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Modelling of water loss and solute uptake during osmotic drying of carrots using weibull distribution approach

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Abstract

Osmotic drying of carrots *(Daucus carota)* was carried out at different combinations of temperatures (30, 40 and 50°C) and concentrations (50, 55 and 60%) of sucrose solution. Since it is a combination of simultaneous water and solute diffusion process that occurs counter currently, mathematical model of both water loss and solute uptake were developed using Weibull distribution approach. The shape parameter (β) and the scale parameter (α) of the model were calculated from the experimental values of water loss and solute uptake. The β values for water loss and solute uptake for the model were found to be 0.70 and 0.756, respectively and were statistically independent of both temperature and concentration of sucrose solution. The water loss rate constant ($\frac{1}{\alpha_w}$) was ranged from 0.0049 min^{-1} to 0.0071 min^{-1}. Similarly the solute uptake rate constant ($\frac{1}{\alpha_s}$) was ranged from 0.007 min^{-1} to 0.0118 min^{-1}. Second order quadratic equations with temperature and concentration of sucrose solution were found to fit well in describing the effect of variables on the responses studied. The Weibull parameters 'α' and 'β' were found adequate to predict the water loss and solute uptake within the range of temperature and concentration of sucrose solution considered.

Introduction

Osmotic drying of fruits and vegetables is an innovative approach in the field of drying and dehydration. It is a technique in which high moisture fruits and vegetables are brought to intermediate moisture level prior to final drying by hot air, vacuum, microwave or freeze-drying. The high nutritional and organoleptic qualities of osmotic treated products and the energy saving during drying of osmotically treated samples have consistently sought the attention of researchers (Lerici *et al*., 1985; Lenart and Lewicki, 1988; Rahman and Lamb, 1991; Jayaraman and Das Gupta, 1992; Torreggiani 1993; Karathanos *et al*., 1995; Spiazzi and Mascheroni, 1997; Rastogi *et al*., 2002).

Fruits and vegetables are immersed in hypertonic solution during osmotic treatment for partial removal of water from living tissues. During the process, diffusion of water in and out of the tissues is continued till equilibrium achieved. The driving force is the water activity gradient caused due to the osmotic pressure. Since the natural cell walls of fruits and vegetables are not perfect semi-permeable membranes, there is always some solid diffusion into the cells through the cell walls. It means that simultaneous water and solute diffusion occurs in the tissues of the fruits and vegetables tissues (Yao and LeMaguer, 1994).

The parameters influencing the osmotic drying can be broadly classified as product parameters and osmotic process parameters. The product parameters influencing the performance of osmotic drying are size, shape and properties of commodity like bulk density, porosity, pore size, and pore size distribution (Lazarides, 1994; Lazarides *et al*., 1997; Cunha *et al*., 2001). Mass transfer phenomena of water and solutes depend on osmotic process parameters like composition of the osmotic solution, solution to product ratio, concentration of osmotic solution, temperature of osmotic treatment etc (Ponting *et al*., 1966; Contreras and Smyrl, 1981; Rastogi and Raghavarao, 1994; Lazarides *et al*., 1997; Cunha *et al*., 2001; Rastogi *et al*., 2002).

During osmotic drying of food materials it is desired to achieve maximum possible water removal rates while keeping solute uptake to a minimum. The ratio of water removal to solute uptake is termed as process efficiency (Lazarides, 1994). In order to design an efficient osmotic drying system, it is

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required to develop a reliable model for accurate prediction of water loss and solute uptake by food materials.

Mathematical models have been developed to describe water loss and solute uptake as a function of osmotic temperature, concentration of osmotic solution and duration of osmotic treatment (Magee *et al*., 1983; Biswal *et al*., 1991). For prediction of mass transport phenomena, mathematical models following Fick's second law have been developed by various researchers (Monsalve-González *et al*., 1993; Lazarides *et al*., 1995; Spiazzi and Mascheroni, 1997; Lazarides *et al*., 1997; Nieto *et al*., 2001). Some more models have been suggested considering- the concept of irreversible thermodynamics (Toupin *et al*., 1989; Marcotte *et al*., 1991; Yao and LeMaguer, 1996), cellular physiology and structure of fruit/ vegetable tissue (Spiazzi and Mascheroni, 1997; LeMaguer *et al*., 2002), hydrodynamics mechanism (Fito *et al*., 1996; Fito and Chiralt, 1996), stochastic modeling (Cunha *et al*., 2001) etc. However, some models are simple and validate the experimental data, but their use is limited to certain cases and they do not take into account the mechanism in which the results depend. Some other models with very complex mechanisms find difficulties to represent the experimental validation owing to the number of parameters involved in the models. This paper describes a model to predict the water loss and solute uptake in carrots following a Weibull probabilistic distribution approach.

