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Modelling of osmotic dehydration of kedondong fruit (*Spondias dulcis*) immersed in natural pineapple juice

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Abstract

Kedondong (*Spondias dulcis*) is a type of underutilized fruits in Malaysia which are rich in nutrients such as vitamin C, carotenoids and vitamin A. Osmotic dehydration is a type of preservation technique by transforming fruit in dehydrated form to avoid further deterioration. In this research, kedondong were dehydrated by immersing the fruit pieces in natural pineapple juice at 25 ℃, 50 ℃ and 70 ℃. Results showed that moisture loss and solute gain within the samples increased with temperatures due to increasing permeability of fruit membranes and reducing viscosity of the osmotic agent. Results from mathematical modelling showed that Page and Two-term models predicted well the dehydration kinetics within the temperature range 25 ℃ – 70 ℃. Effective moisture diffusivities were estimated in the order of magnitude 1.58×10^{-10}-1.84×10^{-10} m^2/s within temperature range of 25℃-70℃.

Keywords: Dehydration, Diffusion, *Spondias dulcis*, Modelling

1. Introduction

Osmotic dehydration is usually conducted by immersing food material pieces into high sugar or salt content solutions, causing transfers of water and solute to occur concurrently through layers of tissue membranes [1]. Generally conducted for the improvement of nutritional, sensorial and functional properties of the food product, osmotic dehydration has also received greater attention as an effective method for the preservation of fruits and vegetables [2,3]. In recent years, there is a demand towards high quality healthy food products whereby osmotic dehydration using salt or sucrose solutions are less preferred. Uptake of additional salts and sugars in food diet are detrimental to human health and could cause high blood pressure, increase blood glucose, obesity and etc. In Malaysia, Dans et al. [4] outlining Malaysian youths having the highest rates of diabetes at 11.6% which is one of the highest in the Southeast Asian region and there is also a worrying trend of prevalence of hypertension in adults from 32.9% to 43.5% (Year 1996 - 2011).

Kedondong fruit (*Spondias dulcis*) is native to Malaysia and this fruit is rich in nutrients such as vitamin C, carotenoids and vitamin A, as well as small amount of protein and minerals like phosphorus, calcium, magnesium, sodium and zinc [5]. Traditionally, this fruit is consumed fresh or as pickles and it can also be made into fruit juice. However, kedondong fruits are not widely consumed and utilized by locals due to its short shelf life after harvesting. Therefore, a suitable preservation technique is required to process the fruits to prevent quality deterioration.

As such, utilizations of natural fruit juices as osmotic agents have been studied by researchers such as Konopacka et al. [6] and Chambi et al. [7]. However, to our best knowledge, investigations on osmotic dehydration of kedondong fruits have not been reported in literatures. For the purpose of this study, pineapple juice was chosen based on preliminary studies carried out using selected natural fruit juices (pineapple, apple, orange and kedondong) and it was found that pineapple juice was able to dehydrate the kedondong fruit slices with the highest percentage reduction in moisture content [8]. The objectives of the studies are described as follow:

- To investigate the kinetics of osmotic dehydration of kedondong fruit samples in pineapple juice
- To model the dehydration kinetics using semi-theoretical models
- To determine the effective moisture diffusivities during osmotic dehydration

Nomenclature

a,b,g,k,n	constants in empirical models
D_e	effective moisture diffusivity, m^2/s
D_0	constant, m^2/s
E	activation energy, kJ
H	half-thickness of the sample, m
MC	moisture content, %
ML	moisture loss, %
MR	moisture ratio
MR_{pre}	predicted moisture ratio
MR_{exp}	experimental moisture ratio
M_t	moisture content after time t, g H_2O/g dry solid
M_e	moisture content at equilibrium, g H_2O/g dry solid
M_i	initial moisture content, g H_2O/g dry solid
M_0	weight of initial moisture, g
M	weight of final moisture, g
N	number of observations
R^2	coefficient of determination
R	gas constant, 8.314 J/mol/K
RMSE	root mean square error
SG	solute gain, %
S_0	weight of initial solute, g
S	weight of final solute, g
t	time, h
T	absolute temperature, K
W_t	weight of sample after time t, g
W_{bd}	weight of bone dried sample, g
W	weight of initial sample, g
χ^2	chi squared
z	number of constants

