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Mass transfer kinetics of osmotic dehydration of cherry tomato

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Abstract

Cherry tomato samples were osmotically dehydrated in different hypertonic NaCl solutions (with or without sucrose) at two different concentrations. Mass transfer kinetics were modelled according to Peleg, Fick and Page equations. The Peleg equation presented the best fitting for water loss and Page model showed the best predictive capacity for salt gain data. The effective diffusivity determined using Fick's second law applied to a spherical geometry was found to be in the range of 0.43×10^{-9}–1.77×10^{-9} m^2/s for water loss and 0.04×10^{-9}–0.54×10^{-9} m^2/s for salt gain. Increased solution concentration resulted in higher water loss and salt gain. An addition of sucrose to osmotic solutions decreased the driving force of the process.

Keywords: Cherry tomato; Effective diffusivity; Empirical models; Mass transfer; Osmotic dehydration

1. Introduction

The development of intermediate moisture (IM) foods for human consumption has received much attention in recent years. IM tomato products produced by osmotic dehydration have several advantages such as a higher nutritional content than any other drying methods because osmotic dehydration has little effect on the various internal components. In addition, the ready-to-use feature makes IM tomatoes attractive to the pizza and other catering business (Shi, Le Maguer, Wang, & Liptay, 1997).

Osmotic dehydration is an important process that enables the partial removal of water by direct contact of a product with a hypertonic medium (Lazarides, Katsanidis, & Nickolaidis, 1995). This gives rise to two major simultaneously countercurrent mass transfer fluxes, namely water flow from the product to the surrounding solution and solute infusion into the product. Leakage of the product natural solutes (sugars, organic acids, mineral, etc.) is quantitatively neglectable, but may be important for the organoleptic and nutritional value of the product (Heng, Guilbert, & Cuq, 1990; Mizrahi, Eichler, & Ramon, 2001; Ponting, 1973).

The kind of osmotic agent used and hence its molecular weight or ionic behaviour strongly affects the kinetics of water removal and the solid gain. The most commonly used osmotic agents are sucrose and sodium chloride (Ertekin & Cakaloz, 1996). Previous works have also pointed out the effectiveness in combining both solutes (Islam & Flink, 1982; Lenart & Flink, 1984; Lerici, Pinnavaia, Dalla Rosa, & Bartolucci, 1985).

The purpose of the present work was to study mass transfer parameters during the osmotic dehydration of cherry and examine the predictive capacity of Peleg, Fick and Page equations to the experimental data.

2. Theory

Peleg (1988) proposed an equation to describe sorption curves that approach equilibrium asymptotically. This equation was redefined by Palou, Lópz-Malo, Argaiz, and Welti (1994) in terms of soluble solids and moisture content. Park, Bin, Brod, and Park (2002) rewrote the same equation as

$$\overline{MC(t)} = MC_0 \pm \frac{t}{k_1 + k_2 t} \tag{1}$$

where $\overline{MC(t)}$ is the amount of water or solids at time t, g; MC_0 is the initial amount of water or solids, g; t is the time, h; k_1 and k_2 are Peleg constants.

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Considering the cherry tomato as a sphere with initially uniform water or solids content (MC_0), the solution for Fick's equation for constant process conditions is (Crank, 1975):

$$W_{\mathrm{A\,or\,S}} = \frac{6}{\pi^2} \sum_{i=0}^{\alpha} \frac{1}{i^2} \exp\left[-i^2 \pi^2 D_{\mathrm{ef}} \frac{t}{r^2} \right] \tag{2}$$

where D_{ef} is the effective diffusivity of water loss or salt gain, m^2/s; i is the number of series terms; r is the sphere radius, m; t is the time, s;

Allowing the calculation of effective diffusivity for water loss and salt gain based on the dimensionless amount of water loss (W_{A}) and salt gain (W_{S}):

$$W_{\mathrm{A\,or\,S}} = \frac{\overline{MC(t)} - MC_{\mathrm{eq}}}{MC_0 - MC_{\mathrm{eq}}} \tag{3}$$

where MC_{eq} is the equilibrium amount of water loss or salt gain, g.