Materials and Methods

The carrots *(Daucus carota)* were procured from the local market. Those were kept in refrigerator before using in the experiment. Prior to experiment, carrots were washed with clean water. Then samples of carrots were prepared by cutting them in cylindrical shapes of ~10 mm diameter by a de-corer and cutting into ~5 mm thickness by a hand knife. Sugar solutions of 50%, 55% and 60% (w/w) strength were used. The concentrations of these solutions were verified using a standard refractometer. The temperatures of osmotic solutions considered in the experiment were 30, 40 and 50°C. The solution to sample ratio was maintained at 12:1. The weighed samples were immersed in the sugar solution in a beaker. The beaker with solution was lead to the desired temperature and maintained in a serological water bath before osmotic treatment. The water level in serological water bath was 2-3 cm below the top of the beaker. Osmotic treatment continued till equilibrium condition was achieved. The samples were removed from the solution at intervals of 15 min for the first one hour, 30 min for the next 1.5 h and 60 min for the remaining time to monitor the moisture loss of samples with osmotic treatment time. At each time interval, the respective glass beaker was removed from the water bath and the sample pieces were immediately placed on the blotting paper to remove the surface solution and weighed. Moisture content of the oven-dried, at 105°C for 24 h, samples were also determined. All the experimental measurements were replicated thrice and the responses determined for each sample were water loss (g H_2O / g initial mass of sample) and solute uptake (g solute gain/ g initial mass of sample). Water Loss (WL) and solute gain/ uptake (SG) were determined using the following expressions.

$$WL = \frac{\left[(M_i - M_s) - (M_{ot} - M_{os})\right]}{M_i} \quad (1)$$

$$SG = \frac{(M_{os} - M_s)}{M_i} \quad (2)$$

Results and Discussion

Model development considering water loss(WL)

The Weibull probabilistic distribution model as described by Cunha *et al.* (2001) can be written for WL and solute uptake by carrot samples in osmotic drying process as

$$\frac{WL}{WL_\infty} = 1 - \exp\left[-\left(\frac{t}{\alpha_w}\right)^\beta\right] \quad (3)$$

$$\frac{SG}{SG_\infty} = 1 - \exp\left[-\left(\frac{t}{\alpha_s}\right)^\beta\right] \quad (4)$$

Figure 1 shows the experimental results of $\frac{WL}{WL_\infty}$ vs. 't' with different combinations of osmotic temperatures (30, 40 and 50°C) and sugar concentrations (50, 55 and 60%). $\frac{WL}{WL_\infty}$ increased asymptotically till a constant value (after seven hours of osmotic treatment) was achieved. That means WL from the samples reached to equilibrium condition after seven hours.

Fitting the $\frac{WL}{WL_\infty}$ vs. 't' curves to polynomial second order equation, 'αw' value (i.e. time 't' at which $\frac{WL}{WL_\infty}$ = 0.632) were calculated. Experimental 'α' values are shown in Table 1.