2. Materials and methods

2.1 Sample

Kedondong and pineapple fruits were purchased from local supermarkets in Semenyih, Selangor (Malaysia). Only the ripe fruits were used for the experiments. The fruits were washed with tape water and wiped dry prior to cutting. For the preparation of fruit samples, kedondong fruits were peeled using knife and cut manually into square samples with dimensions of 1.8 cm × 1.8 cm × 0.5 cm (1.6 ± 0.1 g). For juice preparation, the pineapples were manually peeled, sliced into sizable chunks and blended using a slow juicer (Panasonic, Japan). The juice (Brix = 13.8) once prepared was used immediately for the osmotic dehydration process.

2.2 Osmotic dehydration

The prepared fruit samples were initially weighed and placed into individual 10 mL sample tubes, followed by the pineapple juice with sample to osmotic agent ratio of 1:5 w/w. Osmotic dehydration was carried out at three different temperatures namely 25℃, 50℃ and 70℃. The sample tubes were capped with aluminum foil and placed in a water bath shaker (Memmert, Germany) during osmotic dehydration. Weight measurements were determined throughout the dehydration process for a 24-hour period by taking out the sample and determined using an analytical balance (Sartorius, Germany).

2.3 Moisture content and solid gain

Moisture content of the samples were determined using the oven method as recommended by AOAC [9]. Subsequently, the moisture content (MC), moisture loss (ML) and solute gain (SG) were calculated using the following equations [10].

$$MC\ (\%d.b.) = [(W_t - W_{bd})/W_{bd}] \times 100 \quad (1)$$

$$ML\ (\%) = [(M_0 - M)/W] \times 100 \quad (2)$$

$$SG\ (\%) = [(S - S_0)/W] \times 100 \quad (3)$$

2.4 Mathematical modelling

Five semi-theoretical models (Table 1) were selected and fitted to the experimental data. The models used are typically based on simplified general solutions of Fick's second law of diffusion and linking between the moisture ratios and drying time. The parameters a, b, g, k, and n were calculated via non-linear regression analysis using MS Excel Solver (Microsoft Office Ver. 2013, USA).

Table 1 Thin layer drying models.

Model	Equation	
Newton	$MR = exp(-kt)$	(4)
Henderson-Pabis	$MR = a \cdot exp(-kt)$	(5)
Page	$MR = exp(-kt^n)$	(6)
Logarithmic	$MR = a \cdot exp(-kt) + b$	(7)
Two-term Model	$MR = a \cdot exp(-kt) + b \cdot exp(-gt)$	(8)

Moisture ratio (MR) for kedondong samples during osmotic dehydration were calculated using equation 9.

$$MR = (M_t - M_e)/(M_i - M_e) \quad (9)$$

Three fitting criteria were used to evaluate the model with the best fitting to the experimental data namely Correlation of Determination (R^2), Chi-Squared (χ^2) and Root Mean Square Error (RMSE) in equation 10 – 12. The most suitable model to describe the osmotic dehydration kinetics would show the highest R^2 and the lowest χ^2 and RMSE values, respectively [11–13].

$$R^2 = 1 - \{[\sum_{i=1}^{N}\left(MR_{pre,t} - MR_{exp,t}\right)^2]/[\sum_{i=1}^{N}\left(\overline{MR}_{pre,t} - MR_{exp,t}\right)^2]\} \quad (10)$$

$$\chi^2 = [\sum_{i=1}^{N}\left(MR_{exp,t} - MR_{pre,t}\right)^2]/(N - z) \quad (11)$$

$$RMSE = \left[(\frac{1}{N})\sum_{i=1}^{N}(MR_{pre,t} - MR_{exp,t})^2\right]^{1/2} \quad (12)$$

