Studies on Mass Transfer Kinetics of Aonla Slices

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Abstract – *An investigation was undertaken to study the mass transfer kinetics during osmotic dehydration of aonla slices (Cv. Chakaiya) to remove partial water prior to mechanical drying by using sugar syrup solution (50, 60 and 70⁰Brix), sugar syrup temperatures (40, 50 and 60⁰C) and immersion time (15, 30, 60, 90, 120, 180 and 240 min) maintaining constant solution to fruit ratio of 6:1 (v/w). Effects of syrup concentration, syrup temperature and immersion time on water loss and sugar gain were observed. It was found that water loss and sugar gain both were increased non-linearly with syrup concentration, temperature and immersion time and found in the range of 15.65 to 62.28 and 3.69 to 18.14 %, respectively. Among the seven existing mathematical models tried, the logarithmic model was found adequate to describe the water loss for all the temperature-concentration combinations except treatment of 60⁰C-70⁰B for which power model was found adequate based on regression diagnostic criteria. For sugar gain, cubic model was found best fit for 40⁰C-60 and 70⁰B, 50⁰C-50, 60 and 70⁰B and for 60⁰C- 70⁰B and quadratic model was found best fit for 40⁰C-50⁰B,60⁰C-50 and 60⁰B temperature-concentration combinations. Developed models can be used for predicting water loss and sugar gain during osmotic dehydration of aonla slices within the range of experimental study.*

***Key Words*: Modelling, Water loss, Sugar gain, Aonla, Osmotic dehydration**

1. INTRODUCTION

Osmotic dehydration (OD) is a process for the partial removal of water from plant tissues such as fruits and vegetables by immersion in an aqueous concentrated solution of soluble salts. A driving force for the diffusion of water from the tissue into the solution is provided by the difference in osmotic pressure or concentration gradient between the food and surrounding osmotic solution. A diffusion of water is accompanied by the simultaneous counter diffusion of solute from the osmotic solution into the tissue. Since the membrane responsible for the osmotic transport is not perfectly selective, other solutes such as sugar, organic acids, minerals, salts and vitamins present in the cells can also be leached into the osmotic solution [17]. But this flow can be quantitatively neglected. Kinetics of dewatering and mass transfer have been investigated for apple, banana and potato [18], button mushrooms [7], carrot [14] and for papaya [5]. India is the largest producer of fruits like mango, banana, papaya, sapota, pomegranate and aonla. In India, area under aonla was about 1,03,550 ha with production of about 12,25,210 metric tonnes during the year 2013-14 [2]. Aonla is known for exceptionally high amount of ascorbic acid and is regarded by the Indian scientists as richest and cheapest source of vitamin-C. It contains 600-900 mg of ascorbic acid per 100 g of pulp. Pulp contains protein (0.05%), phosphorus (0.2%), iron (1-2%) and nicotinic acid (0.2 mg/100 g) with a high amount of pectin [12]. The rate of mass transfer (water loss and sugar gain) was found to be a function of many variables such as solution temperature, solution concentration, composition of osmotic solution, immersion time, nature of food and its geometry, solution to fruit ratio. Keeping in view, the perishable nature of aonla (*Emblica officinalis* Gaertn.) fruits, the objective of the present study was to investigate the effect of osmotic process parameters on mass transfer kinetics of aonla slices and to develop the mathematical models for water loss and sugar gain.

2. MATERIALS AND METHODS

Fresh aonla fruits of variety Chakaiya were procured from an orchard of Department of Horticulture, Mahatma Phule Krishi Vidyapeeth, Rahuri (India).