Page (1949) empirical model is given by the following equation:

$$W_{\mathrm{A\,or\,S}} = \frac{MC(t) - MC_{\mathrm{eq}}}{MC_0 - MC_{\mathrm{eq}}} = \exp(-At^B) \tag{4}$$

where A and B are Page's constants.

3. Material and methods

Fresh cherry tomatoes were purchased from a local market. The fruits were sorted visually for color (completely red) and size (average diameter of 2.8 cm). The average initial moisture content was 94% w/w, gravimetrically measured using a vacuum oven at 70 °C for 24 h.

As the cherry tomato waxy skin represents a high resistance to mass transfer, the fruits were perforated with needles (1 mm of diameter) (Shi et al., 1997) to pin hole density of 16 holes/cm^2.

The whole cherry tomatoes, after skin treatment, were osmotically dehydrated in NaCl and NaCl–sucrose (3:2) solutions of different concentrations (10 and 25% w/w) at room temperature (25 °C) and agitation of 70 rpm. The fruits (16 g) were placed in 250 ml beakers containing the osmotic solution and maintained inside a temperature-agitation controlled shaker (Tecnal, TE 421). The weight ratio of osmotic medium to fruit sample was 10:1 to avoid significant dilution of the medium and subsequent decrease of the driving force during the process. Samples were removed from the solution at 30, 60, 90, 120, 180, 240 and 360 min of immersion, drained and the excess of solution at the surface was removed with absorbent paper.

The salt content was determined by Mohr's titration method (Ranganna, 1977) and the water loss by gravimetric measurement, as defined by Hawkes and Flink (1978):

$$\mathrm{WL} = \frac{ww_0 - (tw - ws)}{w_0} \times 100 \tag{5}$$

where WL is the water loss, g water/100 g fresh sample; ww_0 is the weight of water initially present, g; tw is the weight of the sample at the time of sampling, g; w_0 is the initial sample weight, g; ws is the weight of the solids at the time of the sampling, g, determined in a vacuum oven at 70 °C for 24 h. All determinations were made in triplicate.

Curves of water loss and salt gain as a function of time were constructed using experimental data. The equation parameters (k_1, k_2, A and B), as well as the effective diffusivity values were determined for water loss and salt gain using the non-linear estimation from the statistical package Statistica 5.0 (Statistica, 1995). The average relative error was used as a criterion to evaluate the best fitting:

$$P = \frac{100}{n} \sum_{i=1}^{n} \frac{|V_{\mathrm{e}} - V_{\mathrm{c}}|}{V_{\mathrm{e}}} \tag{6}$$

where P is the average relative error, dimensionless; n is the number of experimental data; V_{e} is the experimental value (water loss or salt gain); V_{c} is the calculated value (water loss or salt gain).

4. Results and discussion

The osmotic process was studied in terms of water loss and salt gain (Fig. 1). An initial high rate of water removal (and salt uptake) followed by slower removal (and uptake) in the later stages was observed. Rapid loss of water (and salt gain) in the beginning is apparently due to the large osmotic driving force between the dilute sap of the fresh fruit and the surrounding hypertonic medium. Several research groups have published similar curves for osmotic dehydration of foods (Kowalska & Lenart, 2001; Lazarides et al., 1995; Palou et al., 1994; Park et al., 2002).

Increase in solution concentration resulted in an increase in the osmotic pressure gradients and, hence, higher water loss (and salt uptake) values throughout the osmosis period were obtained. These results indicate that by choosing a higher concentration medium, some benefits in terms of faster water loss could be achieved. However, a much greater gain of solids is observed.

For the mixed systems, the effect of sucrose addition to the osmotic medium in the water loss and salt gain was observed. The water loss (and salt gain) was lower than using salt alone. Sodium chloride increases the driving force for dehydration owing to its water activity

