

MODELLING OF OSMOTIC DEHYDRATION OF SWEET POTATO (*IPOMOEA BATATAS*): DETERMINATION OF MASS EFFECTIVE DIFFUSIVITY COEFFICIENTS

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Abstract. Osmotic dehydration is a process that enables partial removal of water by direct contact of a product with a hypertonic medium. This prompts two major simultaneously countercurrent flows: water flow from the product to the surrounding solution and solutes flow into the product. Leakage of the product solutes (sugars, organic acids, mineral, etc.) is quantitatively negligible, but may be important for the organoleptic and nutritional values of the product. Osmotic pre-treatment improves nutritional, sensorial and functional properties of the dehydrated food without changing its integrity. It also improves the texture as well as stability of the pigment during dehydration and the storage of dehydrated product. The aim of this work was to evaluate the osmotic dehydration of sweet potato (*Ipomoea batatas*) using salt and sucrose solutions. The osmotic process was carried out at different sucrose concentrations (40-60%w/w), salt concentrations (0-10%w/w) and solution temperatures (30-50°C). A non-exponential two parameters model was used to describe the water loss and gain of solids kinetics. The mathematical models were fitted to the experimental data. Values of effective diffusivity calculated from these models varied from 4.07 to 11.19 x 10⁻¹⁰ m²/s for water loss and from 0.91 to 13.06 x 10⁻¹⁰ m²/s for solids gain.

Keywords: Sweet Potato, Osmotic Dehydration and Effective Diffusivity.

1. Introduction

Sweet potato is one of the five most important food crops in developing countries. It is one of the most efficient food crops in terms of caloric value per cultivated area, being relatively easy to grow even on poor and dried soil.

The dry matter production potential of certain varieties of sweet potato vines may be as high as 4.3–6.0 tons per hectare. The value of sweet potato is attributed to high yield, palatability and crude protein content. Sweet potato, which is one of the most important tubers, is largely distributed in the tropical area. It plays a basic role in the people's diet of tropical countries. Tropical tubers are either home processed or industrially processed at various scales. Nowadays, industrial processes must be improved in order to enhance tuber uses and to satisfy consumption requirements (Cnph.Embrapa, 2005).

Osmotic dehydration is widely used for the partial removal of water from plant tissues by immersion in a hypertonic (osmotic) solution. The driving force for the diffusion of water from the tissue into the solution is provided by the high osmotic pressure of the hypertonic solution. The diffusion of water is accompanied by the simultaneous counter diffusion of solute from the osmotic solution into the tissue. Since the membrane responsible for osmotic transport is not perfectly selective, other solutes present in the cells can also be leached into the osmotic solution (Kowalska et al., 2001; Park et al., 2002). The rate of diffusion of water from any material made up of such tissues depends upon factors such as: temperature and concentration of the osmotic solution, size and geometry of the material, the mass ratio between solution and material, and the solution

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agitation. A number of publications have described the influence of these variables on mass transfer rates during osmotic dehydration (Torreggini, 1993; Raoult-Wack et al., 1994; Telis et al., 2004; Rastogi et al., 2004; Azoubel et al., 2004).

Osmotic dehydration is used as a pretreatment in many processes to improve nutritional, sensorial and functional properties of food without changing its integrity (Torreggini, 1993). Osmotic dehydration is generally used as an upstream treatment before further processing such as freezing, freeze drying, vacuum drying and air drying. It also increases sugar to acid ratio, improves texture and stability of the pigment and increase storage (Raoult-Wack et al., 1994). It is effective even at ambient temperature, so heat damage to texture, colour and flavour of food are minimized (Torreggini et al., 2001; Rastogi et al., 2004).

The objectives of the present work were to study the osmotic dehydration of sweet potato and to evaluate the fitting of the Azuara equation to experimental data. Water loss and solids gain were calculated as functions of the solution concentration and temperature.

