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Mass Transfer in Osmotic Dehydration of Potato: A Mathematical Model Approach

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Abstract: Mass transfer was quantitatively investigated during osmotic dehydration of potato. Potato, containing a variety of individual soluble components was immersed in different concentrations of sugar solutions. Water and natural solutes flowed out of the sample into the solution while sugar solutes were taken up from the solution into the product this enriched the unstable final product of the process. An empirical model was developed to predict water loss and solid gain based on a first-order kinetic equation in which the rate constant is a function of the main process variables (solute concentration, size of vegetable (potato) and process temperature). The model was applied to experimental and its parameters were estimated using non-linear regression method. The results showed that all of the above process variables have significant impact on the mass transfer phenomena during osmotic dehydration.

Key words: Solid gain, sugar concentration, water loss, first-order kinetic, hypertonic

INTRODUCTION

Osmotic dehydration is a process of partial removal of water from food products such as fruits and vegetables when they are immersed in a hypertonic (concentrated) solution composed of salt, sorbitol, sugar, etc. This results in products of reduced but relatively high moisture content (20-50%) classified as Intermediate Moisture Foods (IMFs) (Raoult-Wack *et al*., 1991; Rastogi *et al*., 1999). A driving force for water removal (diffusion) is the difference in the osmotic pressure (or chemical potential) of the food and that of the osmotic solution (Rastogi *et al*., 1999). The water loss (or water diffusion) is accompanied by the simultaneous counter-diffusion of solute from the osmotic solution into the food product. Since the membrane responsible for osmotic transport is not perfectly selective, other solutes (as vitamins, minerals, organic acids) present in the food products can also be leached into the osmotic solution (Dixon and Jen, 1977; Giangiacomo *et al*., 1987). This shows that 3 simultaneous mass transfer phenomena arise when water-rich solid particles are immersed in hypertonic solutions (Raoult-Wack *et al*., 1994).

Mass transfer rate during osmotic dehydration depends on many factors such as temperature and concentration of the osmotic solution, the size and geometry of the solid material, the solution solid material ratio and the agitation of the solution (Raoult-Wack *et al*., 1992, 1994; Rastogi *et al*., 1997a, b; Cunha *et al*., 2001, 2002; Azoubel *et al*., 2003; Martinez *et al*., 2007; Tonon *et al*., 2007).

Osmotic dehydration differs from conventional drying methods in two major ways (Raoult-Wack, 1994). Firstly, a soaking process (immersion) achieves both a dewatering and a formulation effect of solid product. Secondly, a soaking process does not generally produce a stable product. Thus, osmotic dehydration is useful as a pre-processing step prior to drying and freezing of foods, including fruits and vegetables, meat and seafood products (Lerici *et al*., 1985; Quintero-Ramos *et al*., 1993; Collignan and Raoult-Wack, 1994; Rahman *et al*., 2001). The beneficial effects of osmotic dehydration include higher quality of the final product and lower energy requirements (Heng *et al*., 1990; Panagiotu *et al*., 1998).

To explain the simultaneous flow in an osmotic dehydration process, several models have been proposed. Three approaches of these models are:

- The approach based on cellular structure (Toupin *et al*., 1989; Marcotte and Le Maguer, 1992; Yao and Le Maguer, 1996).
- The approach based on Fick's law (Beristian *et al*., 1990; Azuara *et al*., 1992; Ramallo *et al*., 2004).
- The approach based on macroscopic expression of rate (Biswal and Le Maguer 1989; Yang and Le Maguer, 1992).

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The present study aims to evaluate the effect of process variables (solute concentration, temperature, sample size and processing time) on mass transfer phenomena in the osmotic dehydration of potato in order to predict water loss and solid gain with acceptable accuracy.

MATERIALS AND METHODS

Sample preparation: Fresh potatoes were purchased from a local market (Wazo market) at Ogbomoso in Nigeria. The samples were washed, peeled, sliced and cut into several sizes of thickness (5, 10, 15 and 20 mm, respectively) prior to dehydration. Commercial sugar (sucrose) purchased from a local store in Ogbomoso was used as the osmotic agent. The osmotic solutions used had different amounts of sugar content (45, 60 and 75%) expressed in percentage of weight of sugar per weight of total solution (w w^{-1}).

