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Kinetic Modeling of Mass Transfer during Osmotic Dehydration of Ziziphus jujube

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ABSTRACT: Osmotic dehydration of jujube slices was performed to evaluate the influence of solution temperature (30, 40 and 50°C), sucrose concentration (40, 45 and 50% w/v) and sample to solution ratio (1:10, 1:15 and 1:20) on mass transfer kinetics. Modeling of mass transfer kinetics for water loss and solid gain were carried out using Magee, Azuara and Peleg models. Effective moisture and solid diffusivities and activation energy were also determined. The results showed that an increase in sucrose concentration as well as solution temperature led to an increase in water loss and solid gain of jujube samples during osmotic dehydration. Azuara model was the most suitable model to describe the osmotic drying process for both moisture loss and solid gain because of high R^2 values and small values of RMSE and SSE. The effective moisture and solid diffusivities ranged from 2.734 to 5.617×10^{-10} and 3.0828 to 5.964×10^{-10} m^2/s, respectively. The results indicated that osmotic solution concentration has a reverse relationship with moisture and solid activation energy.

Keywords: *Effective Diffusivity, Jujube, Mass Transfer Kinetics, Osmotic Dehydration*.

Introduction

The shelf-life of fresh food such as fruits and vegetables is fairly short. Considering that these raw material are valuable for food industries; an increase in preservation time of them are very important (Misljenovic *et al*., 2011). After harvesting the agricultural products, the effort is done to maintain the quality and shelf-life of products. Hot air convective drying is a commonly used drying method which significantly extends the postharvest preservation of agricultural products. However, the main problems of conventional drying are reduction in product quality (tough texture, extensive enzymatic browning and low nutritional quality) due to degradation of bioactive and deterioration of aroma compounds occurred because of exposure to high temperature and oxygen (Araya-Farias *et al*., 2014; Zielinska *et al*., 2015).

As an alternative drying and food protection methods, osmotic dehydration demonstrates to be the energy-efficient pretreatment methods for food and fruit drying (Rodriguez *et al*., 2016). Osmotic dehydration process is a suitable process for partial removal of water from the cellular materials such as fruits and vegetables in a concentrated aqueous solution without any

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phase variation (de Mendonça *et al*., 2016; Germer *et al*., 2016). This pretreatment method reduces the physical, chemical and biological changes and improves the nutritional, sensorial and functional properties of food during the high temperature drying (Lemus-Mondaca *et al*., 2015).

Various process variables may influence strongly the kinetics of water loss, solid gain and the equilibrium moisture content, such as the osmotic agent, solution concentration, temperature, immersion time, solid to solution ratio, geometry and nature of food and agitation (Barbosa Júnior *et al*., 2013; Oladele & Odedeji, 2008). However, concentration and temperature of the osmotic solution are the main factor influencing mass transfer during osmotic dehydration (Ozen *et al*., 2002).

Osmotic dehydration involves two types of simultaneous transfer, (i) diffusion of water from food or fruit to solution; (ii) diffusion of counter-current flow of solid from osmotic solution to the (product) food or fruit. Leaching out of solid from food and fruit such as acids, minerals, acids, sugars, vitamins is considered quantitatively negligible in mass transfer process of osmotic dehydration (Wiktor *et al*., 2014; Lemus-Mondaca *et al*., 2009).

Mathematical modelling is demonstrated to be a useful tool to control the composition of osmotically dehydrated product, attain more required sensorial properties in this material, predict yields and mechanisms and minimize consumption of energy (Collignan *et al*., 2001). Several studies have been carried out to model mass transfer kinetics during osmotic dehydration (Aires *et al*., 2018; Heredia, & Andrés, 2008; Azarpazhooh, & Ramaswamy, 2009). Fick’s second law is one of the applied models to describe the mass transfer kinetics during osmotic dehydration process (Aires *et al*., 2018; da Silva Júnior *et al*., 2017). Empirical mathematical models such as Magee (Magee *et al*., 1983), Azuara (Azuara *et al*., 1992) and Peleg (Peleg, 1988) models have been also used to correlate experimental data in osmotic dehydration of various agri-food products (Lemus-Mondaca *et al*., 2015; Waliszewski *et al*., 2002). These models determine the values of water loss and solid gain (Mayor *et al*., 2007).

Ziziphus jujuba Miller, belonging to the plant family Rhamnaceae, has been growing in Europe and Asia specially in Iran, Pakistan, Lebanon, India, China, Bangladesh, Korea. Jujube fruits contain high moisture, various nutrients and chemicals including vitamin C, polysaccharides, protein, phenolic compounds, fiber, organic acid, fatty acids and carbohydrates (Chen *et al*., 2015; Wojdyło *et al*., 2016). It has various healthcare functions thereby it is used as liver protection, antitumor, anti-aging, analeptic, palliative, antibechic, antioxidant and antiobesity. Additionally, it is used for disease treatment such as allergies, urinary troubles, cardiovascular diseases, depression, and insomnia (Goyal *et al*., 2011; Wang *et al*., 2012; Zozio *et al*.,2014).

Jujube is eaten commonly fresh and also used as dried fruit, ingredient of tea and pickles (Choi *et al*., 2011). Due to its rapid ripening after harvest and short shelf life, there is a need to explore methods for expanding its postharvest shelf-life associated with the lowest changes in physico-chemical and sensory characteristics.

Since few studies have tackled the osmotic dehydration of Jujube slices, the main objectives of this research were to study the effect of various parameters such as immersion time, solution temperature and sucrose concentration on water loss and solid gain during osmosis process. Modeling of mass transfer kinetics was studied and effective diffusion coefficients of both moisture and solid were assessed at different process conditions.