2. Theory

A two-parameter equation, developed by Azuara et al. (1992) from mass balance considerations, was used to predict the kinetics of osmotic dehydration and the final equilibrium point. The model was tested using kinetic data from ten different experiments and was able to predict water loss and solids gained over long periods of drying. The final equilibrium point was estimated using data obtained during a relatively short period of time. Simple equations were obtained when the model was related to Fick's second law for un-steady one-dimensional diffusion through a thin slab, and diffusion coefficients were readily estimated from these equations.

The mass balance of water inside the food sample is given by Equation (1):

$$WL = WL_{\infty} - WS \quad (1)$$

in which WL is the fraction of water lost by the sample and at any time, WL_{∞} is the fraction of water lost by the sample at equilibrium and WS is the fraction of water that can diffuse out, but remains inside the sample at time t.

In Equation (1) WL_{∞} has a fixed value for the established conditions of temperature and concentration. On the other hand, WL and WS are functions of the rate of water loss and time. A relationship between WL, WS, and a constant (S_1) related to the water loss is given by Equation (2):

$$WL = \frac{S_1 t (WL_{\infty})}{1 + S_1 t} \quad (2)$$

in which S_1 is a constant related to the water loss and t is time.

When $t \rightarrow \infty$ (at equilibrium), WL tends to the asymptotic value WL_{∞} . The values of S_1 and WL_{∞} can be calculated by a non-linear estimation program or by linear regression, using experimental data obtained during a short time and the linear form of Equation (2).

Similar equations can be written for the gain of soluble solids by the product:

$$SG = \frac{S_2 t (SG_{\infty})}{1 + S_2 t} \quad (3)$$

in which SG is the fraction of soluble solids gained by the food at time t; SG_{∞} is the fraction of soluble solids gained by the food at equilibrium, and S_2 is a constant related to the rate of soluble solid incoming to the food sample.

Based on Fick's second law, Crank (1975) proposed an equation for one dimension diffusion in a flat sheet in contact with an infinite amount of solution. Its simplified form when t is small is given by Equation (4):

$$\frac{WL_t}{WL_{\infty}} = 2 \left(\frac{Dt}{\pi l^2} \right)^{1/2} \quad (4)$$

in which WL_t is the amount of water leaving (WL) or solute solids entering (SG) the food sample at time t; WL_{∞} is the amount of water leaving or solute solids entering the sample at infinite time (WL_{∞} or SG_{∞}); D is the effective diffusion coefficient; and l is the half thickness of the slab.

Relating Equation (4) with the proposed model, Equation (5) is obtained, which is a simple expression from which D can be easily calculated at different times.

$$D_t = \frac{\pi t}{4} \left[\left(\frac{S_i l}{1 + S_i t} \right) \left(\frac{WL_{\infty}^{\text{mod}}}{WL_{\infty}^{\text{exp}}} \right) \right]^2 \quad (5)$$

in which $S_i = S_1$ or S_2 ; WL_{∞}^{mod} is the equilibrium value obtained from Equations (2) or (3); WL_{∞}^{exp} is the equilibrium value experimentally obtained; D_t is the effective diffusion coefficient at time t, which can be readily obtained.

3. Materials and methods

3.1. Materials

The raw material used was the sweet potato variety Mona Lisa acquired in a local market. Samples were hand peeled and cut into slices 0.5 mm thick. Sliced sweet potatoes were dipped in a 2% potassium metabisulphite solution for 10 min to prevent non-enzymatic browning, drained and immersed in osmotic solutions. Commercial sucrose and salt were used as osmotic agent.

3.2. Osmotic dehydration

The sweet potato slices, after treatment in the potassium metabisulphite solution, were osmotically dehydrated. The osmotic process was carried out at different sucrose concentrations (40-60%w/w), salt concentrations (0-10%w/w) and solution temperatures (30-50°C) with agitation of 90 rpm. The slices were placed in 250 ml beakers containing the osmotic solution and maintained inside a temperature-controlled bath (Tecnal, TE 421). The mass 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 15, 30, 45, 60, 75, 90, 120, 150, 180 and 240 min after immersion, drained and the excess of solution on the surface was removed by absorbent paper.