2.5 Effective moisture diffusivity

Effective moisture diffusivity values (D_e) were determined using Fick's second law equation in slab geometry by assuming moisture migration by diffusion, no shrinkage, constant effective moisture diffusivity and constant temperature [14]. The following equation was used (equation 13).

$$MR = (\frac{8}{\pi^2})\sum_{n=0}^{\infty}(1/(2n+1)^2)\, exp[(-(2n+1)^2\pi^2 D_e t)/(4H^2)] \quad (13)$$

The above equation can be further simplified by including only the first term (equation 14) and by applying natural logarithm at both sides (equation 15).

$$MR = (\frac{8}{\pi^2})\, exp[-(\pi^2 D_e t)/(4H^2)] \quad (14)$$

$$ln\, MR = ln\left(\frac{8}{\pi^2}\right) - [(\pi^2 D_e t)/(4H^2)] \quad (15)$$

The effective moisture diffusivity was determined graphically by plotting ln MR (y-axis) versus drying time (x-axis), whereby the straight-line plot would produce a slope which can be used to determine the effective moisture diffusivity using equation 16.

$$Slope = -D_e[\pi^2/(4H^2)] \quad (16)$$

Finally, the effective moisture diffusivities estimated were related to drying temperature using an Arrhenius relationship as shown in equation 17 [15].

$$D_e = D_o exp^{-E/RT} \quad (17)$$

3. Results and discussion

3.1 Dehydration kinetics

The variation of moisture loss and solute gain during the osmotic dehydration process at different temperatures (25 ℃, 50 ℃, and 70 ℃) are shown in Figures 1 and 2, respectively. It could be observed that temperature plays a large influence towards the moisture loss and solute gain within the samples. In terms of moisture loss, an increase in temperature of the osmotic agent sequentially increased the moisture loss of the respective samples. The recorded final moisture loss at 25 ℃, 50 ℃, and 70 ℃ were 22.95%, 26.03% and 27.98%, respectively. Figure 1 also shows that the rapid rate of moisture loss within the first three hours of immersion, with gradual increased in moisture loss thereafter. This observation is in agreement with the osmotic dehydration studies reported by Moreira et al. [16], whereby the rate of water loss was initially high and gradually decreased as the system approached equilibrium condition.