Experimental design: Approximately 10 g of sliced potatoes were immersed in a beaker containing sugar solution. The beaker was placed in a temperature-controlled water bath at a known temperature. To avoid evaporation of water at high temperatures, the beaker was closed. At the end the immersion period in the sugar osmotic solution, the samples were gently blotted dry with tissue paper in order to remove the excess solution and were then weighed. The potato samples were then dried in an air oven at 70°C for 24 h in order to estimate the solid weight of the vegetable (potato) and to calculate the moisture content of the osmotically-treated vegetable. A total number of 39 experiments, divided into 2 groups, were carried out as follows:

Group 1: The effect of sugar concentration, process temperature and time of immersion was investigated using concentrations of 45, 50, 60 and 75% w w^{-1}, solution temperatures of 50, 60 and 70°C and process times of 2, 4 and 6 h.

Group 2: The effect of the sample size of the vegetable (potato) was studied by repeating the osmotic process experiments using 60% w/w sugar concentration, 60°C solution temperature, process times of 2, 4 and 6 h for all the different sample sizes (5, 10, 15 and 20 mm).

All the experiments in groups 1 and 2 were replicated two times. The experimental data for water loss and solid gain as estimated from Eq. 1 and 2, respectively are presented in Table 1.

Moisture content determination: Moisture content determinations of the fresh and osmotically dehydrated potatoes were performed according to standard methods (AOAC, 1985).

Mathematical modelling of mass transfer in potato: The osmotic dehydration process can be represented by 2 parameters:

- The Water Loss (WL).
- The Solid Gain (SG).

The solid gain represents the amount of solid that diffuses from the osmotic solution into the potato less the solids of potato that are lost to the solution. The Water Loss (WL) and the Solid Gain (SG) of the potato after time t of osmotic treatment are defined as:

$$WL = \frac{(M_o - m_o) - (M_t - m_t)}{M_o} \tag{1}$$

$$SG = \frac{m_t - m_o}{M_o} \tag{2}$$

Where,

M_o = Initial mass of fresh potato.
m_o = Dry mass of fresh potato.
M_t = Mass of potato after time t of osmotic treatment.
m_t = Dry mass of potato after time t of osmotic treatment.

The mass transfer phenomena within the osmotic process were described by the application of first-order kinetic model in which the rate constant is a function of the process variables. In the application of this model, the following assumptions were made:

- The osmotic treatment is an isothermal and equilibrium process.
- The initial water and sugar concentrations in the potato are uniform.
- The mass ratio of the osmotic agent solution to the potato is greatly high so that the solution concentration could be taken as constant.
- The leaching of the potato's own solutes into the solution is considered negligible and therefore only 2 diffusional processes (water diffusion from potato into the osmotic solution and solute agent diffusion from aquatic solutions into the potato) are considered to be significant.
- The 2 significant diffusional processes are considered independent of each other.

Therefore, water loss kinetic model

$$\frac{d(WL)}{dt} = -K_{WL}(WL - WL_e) \tag{3}$$

Table 1: Experimental data for thirty-nine osmotic experiments

					Potato	
S/no	Time, t (h)	Concentration, C (w w⁻¹)	Temperature, T (°C)	Sample size, d (mm)	Water loss (WL)	Solid gain (SG)
Group 1						
1	2	45	50	10	0.23	0.00
2	4	45	50	10	0.27	0.01
3	6	45	50	10	0.28	0.05
4	2	60	50	10	0.40	0.06
5	4	60	50	10	0.55	0.10
6	6	60	50	10	0.55	0.12
7	2	75	50	10	0.37	0.05
8	4	75	50	10	0.50	0.12
9	6	75	50	10	0.56	0.14
10	2	45	60	10	0.28	0.05
11	4	45	60	10	0.48	0.13
12	6	45	60	10	0.48	0.14
13	2	60	60	10	0.37	0.07
14	4	60	60	10	0.52	0.14
15	6	60	60	10	0.52	0.15
16	2	75	60	10	0.33	0.07
17	4	75	60	10	0.49	0.13
18	6	75	60	10	0.56	0.17
19	2	45	75	10	0.35	0.09
20	4	45	75	10	0.47	0.15
21	6	45	75	10	0.48	0.20
22	2	60	75	10	0.35	0.08
23	4	60	75	10	0.48	0.20
24	6	60	75	10	0.50	0.24
25	2	75	75	10	0.23	0.09
26	4	75	75	10	0.47	0.25
27	6	75	75	10	0.51	0.20
Group 2						
28	2	60	60	5	0.50	0.14
29	4	60	60	5	0.59	0.18
30	6	60	60	5	0.60	0.20
31	2	60	60	10	0.34	0.06
32	4	60	60	10	0.48	0.14
33	6	60	60	10	0.52	0.17
34	2	60	60	15	0.20	0.03
35	4	60	60	15	0.34	0.11
36	6	60	60	15	0.42	0.14
37	2	60	60	20	0.19	0.01
38	4	60	60	20	0.26	0.06
39	6	60	60	20	0.26	0.08