Equation (3) can be written as:

$$\left(1 - \frac{WL}{WL_\infty}\right) = \exp\left[-\left(\frac{t}{\alpha_w}\right)^\beta\right]$$

$$\text{or, } \frac{1}{\left(1 - \frac{WL}{WL_\infty}\right)} = \exp\left[\left(\frac{t}{\alpha_w}\right)^\beta\right]$$

Table 1. Scale parameters 'α_w and α_s' from experimental data of water loss and solute uptake respectively

Sugar Concentration (%)	Osmotic Temperature (°C)	α_w (min)	Regression coefficient (R^2)	α_s (min)	Regression coefficient (R^2)
50%	30	202.4	0.990	84.75	0.950
	40	190.9	0.998	120.36	0.993
	50	141.2	0.987	112.48	0.963
55%	30	156.9	0.991	80.30	0.947
	40	155.1	0.997	103.08	0.982
	50	149.6	0.994	143.77	0.993
60%	30	164.4	0.991	104.20	0.942
	40	166.4	0.990	137.71	0.964
	50	144.0	0.993	91.23	0.943

$$\text{or, } \ln\left[\frac{1}{\left(1-\frac{WL}{WL_\infty}\right)}\right] = \left(\frac{t}{\alpha_w}\right)^\beta$$

$$\text{or, } \ln\left[\ln\left[\frac{1}{\left(1-\frac{WL}{WL_\infty}\right)}\right]\right] = \beta\ln\left(\frac{t}{\alpha_w}\right) \qquad (5)$$

Plots of $\ln\left[\ln\left[\frac{1}{\left(1-\frac{WL}{WL_\infty}\right)}\right]\right]$ vs. $\ln\left(\frac{t}{\alpha_w}\right)$, for different temperatures and sugar concentrations, showed straight line curves having slope β (i.e. shape parameter of the model). The average value of β was found to be 0.70. The Least Significant Difference Test (LSDT) analysis showed the average values of β were not significantly different at 5% level for all experimental conditions studied.

Model development considering solute gain / Uptake(SG)

Figure 2 shows the experimental results of $\frac{SG}{SG_\infty}$ vs. 't' with different combinations of osmotic temperatures and sugar concentrations. $\frac{SG}{SG_\infty}$ increased with time till a constant value was achieved after seven hours of osmotic treatment. α values were calculated from the plots of $\frac{SG}{SG_\infty}$ vs. 't' using polynomial second order equation. α values for solute uptake are shown in Table 1.

Equation (4) can be written as:

$$\left(1-\frac{SG}{SG_\infty}\right) = \exp\left[-\left(\frac{t}{\alpha_s}\right)^\beta\right]$$

$$\text{or, } \frac{1}{\left(1-\frac{SG}{SG_\infty}\right)} = \exp\left[\left(\frac{t}{\alpha_s}\right)^\beta\right]$$

$$\text{or, } \ln\left[\frac{1}{\left(1-\frac{SG}{SG_\infty}\right)}\right] = \left(\frac{t}{\alpha_s}\right)^\beta$$

$$\text{or, } \ln\left[\ln\left[\frac{1}{\left(1-\frac{SG}{SG_\infty}\right)}\right]\right] = \beta\ln\left(\frac{t}{\alpha_s}\right) \qquad (6)$$

Plots of $\ln\left[\ln\left[\frac{1}{\left(1-\frac{SG}{SG_\infty}\right)}\right]\right]$ vs. $\ln\left(\frac{t}{\alpha_s}\right)$, for different temperature and sugar concentrations, showed straight line curves with β as slope. The average value of β was found to be 0.756. From LSDT, the average values of β were not found significantly different at 5% level for all experimental conditions.

The WL rate constant ($\frac{1}{\alpha_w}$) increases with increase in concentration and in temperature (Figure 3). It was increased from 0.0049 min^{-1} (at 30°C and 50% concentration) to 0.0061 min^{-1} (at 30°C and 60% concentration). It was also varied from 0.0068 min^{-1} (at 50°C and 50% concentration) to 0.0071 min^{-1} (at 50°C and 60% concentration). On the other hand, the sugar uptake rate constant ($\frac{1}{\alpha_w}$) changed from 0.0118 min^{-1} (at 30°C and 50% concentration) to 0.0096 min^{-1} (at 30°C and 60% concentration) and also varied from 0.0080 min^{-1} (50°C and 50% concentration) to 0.0110 min^{-1} (50°C and 60% concentration) (Figure 4). It is always desirable in osmotic dehydration that the WL should be as maximum as possible with minimum or no solute uptake by the food materials. From the studied osmotic concentrations and temperatures, it is depicted that the high temperature and low concentration i.e. 50°C and 50% concentration favors for optimum water loss with minimum solute uptake.