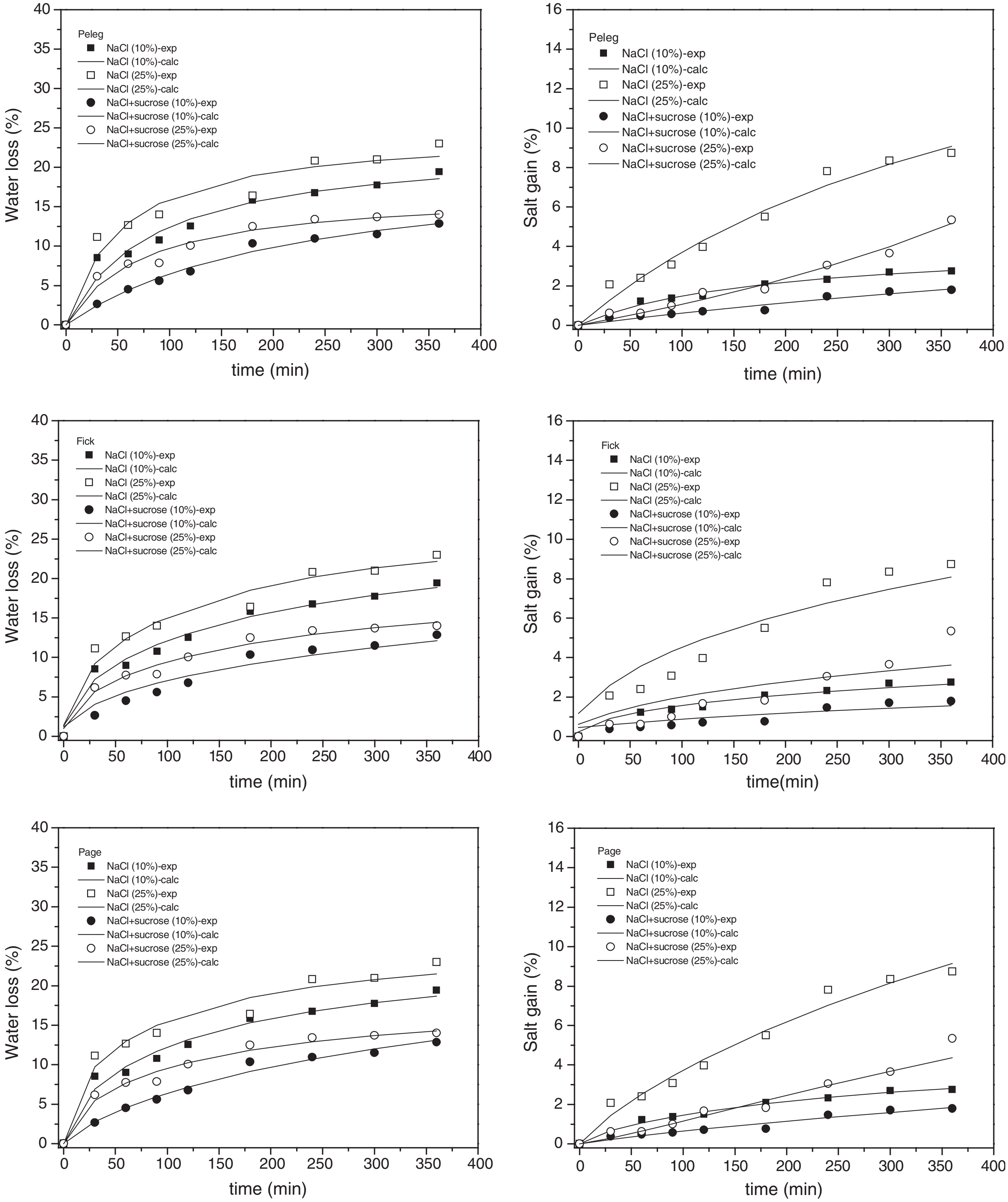

Fig. 1. Cherry tomato water loss and salt gain versus time.

lowering capacity and its low molecular weight allows a higher rate of penetration in the material. However, its use is limited since a salty taste is imparted to the food. In addition, sucrose allows the formation of a sugar surface layer, which becomes a barrier to the removal of water and the solute uptake.