Materials and Methods

- *Materials*

Fresh jujube, commonly known as "*Annab*" in Iran, with uniform size and a red peel surface color (free from visible blemishes or damage) were harvested in October, 2015, from Farouj city, Khorasan Province, north east of Iran. The average initial moisture content of jujube samples was 63.13% expressed in wet basis (wb), as determined by drying in the oven at 105°C until the difference between two successive weighing was negligible (Wang *et al*., 2016). Jujube was stored at 4°C in a refrigerator until used. Commercial sucrose (Redpath Canada Ltd., Montreal, QC) was used as the osmotic agent.

- *Sample preparation*

The preparation was carried out according to the method described by Chen *et al*. (2015). Briefly, fresh jujube was immersed in 20 g/L sodium hydroxide (NaOH) solution at 80 °C for 1 min to destroy the skin structure that can shorten the drying time. The jujube was then taken out and washed with running tap water to rinse out the NaOH from the jujube surface. For color protection, jujube was soaked in 0.5% citric acid solution for 10 min. Finally, jujube was washed and sliced into small parts with the thickness of 6 mm.

- *Osmotic dehydration process*

Experiments were conducted at three levels of sucrose concentration (40, 45 and 50% (w/v)) and sample to solution ratio (1:10, 1:15 and 1:20). The temperature of osmotic solution was constant at 30, 40 and 50°C using water bath (BM402, Nuve, Turky). For evaluation of the kinetics of osmotic dehydration at various conditions, samples were withdrawn from the bath each 30, 60, 90, 150, 210, 270, 320 and 380 min, drained, and blotted with absorbent tissue to remove the excess of solution. The WL and SG of samples during osmotic process was determined. All experiments were performed in triplicate order.

The kinetic of osmotic dehydration process and the overall exchange of solutes and water between the jujube slices and the osmotic solution, WL and SG were determined for each sample during osmotic dehydration by using Eqs. (1) and (2) (Dehghannya *et al*., 2017):

$$WL(\%) = \frac{(w_0 M_0 - w_f M_f)}{w_0} \qquad (1)$$

$$SG(\%) = \frac{(w_f(1-\mathrm{M_f}) - w_0(1-\mathrm{M_0}))}{w_0} \qquad (2)$$

where WL is the water loss (g water/g product), SG is the solid gain (g solid/g product), w is the jujube weight (g), M is the moisture content on wet basis (g water/g sample), 0 indicates the primary fresh sample before process and f is the final sample after process.

The moisture and solid ratio, the dependent variables of the diffusive model, were calculated using Eqs. (3) and (4):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \qquad (3)$$

$$SR = \frac{X_t - X_e}{X_0 - X_e} \qquad (4)$$

where MR and SR is the moisture and solid ratio of jujube samples during the osmotic dehydration (dimensionless), respectively. M_t, M_0 and M_e are the moisture content at any time, the initial moisture and equilibrium moisture contents on wet basis (g water/g sample), respectively. X_t, X_e, X_0 are the solid content at any time, the initial solid and equilibrium solid contents on dry basis (g solid/g sample), respectively.

- *Mathematical modeling of mass transfer kinetic*

Various studies have been conducted to better understanding of mass transfer mechanism during osmotic dehydration process which resulted to present the experimental models. In this study, mass transfer kinetics during osmotic dehydration process were modeled according to Magee, Azura and Peleg models as presented in Table 1. Various sucrose concentration (40, 45 and 50% (w/v)), sample to solution ratio (1:10, 1:15 and 1:20) and temperature of osmotic solution (30, 40 and 50°C) were evaluated for osmosis process.

The experimental data were fitted to the given models using Matlab R2008a and each constant of the selected mathematical models were obtained. The fitting of the models to experimental data was evaluated with regression coefficient (R^2), square sum of errors (SSE) and the root mean square error (RMSE). The highest value of R^2 (close to one) and the lowest values of SSE and RMSE (close to zero) were chosen for goodness of fit (Goyal *et al.*, 2011).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{expi}-MR_{prei})^2}{\sum_{i=1}^{N}(MR_{expi}-MR_{ave})^2} \tag{5}$$

$$RMSE = \left[\frac{\sum_{i=1}^{N}(MR_{pred\,i}-MR_{expi})^2}{N}\right]^{\frac{1}{2}} \tag{6}$$

$$SSE = \sum_{i=1}^{N}\left(MR_{prei} - MR_{expi}\right)^2 \tag{7}$$

where, $MR_{exp,i}$ and $MR_{pre,i}$ are the experimental and predicted dimensionless moisture ratios, respectively, N is the number of observations.

- *Estimation of effective moisture and solid diffusivities*

Diffusion is considered as a dominant mechanism of moisture transfer to the surface of the product. The mass transfer phenomena during osmotic dehydration process of biological products and fruits can be described by Fick's diffusion law (Koprivica *et al.*, 2014).

Assuming that the controlling mechanism of one-dimensional transport in an infinite slab is internal mass transfer and considering constant temperature and effective diffusion, the analytical solution of the Fick's second law is given by Eq. (8), proposed by Crank (1975).

$$\mathrm{MR\ or\ SR} = \frac{8}{\pi^2}\sum_{i=0}^{\infty}\frac{1}{(2i+1)^2}\exp\left[\frac{-(2i+1)^2\pi^2 D_{eff}}{4L^2}t\right] \tag{8}$$

where, D_{eff} is the effective diffusion coefficient (m^2/s), i is the number of terms, L represents half of the sample thickness (m), and t is the drying time (s).

For long drying periods, only the first term of the series is taken into consideration and can be applied to determine the water and solid diffusion coefficients for each temperature as below:

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{ew}}{4L^2}t\right) \tag{9}$$

$$SR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{es}}{4L^2}t\right) \tag{10}$$

Table 1. Mathematical models used for determination of mass transfer kinetics

No.	Model	Equation	Reference
1	Magee (water loss)	$WL_t = a + k\sqrt{t}$	Magee *et al.* (1983)
2	Magee (solid gain)	$SG_t = a + k\sqrt{t}$	Magee *et al.* (1983)
3	Azuara (water loss)	$WL_t = \frac{S_1 t(WL_\infty)}{1 + S_1 t}$	Azuara *et al.* (1992)
4	Azuara (solid gain)	$SG_t = \frac{S_2 t(SG_\infty)}{1 + S_2 t}$	Azuara *et al.* (1992)
5	Peleg (water loss)	$WL_t = \frac{t}{K_1 + K_2 t}$	Peleg (1988)
6	Peleg (solid gain)	$SG_t = \frac{t}{K_1 + K_2 t}$	Peleg (1988)

where, D_{ew} is the moisture diffusion coefficient (m^2/s) and D_{es} is the solid diffusion coefficient (m^2/s).