solid gain kinetic model

$$\frac{d(SG)}{dt} = -K_{SG}(SG - SG_e) \quad (4)$$

Where,

K_{WL} = Rate constant for water loss.
K_{SG} = Rate constant for solid gain.
Wl_e = Water loss at infinite process time.
Sg_e = Solid gain at infinite process time.
t = Process time.

However, at zero time (t = 0), there is no water loss nor solid gain. Hence, Eq. 3 and 4 were integrated to give the following:

$$WL = WL_e\left(1 - \exp(-K_{WL}\,t)\right) \quad (5)$$

$$SG = SG_e\left(1 - \exp(-K_{SG}\,t)\right) \quad (6)$$

Furthermore, it was assumed that there is a dependence of K_{WL} and K_{SG} on the following process variables:

- Osmotic solution Concentration (C).
- Process Temperature (T).
- Sample size (diameter or thickness of potato slice) (d).
- WL_e and SG_e were assumed to be dependent on.
- Osmotic solution Concentration (C).
- Process Temperature (T).

From these assumptions made, the effect of process variables on mass transfer during osmotic process can therefore, be embodied into the following empirical equations:

$$K_{WL} = K_p \left(\frac{C}{100}\right)^{K_C} \left(\frac{T}{100}\right)^{K_T} \left(\frac{d}{10}\right)^{K_d} \quad (7)$$

$$K_{SG} = K_p \left(\frac{C}{100}\right)^{K_C} \left(\frac{T}{100}\right)^{K_T} \left(\frac{d}{10}\right)^{K_d} \quad (8)$$

$$WL_e = R_{eo} \left(\frac{C}{100}\right)^{R_{eC}} \left(\frac{T}{100}\right)^{R_{eT}} \quad (9)$$

$$SG_e = \gamma_{eo} \left(\frac{C}{100}\right)^{\gamma_{eC}} \left(\frac{T}{100}\right)^{\gamma_{eT}} \quad (10)$$

The proposed mathematical model is summarised in Table 2.

The estimate of the above 14 parameters (R_{eC}, R_{eT}, R_{eo}, K_p, K_C, K_T, K_d, for water loss and γ_{eo}, γ_{eC}, γ_{eT}, K_p, K_C, K_T, K_d, for solid gain) was carried out using a non-linear regression analysis method separately for water loss and solid gain of potato during the osmotic dehydration process.

The non-linear regression analysis is based on the minimisation of the residual Sum of Squares (SST).

$$SST = \sum_{i=1}^{N} \sum_{j=1}^{n} \left(R_{exp_{ij}} - R_{cal_j}\right)^2 \quad (11)$$

Where,

R_{exp} : The experimental value of the dependent variables (water loss or solid gain of potato after time t of osmotic process) of j_{th} replicate of the i_{th} experiment.

R_{cal} : The calculated value of the model for the i_{th} experiment.

n : The number of replicates in the i_{th} experiment.

N : The total number of experiments.