Peleg, Fick and Page equations were used to fit the experimental data. Peleg parameters obtained from the

Table 1
Values of Peleg's equation parameters for water loss and salt gain

Sample	Water loss				Salt gain			
	k_1	k_2	R^2	P (%)	k_1	k_2	R^2	P (%)
NaCl 10%	3.67	0.04	0.97	6.72	43.19	0.24	0.99	4.15
NaCl 25%	2.18	0.04	0.96	7.48	22.01	0.05	0.98	9.79
NaCl–sucrose 10%	10.61	0.05	0.99	4.24	148.89	0.13	0.95	13.84
NaCl–sucrose 25%	4.36	0.06	0.97	5.92	103.08	−0.09	0.98	12.26

non-linear regression analysis are shown in Table 1. It can be observed an inverse relationship between k_1 and solution concentration. In contrast, the mixed solution had higher values compared to the salt medium at the same concentration. The parameter $1/k_1$ describes the initial rate of mass exchange. From the observations made, a maximum value for $1/k_1$ was obtained for salt dehydrated samples at higher concentrations. This behaviour could be due to a cellular response to the osmotic pressure increment, as observed by Sachetti, Gianotti, and Dalla Rosa (2001) in the osmotic process of apple in salt–sucrose solutions.

The k_2 parameter did not exhibit a trend with the increase of concentration for water loss. However, higher concentrations gave decreased k_2 for salt gain. Adding sucrose to the solution resulted in the increase of the parameter for water loss, while salt gain showed the inverse behaviour. Park et al. (2002) did not found any relation between Peleg's equation parameters with the increase of sucrose concentration at constant temperature in the osmotic dehydration of pears.

The effective diffusivities of water loss and salt gain calculated using Fick's model are presented in Table 2. It can be observed that diffusion is improved by higher solute concentration, as well as when salt is used as osmotic agent. Comparison of diffusivities reported in literature is difficult because of the different estimation methods and models employed together with the variation in food composition and physical structure. Park et al. (2002) working with pear cubes found that D_{ef} ranged from 0.35×10^{-9} to 1.92×10^{-9} m^2/s for water loss and from 0.20×10^{-9} to 3.60×10^{-9} m^2/s for sugar gain at different temperatures (40–60 °C). Lazarides, Gekas, and Mavroudis (1997) found values ranging from 1.42×10^{-10} to 4.69×10^{-10} m^2/s for moisture diffusivity and from 0.73×10^{-10} to 2.41×10^{-10} m^2/s solute diffusivity of apple slices at different temperatures (20–50 °C) and sucrose solution concentrations (45–65%).

Page's equation parameters obtained for water loss are shown in Table 3. For water loss it can be observed that parameter A increased with solution concentration and decreased by adding sucrose to the osmotic medium, while the parameter B had the inverse behaviour. For salt gain, the parameter A did not show any trend with solution concentration, but it decreased when the mixed solution was used. The parameter B increased at higher concentrations, as well as when sucrose was part of the solution.

The best fitting for water loss experimental data was obtained using Peleg equation. Page empirical model

Table 2
Values of Fick's equation parameters for water loss and salt gain

Sample	Water loss			Salt gain		
	D_{ef} (m^2/s)	R^2	P (%)	D_{ef} (m^2/s)	R^2	P (%)
NaCl 10%	1.21×10^{-9}	0.98	7.03	0.54×10^{-9}	0.96	6.28
NaCl 25%	1.77×10^{-9}	0.97	16.71	0.17×10^{-9}	0.89	5.81
NaCl–sucrose 10%	0.43×10^{-9}	0.94	7.24	0.04×10^{-9}	0.77	3.88
NaCl–sucrose 25%	1.36×10^{-9}	0.98	8.23	0.11×10^{-9}	0.73	8.98

Table 3
Values of Page's equation parameters for water loss and salt gain

Sample	Water loss				Salt gain			
	$A \times 10^2$	$B \times 10$	R^2	P (%)	$A \times 10^2$	$B \times 10$	R^2	P (%)
NaCl 10%	4.32	6.25	0.98	6.96	1.39	7.48	0.99	3.10
NaCl 25%	7.32	5.68	0.97	22.22	0.42	8.41	0.98	2.35
NaCl–sucrose 10%	1.01	7.81	0.99	3.11	0.01	8.89	0.95	1.37
NaCl–sucrose 25%	4.67	6.24	0.98	6.89	0.01	11.86	0.95	3.32

presented a good fitting of the salt gain experimental data. Fig. 1 shows the experimental and calculated results of water loss and salt gain.