The aonla fruits were sorted for uniform size (32.5±1 mm), colour, maturity and physical damage; washed with potable water and then wiped with a muslin cloth to remove surface moisture. Fruits were blanched in boiling water for 5 min and cut to 5 mm thick uniform slices with specially designed radial type aonla cutter. Cut slices were separated with a sharp stainless steel knife and held in water to prevent enzymatic browning until the entire batch was prepared. Slices were then removed from the water and gently blotted with tissue paper prior to osmotic dehydration and determination of moisture content. Moisture content of the fresh as well as osmotically dehydrated aonla slices were determined by vacuum oven method. A pre weighed 3-5 g sample of aonla slices was kept in pre-dried and weighed petri-dishes. The petri-dishes with samples were placed in vacuum oven at 70^{0}C maintaining vacuum between 85 to 100 mm of Hg till it attained constant weight. Petri-dishes were then cooled in desiccators for one hour and weighed. The average moisture content of three replicated samples was reported [13].

2.1 Preparation of sugar syrup as osmotic agent

The sugar syrups of three concentrations (50, 60 and 70^{0}B) were prepared by dissolving known quantity of sugar in distilled water using glass rod as stirrer. Concentration of sugar syrup was checked by using hand refractometers (Erma, Japan make) of appropriate range (0-32, 28-62 and 58-92^{0}B). Sugar was procured from local market and used as osmotic agent as it prevents food discolouration to a large extent and imparts good taste to the final product.

2.2 Experimental procedure

In osmotic dehydration, samples of aonla slices of 5 mm thickness each weighing 75 g were prepared. Constant syrup to fruit ratio (STFR) of 6:1 (v/w) was used. The 500 mL capacity glass beakers containing sugar syrup (50, 60 and 70 ^{0}B) were placed inside the constant temperature circulatory water bath (Make: Classic Scientific India, Thane) at (40, 50 and 60^{0}C) and slices were put into the syrup after attainment of desired temperature. Sodium metabisulphite (0.1%) was added to each beaker containing the syrup. For every 15, 30, 60, 90, 120,180 and 240 min interval, one glass beaker was removed from the water bath and the aonla slices were immediately rinsed with distilled water to remove the solute adhered to fruit surface. Then slices were spread on the tissue paper for 5 min to remove the surface moisture. Weight of osmotically dehydrated aonla slices was recorded. Slices were then put in pre-weighed petri-dish for moisture determination by vacuum oven method. Each treatment replicated thrice and average moisture content was recorded.

2.3 Osmotic dehydration parameters

Lenart and Flink (1984) first defined terminology for mass transport data which helped to study the characteristics of osmosis process during dehydration of product and same had been used by various researchers [13] and [6].

2.3.1 Water loss

Water loss is the quantity of water lost by food during osmotic processing. Water loss (WL) is defined as the net weight loss of the fruit on initial weight basis and was estimated as :

$$WL = \frac{W_i X_i - W_\theta X_\theta}{W_i} \times 100 \qquad \text{... (1)}$$

where,

WL = Water loss (% or g per 100 g mass of sample)

W_θ = Mass of slices after time θ, g

W_i = Initial mass of slices, g

X_θ = Water content as a fraction of mass of slices at time θ.

X_i = Water content as a fraction of initial mass of slices, fraction.

2.3.2 Sugar gain

Sugar molecules from the osmotic solution get diffused to the sample of aonla slices during osmotic dehydration. The loss of water from the sample takes place in osmotic dehydration consequently, it increases the sugar content. Sugar gain is the net uptake of sugar by the slices on initial weight basis. It is computed using following expression:

$$SG = \frac{W_\theta (1 - X_\theta) - W_i (1 - X_i)}{W_i} \times 100 \qquad \text{... (2)}$$

where, SG = Sugar gain ((% or g per 100 g mass of sample).

2.4 Modelling of mass transport kinetics

Water loss and sugar gain were plotted as ordinate against time of osmosis as abscissa and mathematical models for dependent variable Y (WL and SG) and independent variable t (time of osmosis). Models listed in Table 1 were fitted to the experimental data by regression analysis and model constants a, b and c were determined. Statistical package SAS 9.3 was used for analysis of data.