The proposed model is considered acceptable if the standard deviation between experimental and calculated values (lack of fit, S_R) is close to the standard experimental error (S_E). The standard deviation between experimental and calculated values (S_R) and the standard experimental error (S_E) can be calculated by the following equations:

$$S_R = \frac{\sum_{i=1}^{N} n\left(\bar{R}_{exp} - R_{cal}\right)^2}{N - Z} \quad (12)$$

Table 2: Mathematical model

Parameters	Water loss
Process model	
	$WL = WL_e\left(1 - \exp\left(-K_{WL}\, t\right)\right)$
Transport properties model	
R_{eC}, R_{eT}, R_{eo}	$WL_e = R_{eo}\left(\frac{C}{100}\right)^{R_{eC}}\left(\frac{T}{100}\right)^{R_{eT}}$
K_p, K_C, K_T, K_d	$K_{WL} = K_p\left(\frac{C}{100}\right)^{K_C}\left(\frac{T}{100}\right)^{K_T}\left(\frac{d}{10}\right)^{K_d}$
Solid gain	
Process model	
	$SG = SG_e\left(1 - \exp\left(-K_{SG}\, t\right)\right)$
Transport properties model	
$\gamma_{eo}, \gamma_{eC}, \gamma_{eT}$	$SG_e = \gamma_{eo}\left(\frac{C}{100}\right)^{\gamma_{eC}}\left(\frac{T}{100}\right)^{\gamma_{eT}}$
K_p, K_C, K_T, K_d	$K_{SG} = K_p\left(\frac{C}{100}\right)^{K_C}\left(\frac{T}{100}\right)^{K_T}\left(\frac{d}{10}\right)^{K_d}$

$$S_E^2 = \frac{\sum_{i=1}^{N} \sum_{j=1}^{n} \left(R_{exp_{ij}} - \bar{R}_{cal_j}\right)^2}{M_n - N} \quad (13)$$

Where,

$$\bar{R}_{exp} = \sum_{i=1}^{N} \frac{R_{exp_{ij}}}{n}$$

$$M_n = \sum_{i=1}^{n} n_i$$

Z = Number of parameters

However, to distinguish the significance of the model parameters, the following procedure was adopted. First, the minimum SST was evaluated for all the seven parameters and the S_R was estimated. Secondly, omitting one parameter at a time, the values of S_R were evaluated for all combinations of the remaining 6 parameters. In this way, the parameter chosen to be eliminated was the one whose elimination produced the minimum S_R. Therefore, as the former procedure was continued, the minimum S_R was evaluated for 5, 4, 3, 2 and 1 parameters, respectively. Then a compromise was made between model completely and accurately.

RESULTS AND DISCUSSION

Moisture content: The moisture content of the potato was found to be 70%.

Water loss from potato during osmotic dehydration: The effects of the model parameters on the standard deviation between experimental and calculated values (S_R) are presented in Table 3. The elimination of the parameters

Table 3: Effects of the model parameters on S_R

Potato	Eliminated parameters	K_P	K_C	K_T	K_d	R_{eO}	R_{eC}	R_{eT}	S_R(%)
Water loss		1.18	0.12	0.89	- 0.35	1.2	1.32	0.64	7.49
	R_{eT}	1.73	0.09	1.41	- 0.35	1.0	1.38		9.30
	K_C	1.96		1.41	- 0.35	1.0	1.38		9.30
	K_d	2.68		1.50		1.0	1.49		10.56
	K_T	0.83				0.9	1.50		13.56
	R_{eC}	0.83				0.3			15.01
	R_{eO}	0.83				0.3			78.38
	K_O								78.38
S_E (%) = 4.02									
		0.67	0.04	1.85	-1.27	0.50	0.92	0.25	2.07
	K_T	0.67		1.85		0.50	0.92	0.25	2.07
	K_C	0.34		1.47	-1.27	0.53	0.96	0.25	2.36
	K_d	0.46				0.53	0.98	0.25	3.41
	γ_{eT}	0.77				0.39	0.98	0.25	3.99
	γ_{eC}	0.75				0.22			4.01
	γ_{eO}	0.75							24.00
S_E (%) = 1.45									