The average moisture and dry matter content of the samples were determined by drying at 70°C for 24 h in an oven (A.O.A.C., 1984). All the experiments were done in triplicate and the average value was taken for calculations.

Water loss (WL) was expressed as the net water loss from the fresh sweet potato sample after osmotic dehydration based on initial sample mass; solid gain (SG) was defined as the net uptake of solid by the sweet potato sample based on initial sample weight (Uddin et al., 2004):

$$\%WL = \left[\frac{(M_i - M_o)}{W_i} \right] \times 100 \quad (6)$$

$$\%SG = \left[\frac{(S_i - S_o)}{W_i} \right] \times 100 \quad (7)$$

in which M_i is the initial moisture content (g); M_o is the moisture content of osmotically treated sample (g); S_i is the solids content of osmotically treated sample (g); S_o is the initial solids content (g); W_i is the initial total sample mass (g).

4. Results and discussion

Water loss and solid gain of sweet potato slices increase with time. The sweet potato osmotic dehydration experiments were carried out under different concentrations and temperatures. Analyzing the experimental data, it is observed that the water loss increases as the solute concentration or the temperature increases (Table1). The solids gain also tended to increase with increasing either solution concentration or temperature.

Table 1. Influence of temperature and concentration solutions during osmosis of sweet potato at 2h

T (°C)	Sucrose (%w/w)	NaCl (%w/w)	WL (%)	SG (%)
34	44	2	28.52	4.74
46	44	2	29.97	4.57
34	56	2	36.86	5.10
46	56	2	36.81	12.22
34	44	8	34.43	9.38
46	44	8	36.05	11.40
34	56	8	41.14	15.64
46	56	8	42.99	13.12
30	50	5	36.78	10.62
50	50	5	38.88	14.18
40	40	5	31.84	9.43
40	60	5	42.02	14.87
40	50	0	28.81	3.21
40	50	10	38.09	11.04
40	50	5	39.02	13.07

Figure 1 compares the change of the dehydration parameters with predicted results from the Azuara model (Equations 2 and 3) for the conditions: 50%w/w sucrose and 0, 5 and 10%w/w salt solution at 40°C.

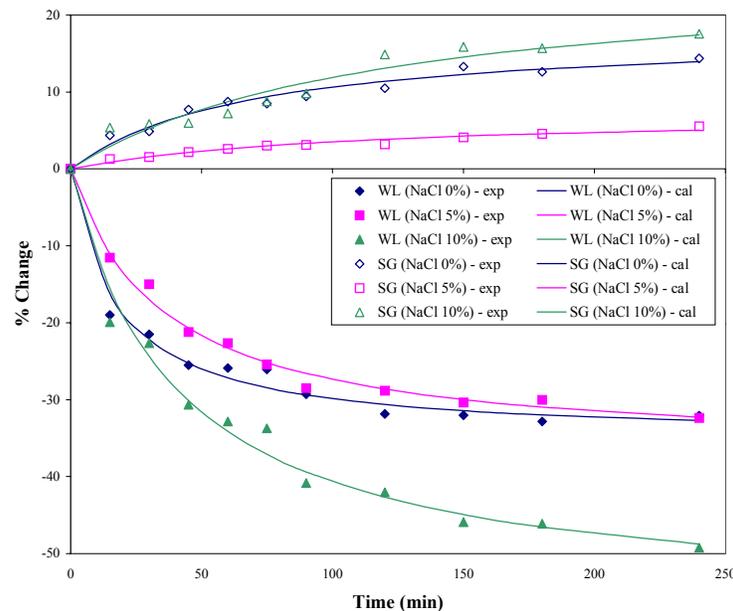


Figure 1. Sweet potato water loss and solids gain versus time at 50%w/w sucrose concentration, 40°C and different NaCl concentrations.