5. Conclusions

The rate of water loss and salt gain in the osmotic dehydration of cherry tomato was directly related to the concentration of the solution. When a mixed NaCl–sucrose solution was used the rates decreased.

Peleg equation presented the best fitting for water loss experimental data and Page model had a good predictive capacity for salt gain data.

The effective diffusion coefficients obtained from Fick equation ranged from 0.43×10^{-9} to 1.77×10^{-9} m^2/s for water loss and from 0.04×10^{-9} to 0.54×10^{-9} m^2/s.

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References

Crank, J. (1975). *The mathematics of diffusion* (2nd ed.). Oxford: Clarendon Press.

Ertekin, F. K., & Cakaloz, T. (1996). Osmotic dehydration of peas: influence of process variables on mass transfer. *Journal of Food Processing and Preservation, 20*, 87–104.

Hawkes, J., & Flink, J. (1978). Osmotic concentration of papaya: influence of process variables on the quality. *Journal of Food Processing and Preservation, 2*, 265–284.

Heng, W., Guilbert, S., & Cuq, J. L. (1990). Osmotic dehydration of papaya: influence of process variables on the product quality. *Science des Aliments, 10*, 831–848.

Islam, M. N., & Flink, L. N. (1982). Dehydration of potato II—osmotic concentration and its effect on air drying behavior. *Journal of Food Technology, 17*, 387–403.

Kowalska, H., & Lenart, A. (2001). Mass exchange during osmotic pretreatment of vegetables. *Journal of Food Engineering, 49*, 137–140.

Lazarides, H. N., Gekas, V., & Mavroudis, N. (1997). Apparent mass diffusivities in fruit and vegetable tissues undergoing osmotic process. *Journal of Food Engineering, 31*, 315–324.

Lazarides, H. N., Katsanidis, E., & Nickolaidis, A. (1995). Mass transfer during osmotic preconcentration aiming at minimal solid uptake. *Journal of Food Engineering, 25*, 151–166.

Lenart, A., & Flink, J. M. (1984). Osmotic concentration of potatoes I. Criteria for the end-point of the osmosis process. *Journal of Food Technology, 19*(1), 45–63.

Lerici, C. R., Pinnavaia, G., Dalla Rosa, M., & Bartolucci, L. (1985). Osmotic dehydration of fruits: influence of osmotic agents on drying behavior and product quality. *Journal of Food Science, 50*, 1217–1220.

Mizrahi, S., Eichler, S., & Ramon, O. (2001). Osmotic dehydration in gel systems. *Journal of Food Engineering, 49*, 87–96.

Page, G. E. (1949). *Factors influencing the maximum of air drying shelled corn in thin layer*. M.Sc. Thesis, USA. Purdue University, Indiana.

Palou, E., Lópz-Malo, A., Argaiz, A., & Welti, J. (1994). The use of Peleg's equation to model osmotic concentration of papaya. *Drying Technology, 12*(4), 965–978.

Park, K. J., Bin, A., Brod, F. P. R., & Park, T. H. K. B. (2002). Osmotic dehydration kinetics of pear D'anjou (*Pyrus communis* L.). *Journal of Food Engineering, 52*, 293–298.

Peleg, M. (1988). An empirical model for the description of moisture sorption curves. *Journal of Food Science, 53*(4), 1216–1219.

Ponting, J. D. (1973). Osmotic dehydration of fruits—recent modifications and applications. *Process Biochemistry, 8*, 18–20.

Ranganna, S. (1977). *Manual of analysis of fruit and vegetables products*. New Delhi: McGraw-Hill Publishing Company, p. 634.

Sachetti, G., Gianotti, A., & Dalla Rosa, M. (2001). Sucrose-salt combined effects on mass transfer kinetics and product acceptability. Study on apple osmotic treatments. *Journal of Food Engineering, 49*, 163–173.

Shi, J. X., Le Maguer, M., Wang, S. L., & Liptay, A. (1997). Application of osmotic treatment in tomato processing-effect of skin treatments on mass transfer in osmotic dehydration of tomatoes. *Food Research International, 30*, 669–674.

Statistica for Windows 5.0. (1995). *Computer program manual*. StatSoft Inc., Tulsa.