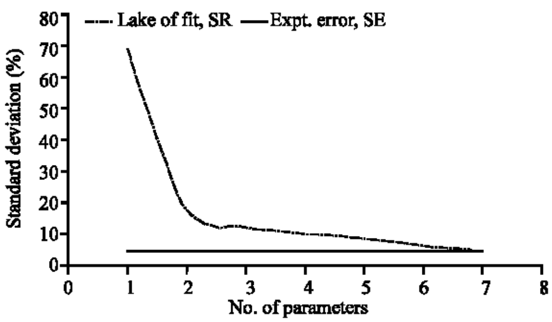

Fig 1a: Standard deviation of model from experimental values for water loss

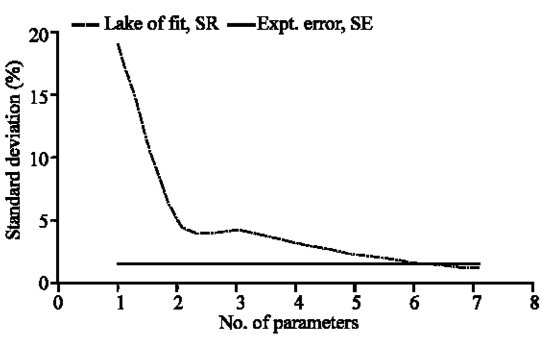

Fig. 1b: Standard deviation of model from experimental values for solid gain

R_{eT} and K_C gave an accurate agreement between experimental and calculated values as observed by comparison of the value of S_R and S_E obtained on reducing the number of parameters. This is an acceptable compromise between model complexity and accuracy (Fig. 1a). The parameters of the proposed model with the elimination of the least significant parameters, R_{eT} and K_C are presented in Table 4.

The experimental data for water loss from potato during osmotic dehydration in sugar solution is shown in

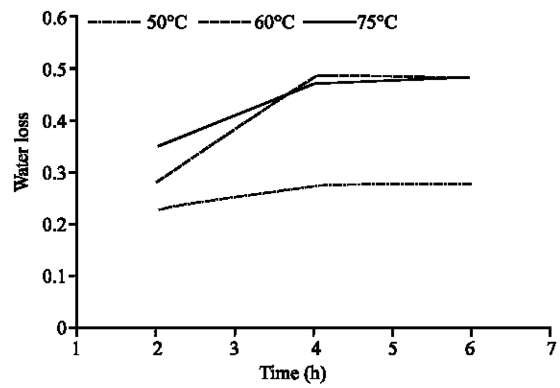

Fig. 2a (i): Effect of osmotic concentration and process temperature on water loss at 45% concentration

Fig. 2. In this figure, the values for water loss produced by the proposed model are shown as continuous lines. As shown in Fig. 2a, the water loss due to osmotic treatment increases as the sugar concentration and process temperature increases. This may reach up to 57% of the initial mass of potato at the highest levels of sugar concentration, process temperature and process duration. This is in agreement with the observation of Ozer *et al.* (2002) in their study of the processing factors affecting the dehydration of diced green peppers. From Fig. 2b, it can be seen that the size of the potato sample had a negative effect on the waster loss (i.e., as sample size increases, water loss decreased). The experimental and predicted data also show that for small potato samples (diameter < 15mm), the equilibrium may be obtained after approximately 4 h of immersion time.

Figure 3a showed the equilibrium water loss for potato at infinite process time. In this figure, the sugar concentration of the osmotic solution and the process temperature had a positive effect on the equilibrium water loss (i.e., equilibrium water loss increases as the osmotic solution concentration and process temperature

Table 4: Results of parameters of estimation

Water loss	K_P	K_C	K_T	K_d	R_{eO}	R_{eC}	R_{eT}	S_R (%)	S_E (%)
	1.96	-	1.41	- 0.35	1.0	1.38	-	9.30	4.02
Solid gain	K_P	K_C	K_T	K_d	γ_{eO}	γ_{eC}	γ_{eT}	S_R (%)	S_E (%)
	0.34	-	1.47	- 1.36	0.53	0.96	0.25	2.36	1.45

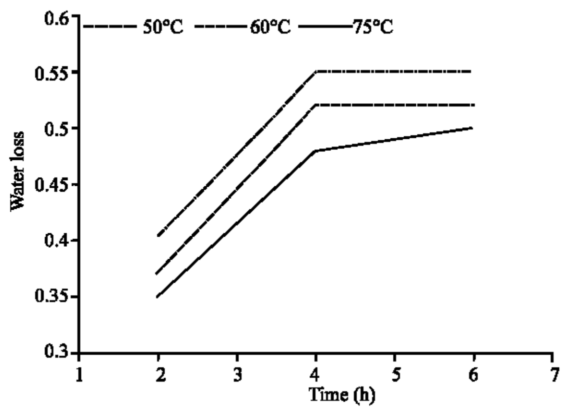

Fig. 2a (ii): Effect of osmotic concentration and process temperature on water loss at 60% concentration