Eqs. (9) and (10) can be expressed in a logarithmic form as follows:

$$\ln(\mathrm{MR}) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{ew}}{4L^2}\right) t \tag{11}$$

$$\ln(\mathrm{SR}) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{es}}{4L^2}\right) t \tag{12}$$

The effective moisture and solid diffusivities are determined by plotting the experimental data in terms of ln(MR) or ln(SR) versus time (min), respectively which give a straight line. The effective moisture and solid diffusivities can then be calculated through the slope of the natural logarithm of moisture and solid ratio to drying time (Eq. 13):

$$Slop = \frac{\pi^2 D_{ew}}{4L^2} \quad or \quad \frac{\pi^2 D_{es}}{4L^2} \tag{13}$$

- *Determination of activation energy*

Considering the effect of process temperature on water and solid diffusion coefficients, activation energy, can be evaluated using Arrhenius equation (Eq. 14). In this equation, Ea is the activation energy (Kj/mol), A is the Arrhenius factor (m^2/s), T is the absolute temperature (K) and R is the universal gas constant (KJ/mol·K).

$$D_{\mathrm{eff}} = A\, exp\left(\frac{E_a}{RT}\right) \tag{14}$$

The activation energy was calculated from the slope of the plot of ln(D_{eff}) versus 1/T (Eq. 15).

$$\ln D_{\mathrm{eff}} = \ln A - \frac{E_a}{RT} \tag{15}$$

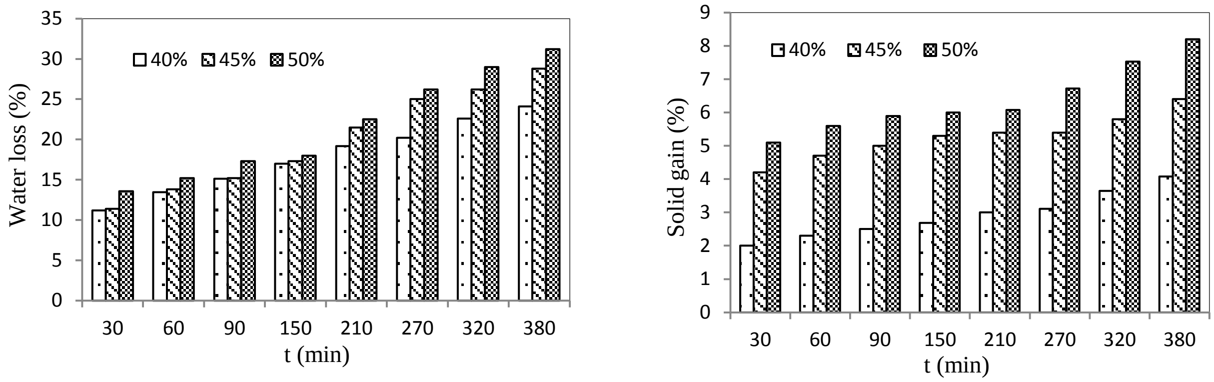
Results and Discussion

- *WL and SG during osmotic dehydration*

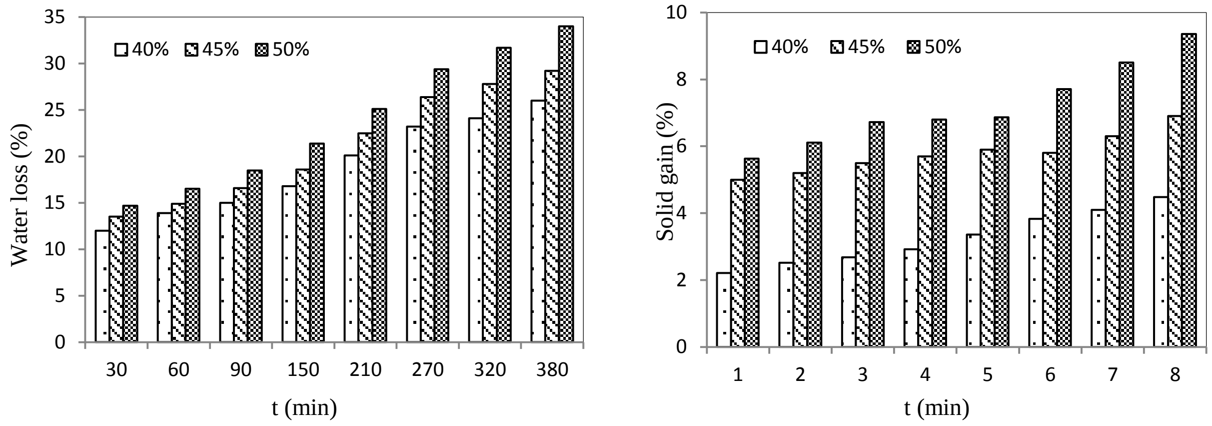
The influence of different sucrose concentrations (40, 45 and 50% (w/v)) and solution temperatures (30, 40 and 50°C) on time-based variation of WL and SG during osmosis process of jujube slices is presented in Figures 1a-c. The results show that WL and SG are function of the variation in sucrose concentration and temperature. With an increase in sucrose concentration as well as solution temperature, the jujube WL and SG increase during osmotic dehydration. However, the effect of sucrose concentration on increase of WL and SG was more significant compared to the temperature. Generally, this may happen because an increase in concentration of the hypertonic solution cause the increase of osmotic pressure gradient; hence the driving force for mass transfer will be increased. Consequently, by increasing the concentration of osmotic solution, along with moisture removal of jujube samples, more solid penetrates inside the tissue and percentage of solid diffusion increases. Another reason for increasing SG may be ascribed to an increase in cell wall permeability due to membrane swelling (Akbarian *et al.*, 2015). The same results were reported by Misljenovic *et al.* (2011) and Dehghannya *et al.* (2017). Furthermore, Figure 1 shows the considerable effect of immersion time on WL and SG of samples. The WL and SG increased with an increase in osmotic process time.