Since is the function of both temperature and concentration of sugar solution (Figure 3 and Figure 4), following second order quadratic equations were fitted well to the observed data.

$$\frac{1}{\alpha_w} = 0.03003 - 1.59X10^{-3}C + 1.8X10^{-5}C^2 + 8.15X10^{-4}T - 7.0X10^{-6}TC - 5.0X10^{-6}T^2 \qquad (7)$$

$$\frac{1}{\alpha_s} = 0.27117 - 8.57X10^{-3}C + 6.8X10^{-5}C^2 - 1.0X10^{-3}T + 2.15X10^{-5}TC - 2.5X10^{-6}T^2 \qquad (8)$$

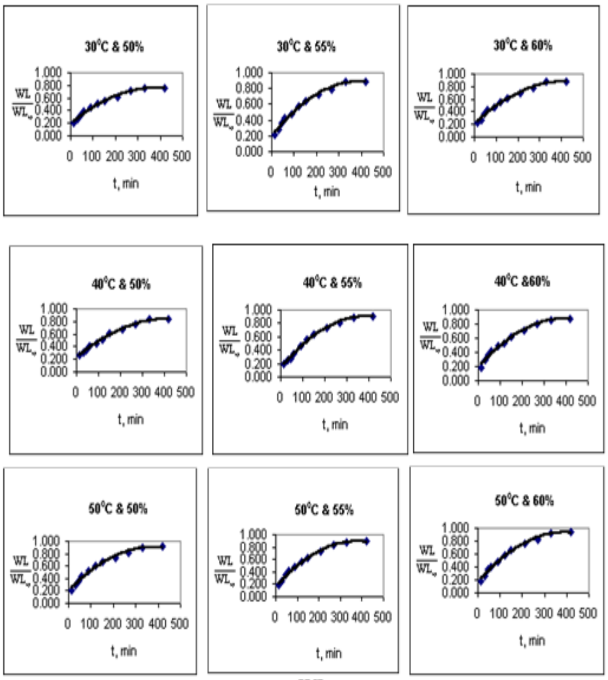

Figure 1. Variation of $\frac{WL}{WL_\infty}$ with time at different combinations of temperatures and sugar concentrations.

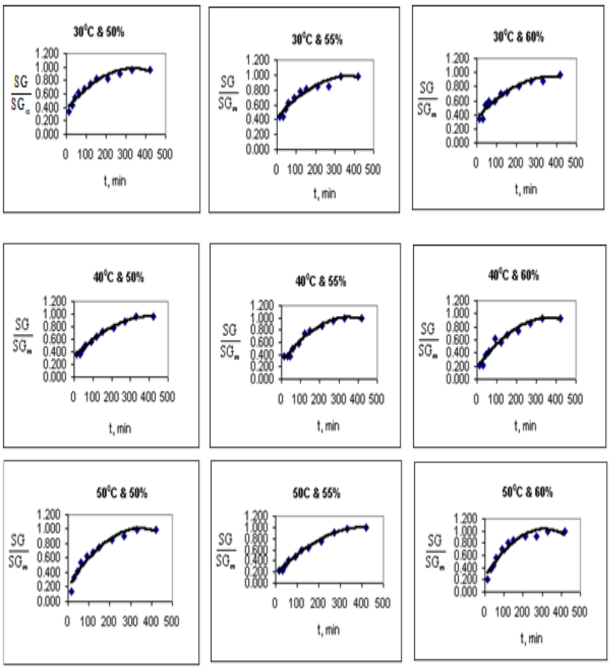

Figure 2. Variation of $\frac{SG}{SG_\infty}$ with time at different combinations of temperatures and sugar concentrations.

Using equations 7 and 8, the Weibull parameters α_w and α_s (for water loss and solute uptake) can be evaluated at any temperature and concentration of the osmotic solution. Putting those values in Weibull probabilistic distribution model as shown in equation 3 and 4, water loss and solute uptake can be predicted at different times.