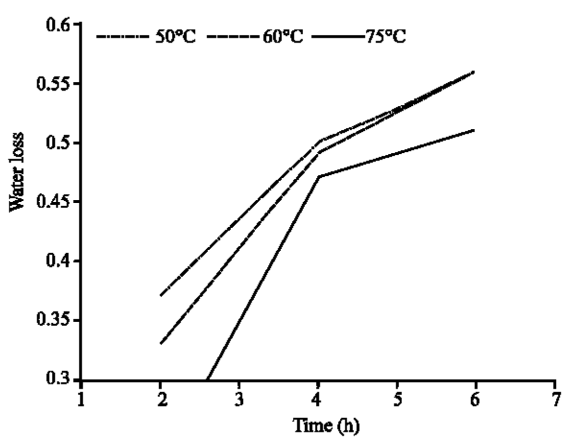

Fig. 2a (iii): Effect of osmotic concentration and process temperature on water loss at 75% concentration

increases). Figure 3c showed the effect of sugar concentration and process temperature on the rate constant for water loss (K_{WL}). In this figure, the rate constant remained almost constant as the solute concentration was increased. The effect of temperature on the rate constant was clearly positive. The effect of potato sample size on the rate constant for water loss (K_{WL}) is shown in Fig. 3e. There was a strong negative effect of sample size on K_{WL} (i.e., as the size of the potato sample was increased, the rate constant for water loss (K_{WL}) decreases).

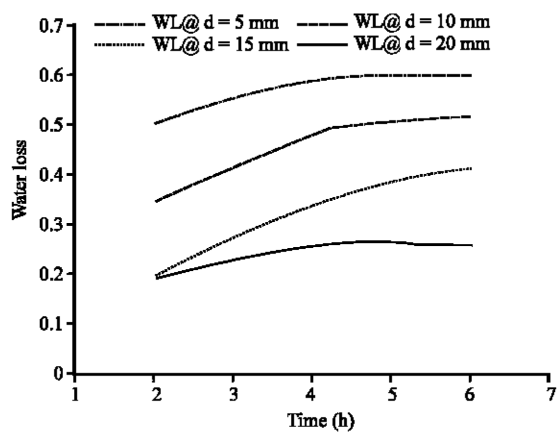

Fig. 2b: Effect of sample diameter on water loss at 60°C

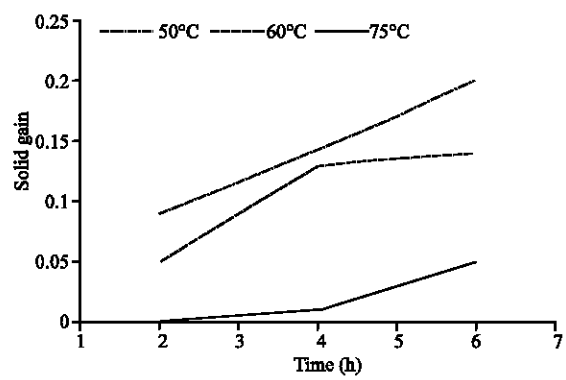

Fig. 3a (i): Effect of osmotic concentration and process temperature on solid gain at 45% concentration

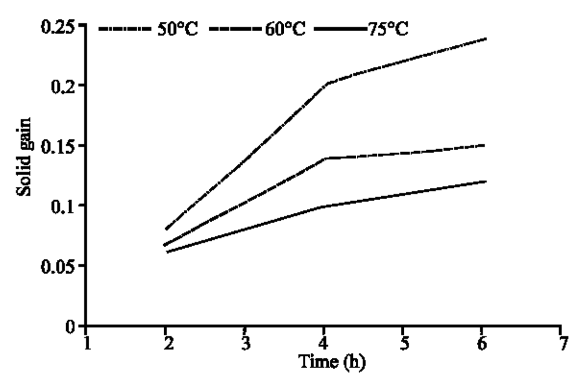

Fig. 3a (ii): Effect of osmotic concentration and process temperature on solid gain at 60% concentration

