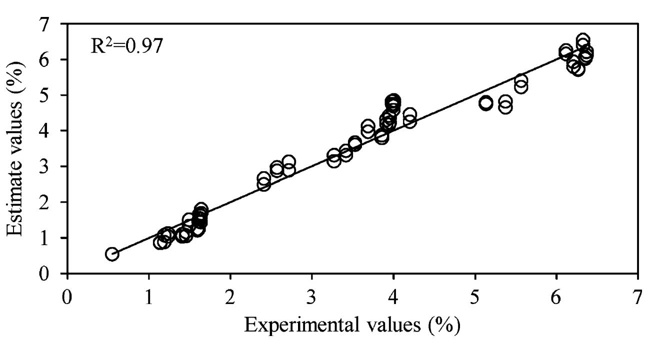

Fig. 2 Parity plot of predicted and observed values of NaCl content in slab bell pepper infused in NaCl solution under different pressure conditions (*circles* experimental data; *solid line* lines fitted by model)

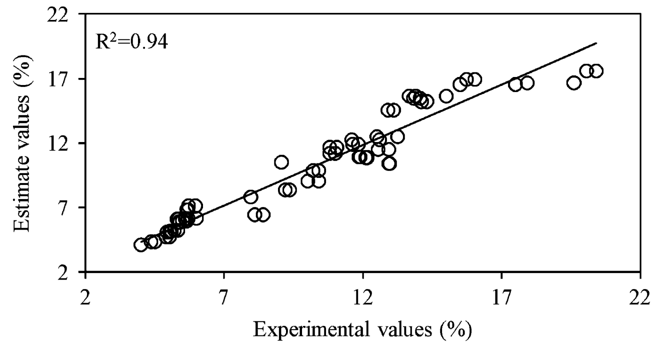

Fig. 3 Parity plot of predicted and observed values of soluble solids content in slab bell pepper during the impregnation of sorbitol solution under different pressure conditions (*circles* experimental data; *solid line* lines fitted by model)

sorbitol solution viscosity could affect the mass transfer of this solute at higher pressures. The proposed model (Eq. 2) adequately describes solutes uptake during the infusion of the NaCl and sorbitol solution under specific conditions of solution concentration and pressure. However, the model does not account for interactive effects between solution concentration and pressure (Tables 2 and 3). Similar results were reported by Moreira and Xidieh (2004), using NaCl solution and sucrose solutions as osmotic agents.

According to the results above, the negative exponential model for NaCl and sorbitol uptake obtained for regression analysis suggests an extended model in which the interaction of both variables is considered. Equations 4 and 5 show these models for NaCl and soluble solids content respectively.

$$Y_{\mathrm{NaCl}} = a + (b_0 + b_1\mathrm{con})[1 - \exp\{-(c_0 + c_2\mathrm{pr})t\}] \tag{4}$$

$$Y_{\mathrm{ss}} = a + (b_1\mathrm{con} + b_2\mathrm{pr})[1 - \exp\{-(c_0 + c_1\mathrm{con} + c_2\mathrm{pr})t\}] \tag{5}$$

Where Y_{NaCl} is the estimated sodium chloride content (%) and Y_{ss} is the estimated of soluble solids content (%); a, b_0, b_1, b_2, c_0, c_1, and c_2 are the coefficients of the models. The extended model parameters for both hypertonic media are shown in Table 4. The models explain 97% of the variance in the data for gained salt percent and 94% for increase in total soluble solids for the sorbitol solution. Both models show the interactive effect of the solution concentration and pressure. The fitted model for sodium chloride uptake shows that the NaCl solution concentrations significantly affects salt uptake in the pepper tissue, while the pressure did not affect the solute uptake rate. In the case of sorbitol, the solution concentration showed a more pronounced effect than pressure on increased total soluble solids percent. The sorbitol uptake rate decreased as pressure increased and increased with a higher sorbitol solution concentration. Both models have the advantage that they include all factors involved in the infusion process and can predict the solute uptake at specific conditions of solution concentration, pressure, and infusion time. However, they are only capable of estimating data within the processing conditions for which they were developed. These can be applied for the product development specifically for bell pepper. Fig. 2 and 3 show plots of predicted and observed values of salt and sorbitol uptake. Fig. 2 shows that salt uptake is predicted satisfactorily by the model due to the easy NaCl diffusion, attributable to its small molecular size and ionic strength. However, there were some deviations in the estimates of soluble solids content by the model during sorbitol solution infusion (Fig. 3). This can be explained by taking into account that this diffused solute accumulates in intercellular spaces and does not diffuse through the cell wall, which interferes with mass transfer (Ruiz-López et al. 2008). Also, the solute diffusion can change due to changes in the physical properties of the food such as porosity and cell permeability (Torreggiani 1993; Rastogi and Raghavarao 2004a). This becomes more evident for sorbitol solution where the physical properties such as molecular size and viscosity can cause deviations from the model. Similar findings were reported by Rastogi and Raghavarao (1996) where they proposed a mathematical model based on osmotic pressure during infusion of coconut.

Conclusions

An empirical model was developed to take into account the kinetic parameters related to mass transfer. During impregnation treatment with sodium chloride solutions and sorbitol solution, the rate of solutes uptake was correlated directly with pressure and solution concentration. Even though great differences in solute uptake were not obtained during infusion at different pressures conditions, the results showed that the rate of mass transfer increased at low pressure levels, resulting in fast saturation of the tissue for sorbitol uptake at a pressure of 4.05 kPa in 16 min of infusion time. At higher pressure, an equilibrium condition was not reached. The salt impregnation did not reach equilibrium at the different experimental conditions. A generalized negative exponential model for both NaCl uptake and soluble solid content in bell pepper tissue explained 97% and 94% of the variation, respectively, over the experimental ranges of pressure, concentration, and infusion times. These predicted models can be used for formulation and development of bell pepper products.

Acknowledgements The authors give special thanks to CONACYT for their financial support to develop this research. The paper is based on author Ricardo Quintero's thesis for the MS degree.

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