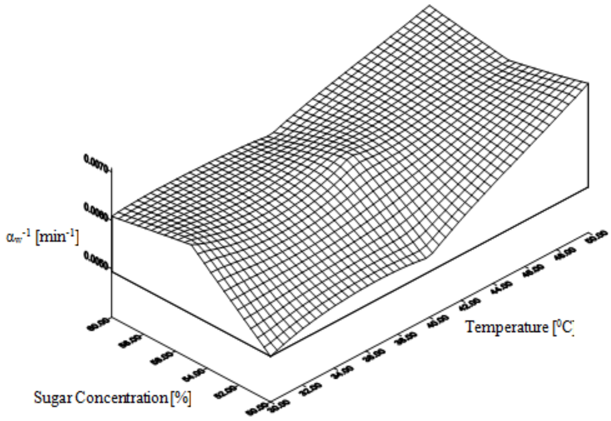

Figure 3. Variation of water loss rate constant (α_w^{-1}) with temperature and concentration of sugar solution

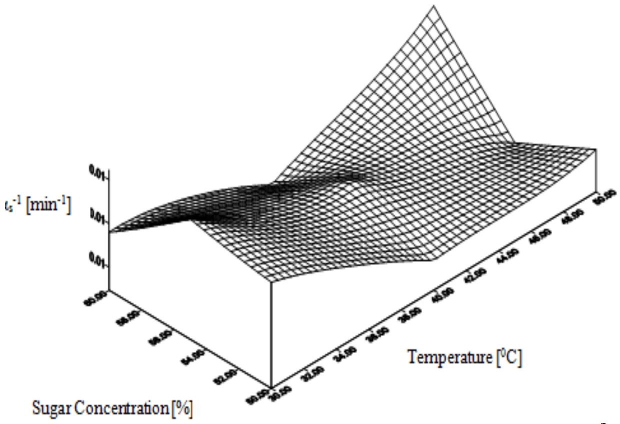

Figure 4. Variation of solute uptake rate constant (α_w^{-1}) with temperature and concentration of sugar solution

Conclusion

Now-a-days lots of research are going on to design an efficient osmotic drying system for fruits and vegetables. Their design and developments depend on a reliable model, which can accurately predict the mass transport phenomena like water loss and solute uptake by food materials. Although numerous models are available to predict such mass transfer phenomena, but their use is limited due to lack of understanding the appropriate mechanism in which their results depend. An attempt was therefore, made with Weibull distribution model to predict the water loss and solute uptake of carrot pieces. The Weibull distribution parameters like scale parameter (α) and shape parameter (β) were found adequate to predict the water loss and solute uptake within the range of temperature and concentration of sucrose solutions considered.

References

Biswal, R.N., Bozorgmehr, K., Tompkins, F.D. and Lix, X., 1991. Osmotic concentration of green beans prior to freezing. Journal of Food Science 56: 1008-1012.

Contreras, J.M. and Smyrl, T.G. 1981. An evaluation of osmotic concentration of apple rings using corn syrup solution. Canadian Institute of Food Science and Technology 14: 310-314.

Cunha, L.M., Oliveira. F.A.R., Aboim, A.P., Frias, J.M. and Pinheiro-Torres, A. 2001. Stochastic approach to the modeling of water losses during osmotic dehydration and improved parameter estimation. International Journal of Food Science and Technology 36: 253-262.

Fito, P., Andrés, A., Chiralt, A. and Pardo, P. 1996. Coupling of hydrodynamics mechanism and deformation-relaxation phenomena during vacuum treatments in solid porous food-liquid systems. Journal of Food Engineering 27: 229-240

Fito, P. and Chiralt, A. 1996. Osmotic dehydration: an approach to the modeling of solid food – liquid operations. In Fito, P., Rodriguez, E. O. and Barbosa-Cánovas, G.V. (Eds) Food Engineering 2000, p. 231-252. New York, USA: Chapman and Hall.

Jayaraman, K.S. and DasGupta, D.K. 1992. Dehydration of fruits and vegetables: recent developments in principles and techniques. Drying Technology 10(1): 1-50.

Karathanos, V.T., Kostaropoulos, A.E. and Saravacos, G.D. 1995. Air-drying of osmotically dehydrated fruits. Drying Technology 13: 1503-1521.