Table -1: Mathematical models for osmotic dehydration kinetics

Model	Equation
Linear	$Y = a + b\,t$
Quadratic	$Y = a + b\,t + ct^2$
Cubic	$Y = a + b\,t + ct^2 + dt^3$
Exponential	$Y = a\,e^{bt}$
Power	$Y = a\,t^b$
Logarithmic	$Y = a + b\,e^t$

2.5 Validation of model for osmotic mass transfer kinetics

In order to validate the model and check the goodness of fit on the basis of highest coefficient of determination (R^2), and adjusted coefficient of determination (Adj. R^2), lowest chi-square statistic, probability, root mean square error (RMSE), mean bias error (MBE) and per cent error modulus between experimental and predicted values were considered and evaluated by performing regression analysis as follows.

$$R^2 = 1 - \left[\frac{SS_{residual}}{SS_{model} + SS_{residual}}\right] \quad \ldots (3)$$

$$\text{Adjusted } R^2 = 1 - \left[\frac{SS_{residual}/(n-p)}{(SS_{model} + SS_{residual})/(n-1)}\right]$$

$$= 1 - \left[\frac{(n-1)}{(n-p)}\right](1 - R^2) \quad \ldots (4)$$

$$\chi^2 = \left[\sum_{i=1}^{n} \frac{(V_{expt.} - V_{pred.})^2}{pred.}\right] \quad \ldots (5)$$

$$RMSE = \frac{1}{n}\left[\sum_{i=1}^{n}(V_{expt.} - V_{pred.})^2\right]^{0.5} \quad \ldots (6)$$

$$\text{Mean Bias Error} = \frac{1}{n}\sum_{i=1}^{n}(V_{expt.} - V_{pred.}) \quad \ldots (7)$$

$$\text{Per cent Error Modulus} = \frac{100}{n}\left|\sum_{i=1}^{n}\frac{(V_{expt.} - V_{pred.})}{V_{pred.}}\right| \quad \ldots (8)$$

where,
Vexpt.= Experimental value of WL or SG (%)
Vpred. = Predicted value WL or SG (%)
n = Number of observations
p = Number of variables

3. Results and Discussion

Average initial moisture content of fresh aonla fruits of variety Chakaiya was found 86.59 (% w. b.).

3.1 Effect of osmotic dehydration process parameters on water loss

Data of water loss as influenced by various sugar syrup concentrations (50, 60 and 70°B), sugar syrup temperatures (40, 50 and 60°C) and immersion time (15, 30, 60, 90, 120, 180 and 240 min) during osmotic dehydration of aonla slices is presented in Table 2 and plotted in Fig. 1. Water loss was very fast at the beginning of the process and rate was gradually decreased with the increase of immersion time for all the treatment combinations. It can be further seen that as the immersion time increased, the water loss was increased; however the equilibrium point could not be reached after short duration (4 h) of the osmotic dehydration process (Fig.1). This result is in confirmation with [8], [5] and [1].

Table -2: Effect of immersion time, temperature and sugar concentration on water loss (%) at 6:1 STFR during osmotic dehydration of aonla slices

Time (min)	40°C			50°C			60°C		
	50°B	60°B	70°B	50°B	60°B	70°B	50°B	60°B	70°B
15	15.65	18.26	19.87	18.24	20.97	25.16	23.45	24.85	33.89
30	26.18	27.35	28.60	29.78	30.78	32.80	32.55	35.89	40.26
60	30.30	32.81	34.60	34.28	37.74	38.91	38.66	42.18	45.27
90	32.85	37.18	38.25	37.50	39.68	42.78	42.79	47.36	51.88
120	37.19	40.68	41.36	40.09	42.35	45.83	46.93	51.67	55.44
180	40.56	42.11	44.11	44.12	49.05	51.78	49.10	56.02	59.40
240	42.58	46.81	48.29	46.73	51.81	53.75	53.28	57.67	62.28