- *Mathematical modeling*

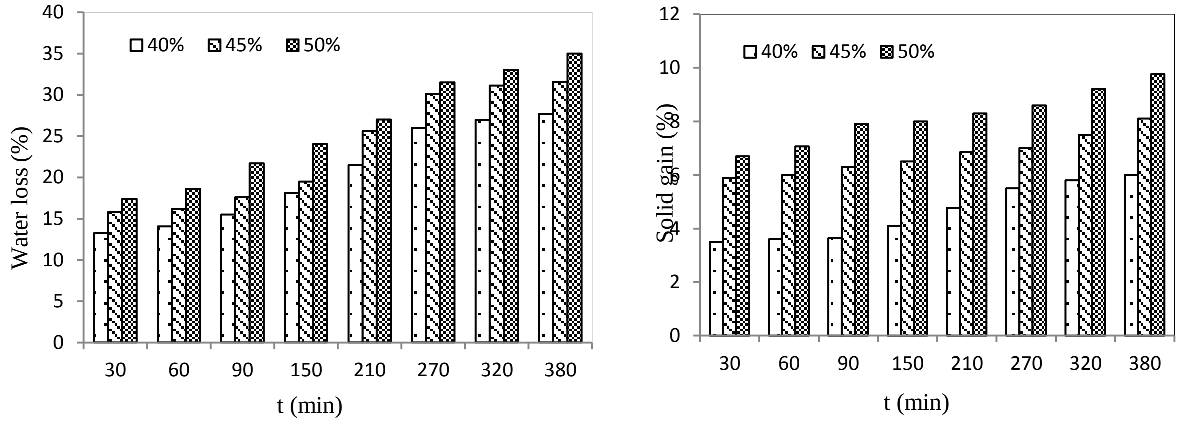
Three mathematical models (Peleg, Magee and Azuara models) were used for modeling the osmosis process of jujube slices. Tables 2 to 4 show kinetic parameters obtained from the mathematical models applied to WL and SG experimental data of jujube samples. The results were reported at different solution temperatures (30. 40 and 50 °C), sucrose concentrations (40, 45 and 50%) and sample to solution ratios (1:10, 1:15 and 1:20). The average value of R^2, RMSE and SSE for fitting the experimental data with Magee, Azaura and Peleg models for WL and SG is presented in Table 5. As shown in Table 5, Azuara model was the best equation which described the osmotic drying process for both WL and SG due to high R^2 values and small values of RMSE and SSE. More compatibility between the experimental and calculated data was achieved using Azuara model at sample to solution ratio of 1:20 compared with sample to solution ratios of 1:10 and 1:15.



(a) 30°C



(b) 40°C



(c) 50°C

Fig. 1. Effect of sucrose concentration, temperature and time on mass transfer kinetic of water loss and solid gain during osmotic dehydration of jujube samples at sample to solution ratio of 1:15 and temperatures of (a) 30°C, (b) 40°C and (c) 50°C, respectively.

Table 2. Fitting the experimental data with Magee model for water loss and solid gain at different osmosis conditions

T (°C)	Sucrose concentration (%)	Sample to solution ratio	Water loss					Solid gain				
			a	k	R^2	RMSE	SSE	a	k	R^2	RMSE	SSE
30	40	1:10	4.392	0.9707	0.9558	0.4715	1.334	1.311	0.1289	0.9553	0.1514	0.1375
		1:15	6.401	0.8875	0.9791	0.4259	1.088	1.191	0.1336	0.9382	0.1862	0.2079
		1:20	7.064	0.9199	0.9789	0.4433	1.182	1.586	0.1249	0.9903	0.0670	0.0270
30	45	1:10	3.385	1.224	0.961	0.8719	4.561	3.245	0.1753	0.9483	0.2225	0.297
		1:15	3.651	1.259	0.9538	0.9255	5.139	3.632	0.1273	0.9153	0.2104	0.2657
		1:20	4.626	1.258	0.9527	0.9897	5.877	4.134	0.1184	0.9467	0.1527	01399
30	50	1:10	4.046	1.287	0.9506	1.011	6.128	4.728	0.1487	0.9407	0.2029	0.2469
		1:15	5.060	1.283	09337	1.506	13.61	3.923	0.1912	0.8680	0.4051	0.9846
		1:20	5.140	1.336	0.9432	1.310	10.29	4.604	0.1834	0.9948	0.0717	0.0310
40	40	1:10	4.064	1.049	0.9625	0.7683	3.542	1.526	0.1564	0.9498	0.1952	0.2287
		1:15	5.658	1.025	0.9674	0.7730	3.560	1.206	0.1593	0.9707	0.1503	0.1359
		1:20	5.791	1.036	0.9204	1.659	16.51	1.375	0.1820	0.9706	0.1721	0.1778
40	45	1:10	3.711	1.251	0.9405	1.229	9.057	3.977	0.1392	0.9679	0.1376	0.1137
		1:15	5.654	1.203	0.9617	1.051	6.702	3.328	0.1131	0.8816	0.2251	0.3041
		1:20	5.650	1.212	0.9332	1.613	15.61	4.519	0.1443	0.9970	0.0431	0.0116
40	50	1:10	4.664	1.418	0.9579	1.058	6.715	4.503	0.1951	0.9778	0.1596	0.1528
		1:15	5.449	1.430	0.9572	1.079	6.980	4.212	0.2325	0.8890	0.4462	1.1950
		1:20	4.986	1.466	0.9472	0.478	13.130	5.299	0.1956	0.9916	0.0979	0.0575
50	40	1:10	4.365	1.139	0.9786	0.645	2.494	1.839	0.1968	0.9304	0.2925	0.5133
		1:15	5.332	1.165	0.9607	1.228	9.052	2.02	0.2009	0.9386	0.2793	0.468
		1:20	5.193	1.257	0.9282	1.766	18.710	3.024	0.1178	0.9213	0.1871	0.2100
50	45	1:10	2.716	1.447	0.9458	1.120	7.523	4.75	0.1205	0.8905	0.2296	0.3163
		1:15	6.268	1.330	0.9472	1.903	21.73	4.906	0.1443	0.9210	0.2297	0.3165
		1:20	6.018	1.415	0.9270	2.224	29.69	5.253	0.1397	0.9769	0.1166	0.0816
50	50	1:10	6.537	1.398	0.9709	0.9501	5.416	5.720	0.1562	0.9592	0.1751	0.1839
		1:15	9.026	1.317	0.9742	0.9399	5.301	5.640	0.1978	0.9500	0.2464	0.3644
		1:20	7.066	1.531	0.9567	1.401	11.78	6.096	0.1857	0.9834	0.1311	0.1031