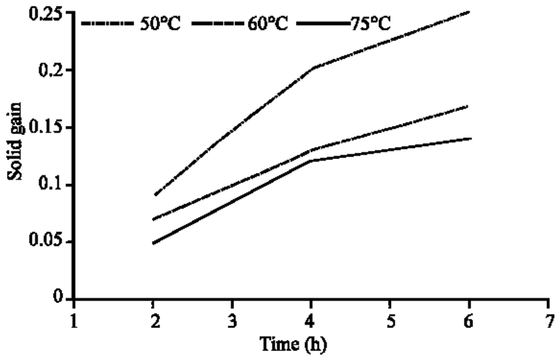

Fig. 3a (iii):Effect of osmotic concentration and process temperature on solid gain at 75% concentration

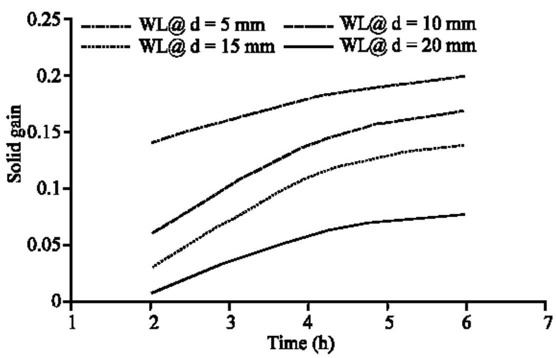

Fig. 3b: Effect of sample diameter on solid gain at 60°C

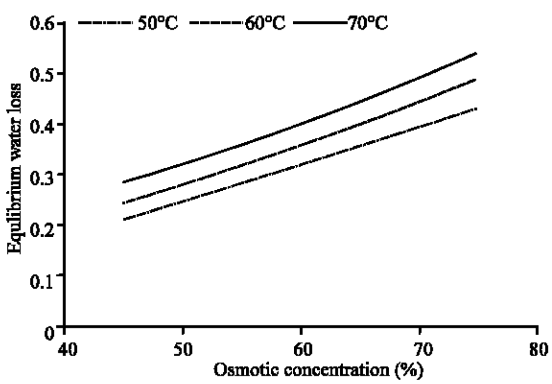

Fig. 4a: Effect of osmotic concentration and temperature on equilibrium water loss

Solid gain by potato during osmotic dehydration: The effects of the model parameters on the S_R for potato are presented in Table 1. The elimination of K_C and K_T gave an acceptable agreement between experimental and calculated values as found by the values of S_R and S_E obtained on reducing the number of parameters (Fig. 1b).

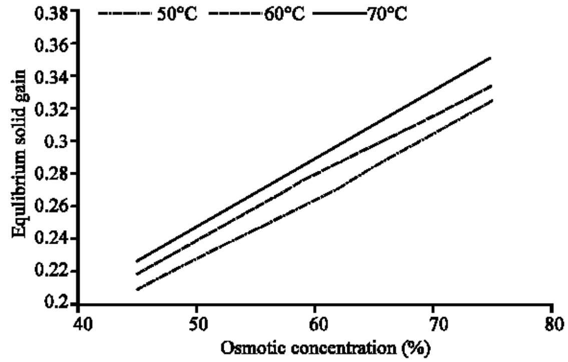

Fig. 4b: Effect of osmotic concentration and temperature on equilibrium solid gain

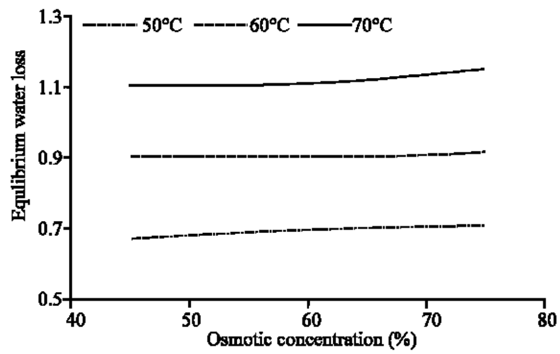

Fig. 4c: Effect of osmotic concentration and temperature on rate constant for water loss

The parameters of the proposed model, estimated using a non-linear regression method, are presented in Table 4.