It can be observed from Table 2, that when sugar syrup temperature was increased from 40 to 50°C for 70°B syrup concentration, water loss increased from 48.29 to 53.75 per cent after 4 h of osmotic dehydration causing 5.46 per cent point increase, however further increase in syrup temperature to 60°C, the water loss was 62.28% showing 8.53% point increase. Similarly, for 60 °B syrup concentration, the water loss was increased from 46.81 to 51.81 per cent when syrup temperature increased from 40°C to 50°C giving only 5.00 per cent point gain and further increase in syrup temperature from 50 to 60°C, the water loss was increased to 57.67 % showing 5.85 per cent point increase. Similar results were obtained for 50°B sugar syrup concentration and also with the corresponding increase of 4.15 per cent point when sugar syrup temperature was increased from 40 to 50°C and 6.55 per cent point increase when temperature was increased from 50 to 60°C. The water loss was in the range of 15.65 to 62.28 per cent.

Low temperature-low concentration (40°C-50°B) gave a low water loss (42.58% after 4 h of osmosis) and a high temperature-high concentration conditions (60°C-70°B) gave a higher water loss (62.28% after 4 h of osmosis). Low temperature-high concentration condition (40°C-70°B) gave a slightly lower water loss of 48.29% after 4 h of osmosis than 60°C- 50°B (53.28% after 4 h of osmosis) indicating a slightly greater temperature effect on water loss (Table 2). This indicated that, water loss can be increased by either increasing the sugar syrup temperature or concentration of solution. However, an increase in temperature of sugar solution by 20°C has more influence on water loss than increase in concentration by 20°B. Similar results were obtained by [19] for osmotic dehydration of apples and [5] for osmotic dehydration papaya cubes.

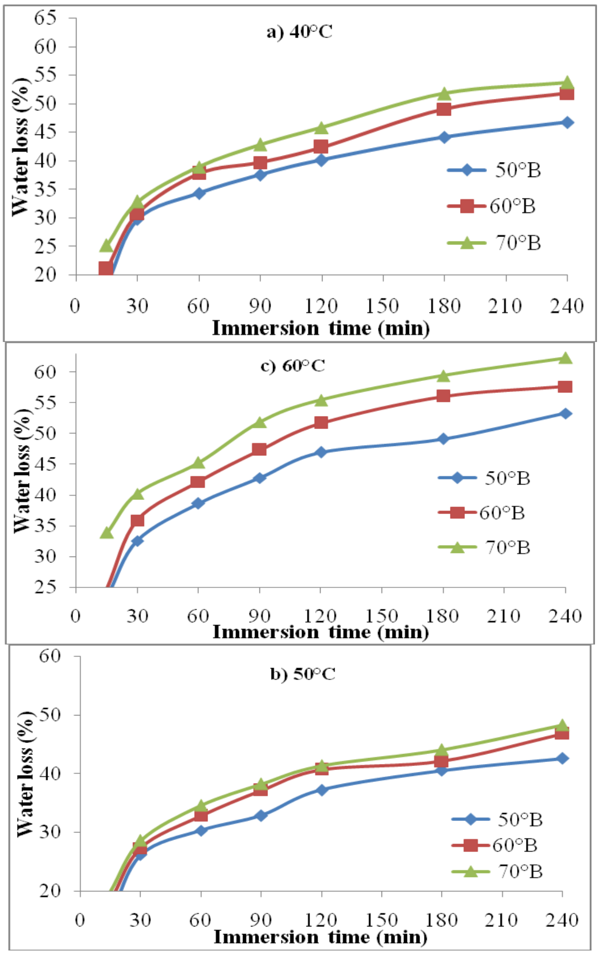

Fig- 1: Effect of immersion time and sugar concentration on water loss (%) at 6:1 STFR during osmotic dehydration of aonla slices at a) 40; b) 50 and c) 60°C

Water loss was very fast at the beginning of process and rate decreased gradually with the increase of duration of osmosis, but did not approach the equilibrium (Fig.1). Similar results were quoted in case of the osmotic dehydration of banana slices by [11]. It was also observed that the water loss increased with increase in syrup concentration also at a particular temperature of syrup. This may be due to increased osmotic pressure in the sugar syrup at higher concentrations, which might have increased the driving force available for water transport. Similar findings were reported by [10] for osmotic dehydration kinetics of pineapple and [9] for apple slices.