Table 3. Fitting the experimental data with Azuara model for water loss and solid gain at different osmosis conditions

T (°C)	Sucrose concentration (%)	Sample to solution ratio	Water loss					Solid gain				
			S_1	WL_∞	R^2	RMSE	SSE	S_2	SG_∞	R^2	RMSE	SSE
30	40	1:10	0.0187	24.930	0.9923	1.1880	8.464	0.0174	4.262	0.9661	0.1307	0.1024
		1:15	0.0153	26.710	0.9921	0.7205	3.114	0.0154	4.308	0.9509	0.1299	0.1012
		1:20	0.0157	28.080	0.9903	0.7540	3.412	0.0223	4.327	0.9925	0.1329	0.1059
30	45	1:10	0.009	33.330	0.9820	0.8334	4.167	0.0330	6.896	0.9980	0.3466	0.7207
		1:15	0.011	34.376	0.9831	0.8738	4.581	0.0377	6.385	0.9861	0.2253	0.3047
		1:20	0.0105	35.150	0.9959	0.8818	4.666	0.0460	6.662	0.9942	0.1871	0.2102
30	50	1:10	0.012	35.536	0.9554	0.8834	4.683	0.0530	7.739	0.9995	0.3162	0.5999
		1:15	0.013	36.523	0.9795	0.8972	4.830	0.0243	8.340	0.9650	0.3077	0.5682
		1:20	0.0105	37.660	0.9928	1.0050	6.061	0.0352	8.561	0.9947	0.1474	0.1303
40	40	1:10	0.011	29.103	0.9812	0.9340	5.234	0.0195	4.957	0.9929	0.2671	0.4280
		1:15	0.0126	29.851	0.9821	1.3000	10.14	0.0142	4.953	0.9636	0.0620	0.0230
		1:20	0.0113	31.181	0.9735	0.8474	4.309	0.0145	5.624	0.9681	0.1093	0.0720
40	45	1:10	0.0100	34.330	0.9745	1.0100	6.117	0.0444	6.868	09983	0.2350	0.3313
		1:15	0.0116	34.364	0.9684	1.0400	6.491	0.0430	6.835	0.9855	0.1966	0.2320
		1:20	0.0110	35.448	0.9879	0.7987	3.828	0.0424	7.604	0.9966	0.1186	0.0843
40	50	1:10	0.0100	38.900	0.9811	0.7425	3.308	0.0328	8.733	0.9914	0.2130	0.2722
		1:15	0.0110	40.000	0.9815	0.7955	3.797	0.0230	9.560	0.9648	0.3421	0.7021
		1:20	0.0110	40.900	0.9856	0.7271	3.172	0.0389	9.469	0.9965	0.2119	0.2693
50	40	1:10	0.0110	31.220	0.9637	0.6525	2.554	0.0151	6.497	0.9528	0.1728	0.1791
		1:15	0.0110	33.200	0.9893	1.0520	6.637	0.0161	6.734	0.9693	0.1801	0.1946
		1:20	0.0100	36.416	0.9830	0.8395	4.228	0.0392	5.497	0.9917	0.2362	0.3347
50	45	1:10	0.0080	38.073	0.9351	0.8519	4.355	0.0657	7.153	0.9985	0.3119	0.5838
		1:15	0.0113	38.314	0.9801	0.9420	5.324	0.0374	8.156	0.9872	0.1445	0.1253
		1:20	0.0110	41.051	0.9595	0.8490	4.325	0.0455	8.292	0.9942	0.1067	0.0683
50	50	1:10	0.0120	39.650	0.9830	0.6019	2.174	0.0526	8.968	0.9977	0.2687	0.4331
		1:15	0.0142	39.682	0.9846	0.6661	2.662	0.0367	9.960	0.9902	0.2520	0.3811
		1:20	0.0113	44.014	0.9941	0.5653	1.917	0.0476	9.980	0.9979	0.2575	0.398

Table 4. Fitting the experimental data with Peleg model for water loss and solid gain at different osmosis conditions