Figure 4 showed the experimental Solid Gain (SG) by potato during osmotic dehydration process in sugar solution. From Fig. 4a, it is seen that the solid gain as a result of osmotic treatment increases as the sugar concentration of the osmotic solution and process temperature increases. This may reach up to 25% of the initial mass of potato at the highest level of sugar concentration, process temperature and process duration.

Figure 4b showed the effect of sample size on the solid gain during osmotic treatment of potato. As the sample size increases, the solid gain by potato also decreases (i.e., sample size had a negative effect on solid gain). This is presumably due to the larger diffusion path for the sugar solute in the larger samples (Panagiotou *et al*., 1998). The experimental and predicted data also showed that for small size potato samples (diameter < 10 mm), the equilibrium may be obtained after approximately 4 h of immersion time.

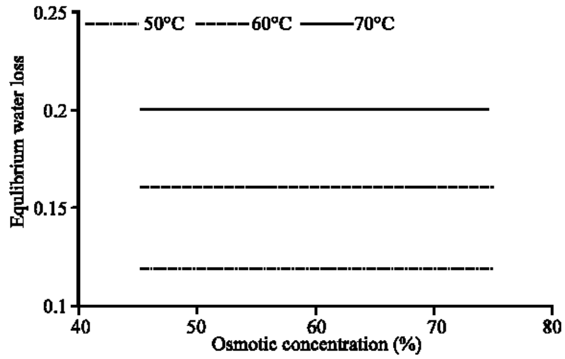

Fig. 4d: Effect of osmotic concentration and tesolid gain

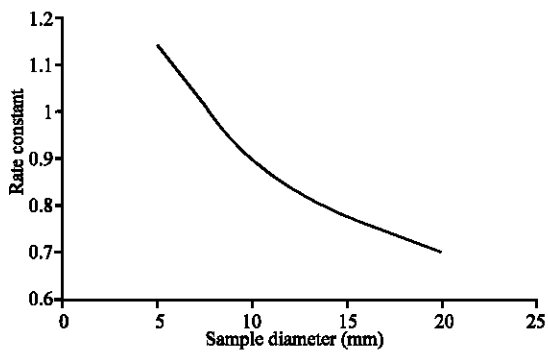

Fig 4e: Effect of sample diameter on rate constant for water loss

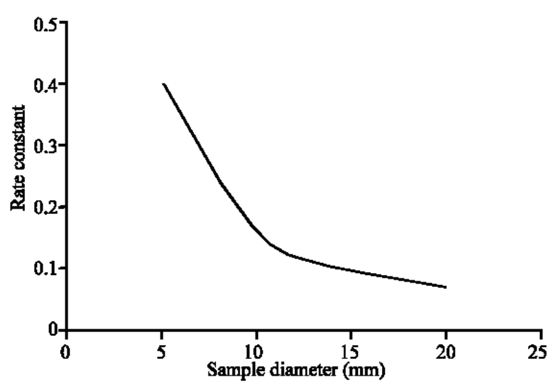

Fig 4f: Effect of sample diameter on rate constant for solid gain

Figure 3b showed the effects of sugar concentration and process temperature on the equilibrium Solid Gain (SG_e). It is also seen that the equilibrium solid gain increases as the sugar concentration and process temperature increases (i.e., sugar concentration and process temperature had positive effects on SG_e). The effects of sugar concentration and process temperature on the rate constant for solid gain (K_{SG}) are shown in Fig. 3d. In this figure, the effect of sugar concentration on the rate constant for solid gain was negligible (i.e., K_{SG} remained constant as the sugar concentration was increased) whereas the effect of temperature on K_{SG} was positive. Figure 3f showed the effect of sample size (diameter) on the rate constant for solid gain (K_{SG}). Here K_{SG} decreased as the sample size increased (i.e., size of sample had a negligible effect on K_{SG}).

CONCLUSION

The present study has shown that the proposed empirical model was able to describe mass transfer process during osmotic dehydration of potato as the values calculated from the proposed model for water loss and solid gain were in good agreement with the experimental data. The study also showed that process temperature and sample size had most significant effect on the kinetic rate of water loss. However, the osmotic solution concentration seemed to have a more significant effect on the equilibrium water loss than process temperature. Furthermore, the kinetic rate of solid gain did not depend on osmotic solution concentration while it depended on process temperature. The osmotic solution concentration seemed to have an important effect on the equilibrium solid gain.

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