Lazarides, H.N. 1994. Osmotic preconcentration: developments and prospectus. In Singh, R.P. and Oliveira, F.A.R. (Eds) Minimal Processing of Foods and Process Optimization-an Interface, p. 73-85. London: CRC Press.

Lazarides, H.N., Gekas, V. and Mavroudis, N. 1995. Mass diffusivities in fruit and vegetable tissues undergoing osmotic processing, In Oliveira, J.C. (Ed). Proceedings of the First Main Meeting of the Copernicus Programme Project 'Process Optimization and Minimal Processing of Foods', Vol-III p. 50-56. Porto Portugal: Escala Superior de Biotechnologia.

Lazarides, H.N., Gekas, V. and Mavroudis, N. 1997. Apparent mass diffusivities in fruit and vegetable tissues undergoing osmotic processing. Journal of Food Engineering 31: 315-324.

LeMaguer, M., Mazzanti, G. and Fernandez, C. 2002. The cellular approach in modeling mass transfer in fruit tissue. In Welti-Chanes, J., Barbosa-Cánovas, G.V., Aguilera, J.M. (Eds). Engineering and Food for the 21st Century, p. 193-215. Boca Raton: CRC Press.

Lenart, A. and Lewicki, P.P. 1988. Osmotic preconcentration of carrot tissue followed by convection drying, In Bruin, S. (Ed). Preconcentration and Drying of Food Materials, p. 307-308. Amsterdam: Elsevier science.

Lerici, C.R., Pinnavaia, G., Dalla, R.M. and Bartolucci, L. 1985. Osmotic dehydration of fruit: influence of osmotic agents on drying behaviour and product quality. Journal of Food Science 50: 1217-1226.

Magee, T.R.A., Hassaballah, A.A. and Murphy, W.R. 1983. Internal mass transfer during osmotic dehydration of apple slices in sugar solutions. International Journal of Food Science and Technology 7: 147-153.

Marcotte, M., Toupin, C.J. and LeMaguer, M. 1991. Mass transfer in cellular tissues, Part-I: The mathematical model. Journal of Food Engineering 13: 199-220.

Monsalve-González. A., Barbosa-Cánovas, G.V. and Cavalieri, R.P. 1993. Mass transfer and textural changes during processing of apples by combined methods. Journal of Food Science 58: 1118-1123.

Nieto, A., Castro, M.A. and Alzamora, S.M. 2001. Kinetics of moisture transfer during air drying of blanched and /or osmotically dehydrated mango. Journal of Food Engineering 50: 175-185.

Ponting, J.D., Walters, G.G., Forrey, R.R., Jackson, R. and Stanley, W.L. 1966. Osmotic dehydration of fruits. Journal of Food Technology 20: 125-128.

Rahaman, Md. and Lamb, J. 1991. Air drying behaviour of fresh and osmotically dehydrated pineapple. Journal of Food Process Engineering 14: 163-171.

Rastogi, N.K. and Raghavarao, K.S.M.S. 1994. Effect of temperature and concentration on osmotic dehydration. Lebensmittel-Wissenschaft-und-Technologie-Food Science and Technology 27: 564-567.

Rastogi, N.K., Raghavarao, K.S.M.S., Niranjan, K. and Knorr, D. 2002. Recent developments in osmotic dehydration: methods to enhance mass transfer. Trends in Food Science Technology 13: 48-59.

Spiazzi, E. and Mascheroni, R. 1997. Mass transfer model for osmotic dehydration of fruits and vegetables I. Development of the simulation model. Journal of Food Engineering 34: 387-410.

Torreggiani, D. 1993. Osmotic dehydration in fruit and vegetable processing. Food Research International 26: 59-68

Toupin, C.J., Marcotte, M. and LeMaguer, M. 1989. Osmotically induced mass transfer in plant storage tissues: a mathematical model, Part-I. Journal of Food Engineering 10: 13-38.

Yao, Z. and LeMaguer, M. 1994. Finite element modeling of osmotic dehydration process. Food Research International 27: 211-212.

Yao, Z. and LeMaguer, M. 1996. Mathematical modeling and simulation of mass transfer in osmotic dehydration process, Part-I: Computational and mathematical models. Journal of Food Engineering 29: 349-360.