T (°C)	Sucrose concentration (%)	Sample to solution ratio	Water loss					Solid gain				
			K_1	K_2	R^2	RMSE	SSE	K_1	K_2	R^2	RMSE	SSE
30	40	1:10	9.817	0.0376	0.9592	1.0690	6.855	2.010	0.0052	0.9667	6.054	219.9
		1:15	11.29	0.0348	0.9801	0.6821	2.791	1.905	0.0054	0.9699	7.267	316.8
		1:20	12.13	0.0361	0.9922	0.6695	2.689	2.281	0.0049	0.9620	2.761	45.74
30	45	1:10	10.06	0.0484	0.9863	0.7865	3.711	4.255	0.0066	0.8744	0.892	4.777
		1:15	10.49	0.0499	0.9902	0.6827	2.796	4.334	0.0050	0.9028	2.561	39.35
		1:20	11.42	0.0500	0.9795	0.4573	1.255	4.794	0.0046	0.9199	1.579	14.97
30	50	1:10	11.00	0.0512	0.9962	0.4344	1.132	5.592	0.0056	0.8559	0.406	0.989
		1:15	11.92	0.0515	0.9871	0.8117	3.953	4.923	0.0078	0.9239	3.140	59.31
		1:20	12.32	0.0534	0.9685	0.6248	2.342	5.618	0.0072	0.9782	1.178	8.319
40	40	1:10	9.720	0.0414	0.9827	0.7558	3.428	2.407	0.0060	0.9061	2.357	33.34
		1:15	11.23	0.0406	0.9888	0.5946	2.121	2.062	0.0064	0.9950	5.410	175.6
		1:20	11.23	0.0420	0.9201	0.9560	5.484	2.358	0.0073	0.9882	4.449	118.8
40	45	1:10	10.47	0.0498	0.9850	0.8474	4.309	4.771	0.0053	0.9063	0.839	4.219
		1:15	12.18	0.0472	0.9855	0.7988	3.829	4.933	0.0076	0.9097	2.442	35.79
		1:20	12.06	0.0489	0.9434	0.7460	3.339	5.318	0.0094	0.9772	1.057	6.699
40	50	1:10	12.38	0.0561	0.9864	0.9051	4.916	5.582	0.0076	0.9605	1.470	12.97
		1:15	13.19	0.0568	0.9955	0.5259	1.657	5.438	0.0094	0.9348	2.751	45.42
		1:20	12.89	0.0584	0.9667	0.9739	5.691	6.391	0.0076	0.9606	0.862	4.456
50	40	1:10	10.66	0.0445	0.9715	1.0490	6.606	2.880	0.0080	0.9757	4.718	133.6
		1:15	11.66	0.0462	0.9730	1.0590	6.727	3.090	0.0081	0.9745	3.644	79.66
		1:20	11.83	0.0510	0.9373	0.9194	5.072	3.690	0.0045	0.8746	2.298	31.69
50	45	1:10	10.58	0.0573	0.9882	0.8639	4.478	5.456	0.0045	0.7978	0.750	3.370
		1:15	13.44	0.0530	0.9527	1.6250	15.84	5.667	0.0058	0.9687	1.919	22.10
		1:20	13.54	0.0570	0.9228	1.6100	15.55	6.014	0.0055	0.9807	1.268	9.653
50	50	1:10	14.18	0.0551	0.9835	0.9833	5.801	6.607	0.0060	0.9039	0.741	3.289
		1:15	16.20	0.0521	0.9876	0.8030	3.868	6.722	0.0078	0.9477	1.374	11.32
		1:20	15.30	0.0610	0.9678	0.6478	2.518	7.145	0.0071	0.9359	0.640	2.434

Table 5. The average value of R^2, RMSE and SSE for fitting the experimental data with Magee, Azaura and Peleg models for water loss and solid gain at various osmotic dehydration condition

Mass Transfer	Sample to solution ratio	Magee model			Azuara model			Peleg model		
		R^2	RMSE	SSE	R^2	RMSE	SSE	R^2	RMSE	SSE
Water loss	1:10	0.8550	0.9072	5.197	0.9720	0.8553	4.562	0.9821	0.8549	4.5817
	1:15	0.9594	1.0923	8.129	0.9823	0.9207	5.285	0.9823	0.8425	4.8220
	1:20	0.9430	1.3200	13.652	0.9838	0.8070	3.990	0.9554	0.8449	4.8820
Solid gain	1:10	0.9466	0.1962	0.2433	0.9883	0.2513	0.4056	0.9052	2.0250	46.272
	1:15	0.9191	0.2643	0.4713	0.9736	0.2044	0.2924	0.9474	3.3900	87.261
	1:20	0.9747	0.1155	0.0933	0.9918	0.1672	0.1858	0.9530	1.7870	26.973

In addition, Peleg model resulted to model WL experimental data better than the Magee model, while the reverse result happened in the SG experimental values. In general, the results obtained by these three mathematical models suggest an acceptable fitting on the experimental data which confirm their effectiveness for modeling mass transfer kinetics during the osmosis process of jujube samples. Similar results were reported by other authors when modeling osmotic dehydration of different product, such as apple (Zúñiga & Pedreschi, 2012), pineapple (Waliszewski *et al.*, 2002) and cranberries (Zielinska & Markowski, 2018).

Figures 2 and 3 show a comparison between WL and SG of the experimental and calculated data using the Azuara model at various temperature (30, 40 and 50°C), sample to solution ratio of 1:20 and sucrose concentrations of 40, 45 and 50% w/v, respectively.