3.2 Effect of osmotic dehydration process parameters on sugar gain

Data of sugar gain as affected by various sugar syrup concentrations (50, 60 and 70^0B), temperatures (40, 50 and 60^0C) and immersion time (15, 30, 60, 90, 120, 180 and 240 min) during osmotic dehydration of aonla slices is presented in Table 3 and plotted in Fig. 2. Sugar gain was very fast during the first hour of the process and rate was gradually decreased with the increase of immersion time. Further, it can be observed that, as the immersion time increased the sugar gain was increased; however the equilibrium point could not be reached after short duration (4 h) of the osmotic dehydration process (Fig. 2). This result is in confirmation with [5] and [1].

Table- 3: Effect of immersion time, temperature and sugar concentration on sugar gain (%) at 6:1 STFR during osmotic dehydration of aonla slices

Time (min)	40°C			50°C			60°C		
	50°B	60°B	70°B	50°B	60°B	70°B	50°B	60°B	70°B
15	3.69	4.63	4.68	5.52	6.63	6.98	9.46	10.02	10.88
30	4.88	5.87	6.81	6.95	7.19	8.67	9.69	11.31	12.33
60	7.10	9.18	10.85	9.14	11.89	12.94	10.60	12.35	13.68
90	8.18	12.31	13.06	10.56	12.49	14.79	11.03	12.50	14.92
120	10.11	12.84	13.16	11.29	13.26	15.53	12.22	13.47	15.88
180	11.82	12.89	13.21	12.25	14.77	16.05	13.55	14.91	16.23
240	12.20	13.61	14.24	13.07	15.81	16.15	15.09	16.14	18.14

When sugar syrup temperature was increased from 40 to 50^0C for 70^0B syrup concentration, sugar gain increased from 14.24 to 16.15 per cent after 4 h of osmotic dehydration causing 1.91 per cent point increase, however further increase in syrup temperature to 60^0C, the sugar gain was 18.14 % showing 1.99 % point increase. Similarly for 60^0B syrup concentration, the sugar gain was increased from 13.61 to 15.81 per cent when syrup temperature increased from 40 to 50^0C giving only 2.20 per cent point gain and further increase in syrup temperature from 50 to 60^0C, the sugar gain was increased to 16.14% showing 0.33 per cent point increase (Table 3). Similar results were obtained for 50^0B sugar syrup concentration also with the corresponding increase of 0.87 per cent point when sugar syrup temperature was increased from 40 to 50^0C and 2.02 per cent point when temperature was increased from 50 to 60^0C. Sugar gain was in the range of 3.69 to 18.14 per cent.

Low temperature-low concentration (40^0C-50^0B) gave a low sugar gain (12.20% after 4 h of osmosis) and a high temperature-high concentration conditions (60^0C-70^0B) gave a higher sugar gain (18.14% after 4 h of osmosis). Low temperature-high concentration condition (40^0C-70^0B) gave a slightly lower sugar gain of 14.24% after 4 h of osmosis than 60^0C- 50^0B (15.90% after 4 h of osmosis) indicating slightly greater temperature effect on sugar gain (Table 3). This indicated that the sugar gain could be increased by either increasing the sugar syrup temperature or concentration of solution. However, an increase in temperature of sugar solution by 20^0C had more influence on sugar gain than increase in concentration by 20^0B. Similar results were obtained by [19] for osmotic dehydration of apples and [5] for papaya cubes. Sugar gain at any concentrations was affected by the temperature of sugar syrup. It was increased non-linearly with increase in syrup temperature and then the rate decreased. This may be due to rapid solid uptake near the surface in the beginning might have resulted in structural changes leading to compaction of these surface layers and increased mass transfer resistance for sugar uptake [8]. Similar trends have been reported for other fruits and vegetables during osmosis [3] and [16].