Table 2. Equilibrium constants predicted from linearized Equations (2) and (3) at different experimental conditions

T (°C)	Sucrose (%w/w)	NaCl (%w/w)	WL _∞ (%)	R ²	SG _∞ (%)	R ²
34	44	2	32.51	0.997	11.99	0.998
46	44	2	35.75	0.997	9.13	0.998
34	56	2	44.29	0.995	5.97	0.994
46	56	2	45.35	0.997	17.50	0.992
34	44	8	41.50	0.999	9.76	0.992
46	44	8	37.73	0.998	16.66	0.994
34	56	8	52.09	0.996	20.86	0.994
46	56	8	45.83	0.998	14.68	0.997
30	50	5	44.93	0.997	11.32	0.999
50	50	5	42.68	0.997	18.42	0.994
40	40	5	35.07	0.997	17.79	0.990
40	60	5	56.94	0.995	32.02	0.998
40	50	0	37.06	0.997	7.18	0.994
40	50	10	48.83	0.997	10.32	0.993
40	50	5	47.60	0.995	14.58	0.991

Depending upon the composition and the temperature of the osmotic solution, the equilibrium conditions are not completely reached in short processing times. Therefore, the equilibrium values were calculated by the Azuara et al. (1992) model. The differences between the experimental and calculated equilibrium values were relatively small.

Equilibrium water loss (WL_∞) and solid gain (SG_∞) values were obtained by Equations (2) and (3) and the results are given in Table 2. In all cases, the regression coefficient was higher than 0.99 indicating the acceptability of the model for the prediction of equilibrium points.

Increases of solution concentrations resulted of increases 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, faster water loss could be achieved. However, a much greater gain of solids would be observed.

Table 3. Effective diffusivity values obtained from the proposed model at different experimental conditions

T (°C)	Sucrose (%w/w)	NaCl (%w/w)	Diffusivity of water, D _w x 10 ¹⁰ (m ² /s)	Diffusivity of solute, D _s x 10 ¹⁰ (m ² /s)
34	44	2	8.52	2.15
46	44	2	5.97	1.43
34	56	2	4.95	7.35
46	56	2	6.02	4.74
34	44	8	5.99	5.76
46	44	8	11.18	5.29
34	56	8	5.73	4.88
46	56	8	8.66	7.58
30	50	5	5.35	13.06
50	50	5	7.06	5.39
40	40	5	6.99	2.73
40	60	5	4.06	0.91
40	50	0	4.46	1.71
40	50	10	5.31	11.56
40	50	5	5.03	6.85

D_t values (water loss or solid gain), considering the slice configuration, were calculated using Equations (5). The values of effective diffusion coefficients obtained for different combinations of concentration and temperature of osmotic solution are presented in Table 3. The values of calculated diffusion coefficients were found to be in the range of $10^{-10} - 10^{-11} \text{ m}^2/\text{s}$ and were in agreement with literature values (Hough et al., 1993; Kaymak-Ertekin et al., 1996). It was observed that D_w values are generally higher than D_s values. Osmotic pressure gradient is the driving force for osmotic mass transfer. An increase in osmotic solution concentration increases this gradient and so the driving force. The transport coefficient D_t increases with an increase in osmotic solution concentration due to changes in the physical properties of the food (such as porosity and cell permeabilization).

The effect of temperature and concentration and the values of effective diffusion coefficients are similar to the ones published for other products (Azuares et al., 1992; Hough et al., 1993; Rastogi et al., 2004; Park et al., 2002; Azoubel et al., 2004).

5. Conclusions

The rate of water loss and salt gain during osmotic dehydration of sweet potato was directly related to the solution concentration. Since the experimental equilibrium conditions were not completely reached in short processing times, the Azuares et al. (1992) model was used to predict the equilibrium point.

When the predicted values were compared to the experimental ones it was found that the model adequately describes the experimental values, especially for water loss. The osmotic dehydration or the process time to attain a specific water loss can be predicted using the proposed model when the model parameters are known. The Azuares equation well described the experimental data and also well predicted water loss and salt gain. The effective diffusion coefficients obtained from the Azuares equation ranged from 4.07 to $11.19 \times 10^{-10} \text{ m}^2/\text{s}$ for water loss and from 0.91 to $13.06 \times 10^{-10} \text{ m}^2/\text{s}$ for solids gain.

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