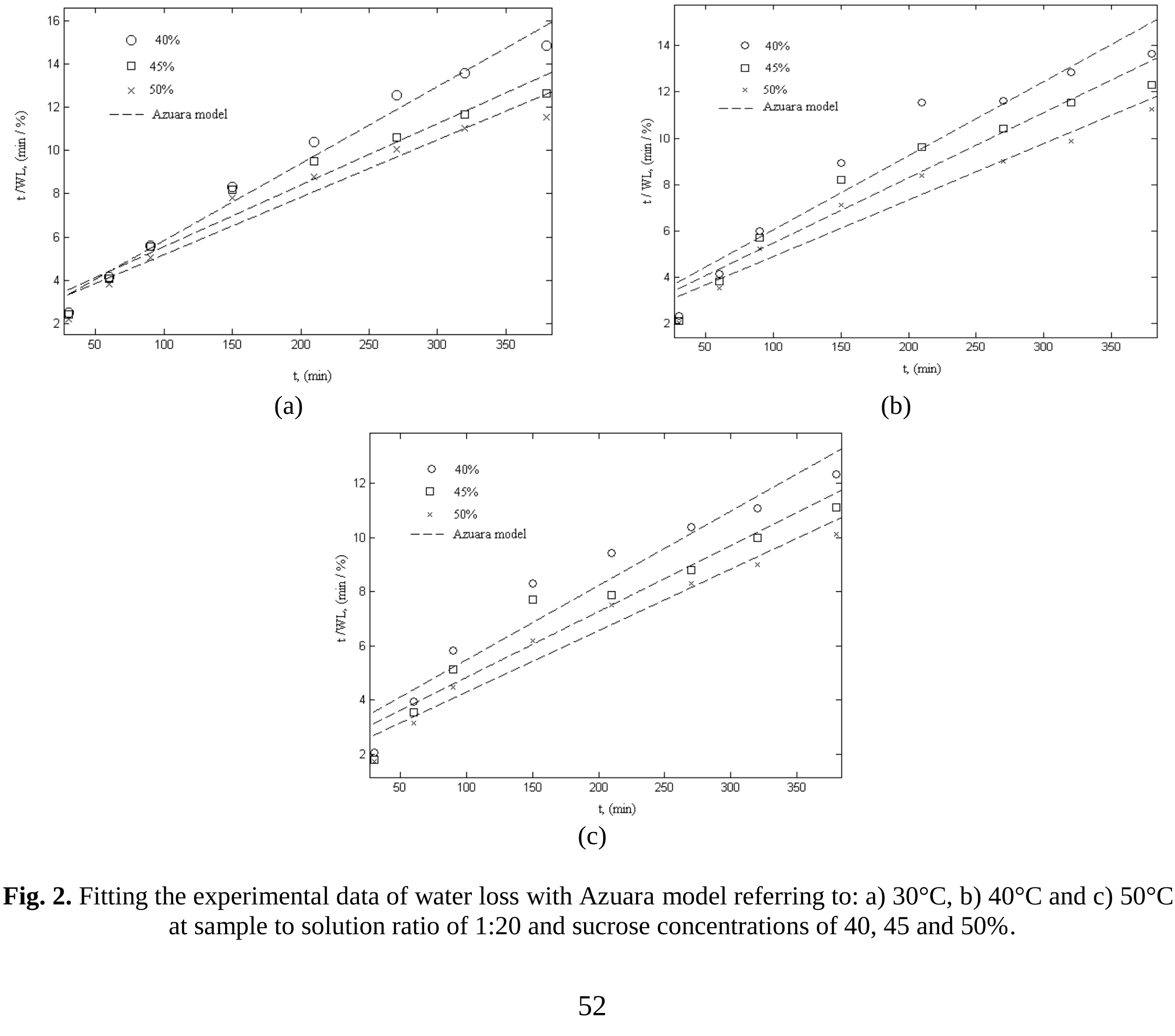
- *Moisture and solid diffusion coefficients*

The effective moisture and solid diffusivities ranged from $2.734\text{-}5.617\times10^{-10}$ to $3.0828\text{-}5.964\times10^{-10}$ m^2/s, respectively, during osmotic dehydration over the solution temperature range of 30 to 50°C and sucrose concentration of 40 to 50% (Table 6). It is observed that the values of both D_{ew} and D_{es}

increased with an increase in temperature and sucrose concentration. Actually, in higher temperature, cell tissue becomes soft that leads to variation in cell wall diffusivity (Pereira *et al.*, 2006). Therefore, tissue diffusivity increases against water removal and sucrose uptake. Using higher osmotic temperatures resulted to swelling and plasticizing of cell membrane and thereby faster transfer of moisture through tissue. In addition, an increase in temperature results to a decrease in viscosity of osmotic solution and better mass transfer rates occur at the contact surface of jujube slices and osmosis solution. On the other hand, an increase in the sucrose concentrations cause an increase in osmotic pressure gradient, increasing the driving force for water removal and solid gain of jujube slices samples, and thus higher effective moisture and solid diffusion coefficients.

- ***Activation energy***

Figures 4 (a) and (b) show the relationship between effective diffusivity coefficients (moisture and solid, respectively) and temperature at different sucrose concentrations. The activation energy was determined from the slope of the plot of $\ln D_{ew}$ and $\ln D_{es}$ versus T^{-1}. The results show a linear trend owing to Arrhenius type dependence. The effect of different solid (sucrose) concentrations on activation energy of moisture loss and solid gain is presented in Table 7. As table shows, osmotic solution concentration has a reverse relationship with moisture and solid activation energies.