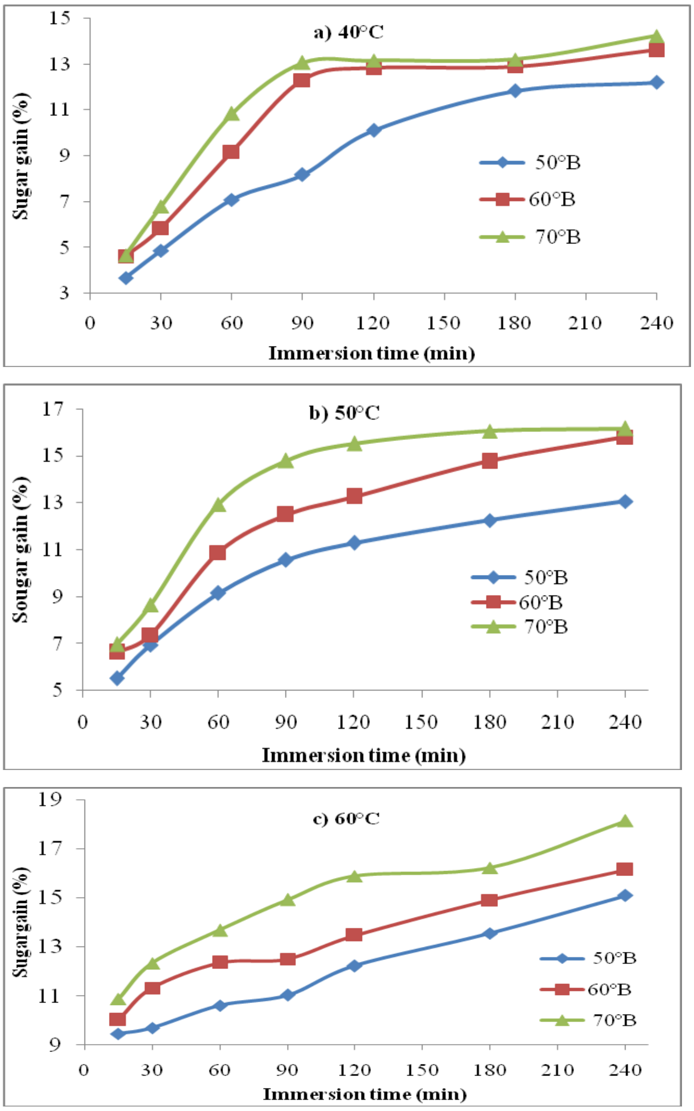

Fig- 2: Effect of immersion time and sugar concentration on sugar gain (%) at 6:1 STFR during osmotic dehydration of aonla slices at a) 40; b) 50 and c)60°C

Sugar gain was very fast at the beginning of process and rate decreased gradually with the increase of duration of osmosis, but did not approach the equilibrium (Fig. 2). Similar results were quoted in case of the osmotic dehydration of banana slices by [11]. It was also observed that the sugar gain increased with increase in syrup concentration also at a particular temperature of syrup. This may be due to increased osmotic pressure in the sugar syrup at higher concentrations, which might have increased the driving force available for sugar transport. Sugar gain was also increased with increase in syrup temperature which may be due to the collapse of cell membrane at higher temperatures. Similar findings were observed by [10] for osmotic dehydration kinetics of pineapple and [9] for apple slices.

3.3 Modelling of water loss and sugar gain

Among the seven existing models *viz.,* linear, quadratic, cubic, exponential, power and logarithmic tried to fit the experimental data of water loss and sugar gain, the best fit equations based on regression diagnostic criteria are presented in Table 4 and 5. Logarithmic model was found adequate to describe the water loss for all the temperature-concentration combinations except the treatment of 60^{0}C-70^{0}B for which power model was found adequate based on regression diagnostic criteria. Per cent error modulus of less than 1% also revealed that the said model were best fit (Table 4).