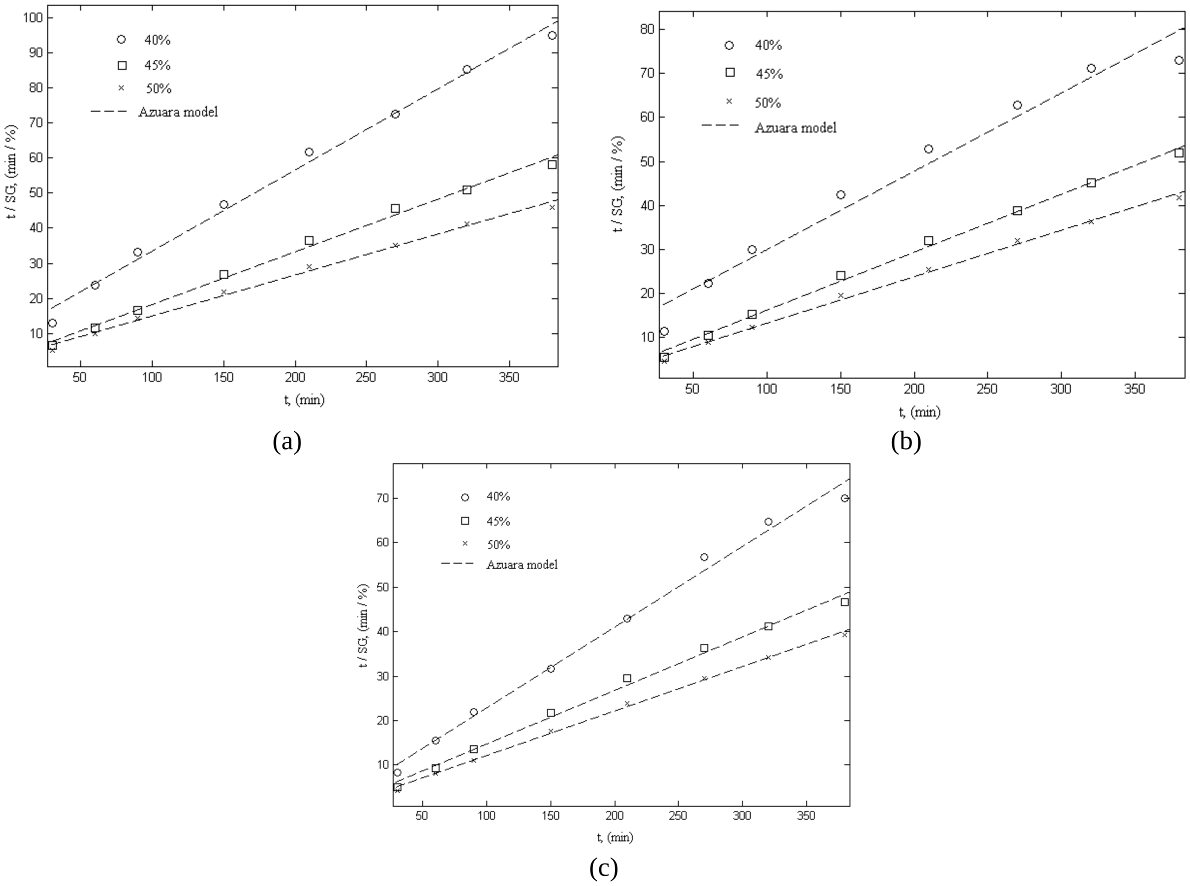


(a)

(b)

(c)

Fig. 2. Fitting the experimental data of water loss with Azuara model referring to: a) 30°C, b) 40°C and c) 50°C; at sample to solution ratio of 1:20 and sucrose concentrations of 40, 45 and 50%.



(a)

(b)

(c)

Fig. 3. Fitting the experimental data of solid gain with Azuara model referring to: a) 30°C, b) 40°C and c) 50°C; at sample to solution ratio of 1:20 and sucrose concentrations of 40, 45 and 50%.

Table 6. Effective moisture and solid diffusivities of jujube samples at various condition of osmotic dehydration

Temperature (°C)	Concentration (%)	$D_{ew}\times10^{10}$ (m^2/s)	$D_{es}\times10^{10}$ (m^2/s)
30	40	2.7342	3.0828
	45	3.5817	4.1614
	50	4.7867	5.2375
40	40	3.0521	3.5817
	45	4.1614	4.4631
	50	5.2902	5.506
50	40	3.5461	3.881
	45	4.4187	4.982
	50	5.6173	5.964

Conclusion

The main problem of hot air drying of agricultural product is high consumption of energy and non-stability of food component against heat. Osmotic dehydration process demonstrated to be one of the most suitable drying methods due to using low temperature and energy and good quality of final product. The present study showed the influence of sucrose concentration and solution temperature on water loss and solid gain during osmotic dehydration of jujube samples. Azuara model presented the mostappropriate model to describe the osmotic drying process for both moisture loss and solid gain (high R^2 values and small values of RMSE and SSE). Therefore, this model can be used to simulate the mass transfer process during osmotic dehydration of jujube slices. The effective moisture and solid diffusivities were estimated in the range of 2.734-5.617× 10^{-10} and 3.0828-5.964 × 10^{-10} m^2/s, respectively. The results showed the reverse relationship of osmotic solution concentration and moisture and solid activation energies.

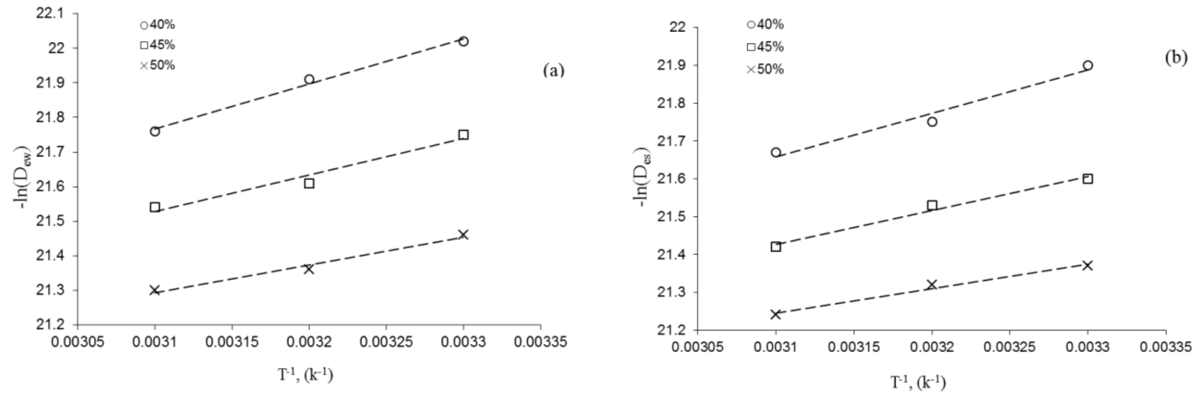


Fig. 4. The relationship between effective a) moisture and b) solid diffusivity coefficients and temperature at different sucrose concentrations.

Table 7. Activation energy at different sucrose concentrations

Sucrose concentration (%)	Activation energy for moisture removal; Ea (Kj/mol)	Activation energy for solid gain; Ea (Kj/mol)
40	10.80	9.5611
45	8.7297	7.4826
50	6.6512	5.4041

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