Table- 4: Best fit models and regression diagnostic criteria for water loss during osmotic dehydration of aonla slices

Temp. (°C)	Prediction equation	R^2	Adj R^2	Prob	χ^2	RMSE	MBE	% Error Modulus
40	WL = -7.8987 + 9.302808 ln(t)	0.98	0.98	0	0.46	1.45	8E-16	0.504
	WL = -7.2897 + 9.820922 ln(t)	0.99	0.99	0	0.20	1.12	7E-15	0.233
	WL = -5.8327 + 9.809788 ln(t)	0.99	0.99	0	0.116	0.79	2E-15	0.140
50	WL = -5.7328 + 9.643104 ln(t)	0.98	0.97	0	0.51	1.59	1E-14	0.523
	WL = -6.9066 + 10.632396 ln(t)	0.99	0.98	0	0.27	1.38	1E-14	0.167
	WL = -2.8769 + 10.315069 ln(t)	0.99	0.99	0	0.06	0.75	9E-15	0.014
60	WL = -3.9519 + 10.423596 ln(t)	0.99	0.99	0	0.11	0.89	7E-15	0.110
	W L = -5.9705 + 11.849911 ln(t)	0.992	0.990	0	0.185	1.18	-5E-16	0.183
	WL = 18.634 $t^{0.22333}$	0.99	0.99	0	0.00	0.02	-1E-16	0.006

It is clear that for sugar gain, cubic model was found best fit for 40^{0}C-60 and 70^{0}B, 50^{0}C-50 , 60 and 70^{0}B and for 60^{0}C- 70^{0}B, whereas, quadratic model was found best for 40^{0}C- 50^{0}B, 60^{0}C- 50 and 60^{0}B temperature-concentration combinations based on regression diagnostic criteria

(Table 5). Several researchers modelled the mass transport data of water loss and sugar gain for various fruits and vegetables. [4] and [11] developed the mathematical models for water loss and sugar gain for papaya cubes and banana slices, respectively.

Table- 5 : Best fit models and regression diagnostic criteria for sugar gain during osmotic dehydration of aonla slices

Temp. (°C)	Prediction equation	R^2	Adj R^2	Prob	χ^2	RMSE	MBE	% Error Modulus
40	SG = 2.5016 + 0.0837 t - 0.0002 t^2	0.99	0.99	0	0.03	0.25	9E-16	0.0486
	SG = 1.496 + 0.193 t- 0.0011 t^2 + 0 t^3	0.99	0.97	0.00	0.16	0.64	-4E-16	0.1814
	SG = 1.175 + 0.243 t- 0.0016 t^2 + 0 t^3	0.99	0.99	4E-04	0.04	0.33	2E-15	0.0614
50	SG = 3.867 + 0.121 t- 0.0006 t^2 + 0 t^3	1.00	1.00	0	0.00	0.07	3E-15	0.0086
	SG = 3.991 + 0.163 t- 0.0009 t^2 + 0 t^3	0.97	0.94	0.008	0.24	0.86	-3E-15	0.0857
	SG = 3.88 + 0.208 t- 0.0012 t^2 + 0 t^3	0.99	0.99	6E-04	0.04	0.37	-2E-15	0.0629
60	SG = 9.0186 + 0.0249 t + 0 t^2	0.99	0.99	0	0.01	0.17	-1E-15	0.0114
	SG = 9.9546 + 0.0348 t + 0 t^2	0.98	0.97	6E-04	0.05	0.39	-2E-15	0.0743
	SG = 9.451 + 0.108 t- 0.0006 t^2 + 0 t^3	0.99	0.99	7E-04	0.01	0.26	-3E-16	0.0014

3. CONCLUSIONS

Aonla slices can be partially dewatered by osmotic dehydration in sugar solution. They can loose 15.65 to 62.28 % water and gain 3.69 to 18.14 % sugar depending upon the sugar syrup concentration (50-70^{0}Brix) and temperature (40-60^{0}C) in 4 h duration of osmosis. Water loss and sugar gain by aonla slices during osmotic dehydration in different sugar syrup concentrations and temperatures were modelled. Models will be useful to know the osmotic dehydration time in getting the desired level of sugar gain in aonla slices. These developed models could be used in food industry for design and control processes.

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