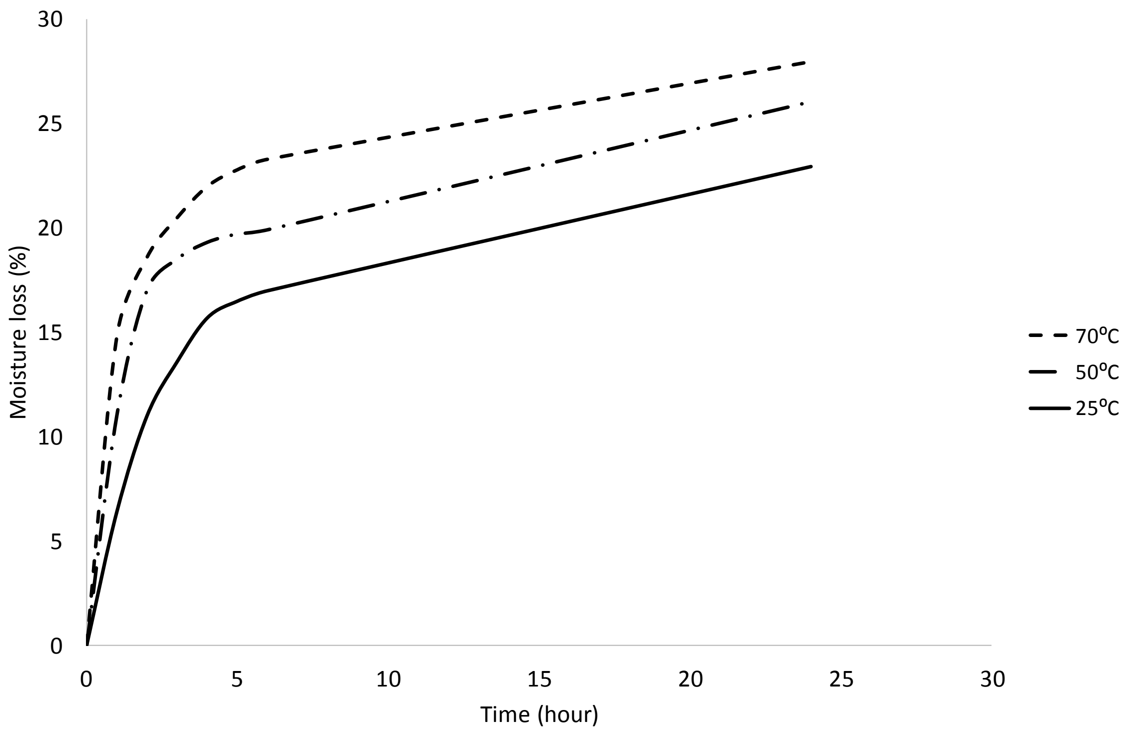

Figure 1 Variation of moisture loss against dehydration time.

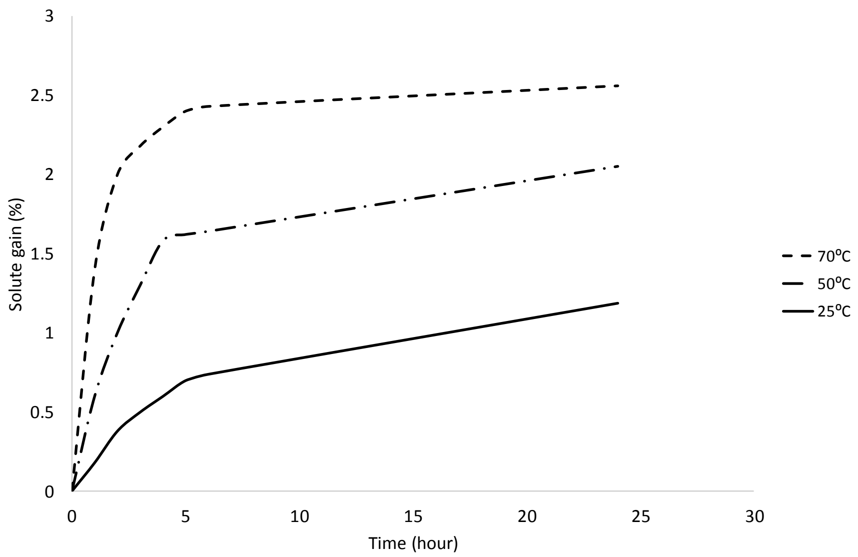

Figure 2 Variation of solute gain against dehydration time.

García-Toledo et al. [17] reported that high temperatures could cause swelling and plasticity of the sample's cellular membrane, increasing permeability and reducing the viscosity of the osmotic agent. This would in turn favour the transfer of moisture across the surface of the product and through its interior. Burhan Uddin et al. [2] also reported that the use of higher temperatures promotes better moisture transfer on the product surface, primarily due to lower viscosity of the osmotic medium.

The kinetics for solute gain behaved similarly to the kinetics of moisture loss, whereby an increase in temperature significantly increased the solute gain of the fruit sample (Figure 2). The greatest rate of solute gain was observed in the first 3 hours during osmotic dehydration, with final solute gain at 1.19 %, 2.05 %, and 2.56 %, respectively, for dehydration temperature of 25℃, 50℃, and 70℃.

3.2 Mathematical modelling

Figure 3 shows variation of moisture ratios with time for the osmotic dehydration experiments. The moisture ratios were fitted into semi-theoretical models and the accuracy of each model was evaluated based on their respective R^2, χ^2 and RMSE values. Table 2 shows the parameters and statistical results obtained from the regression analyses.

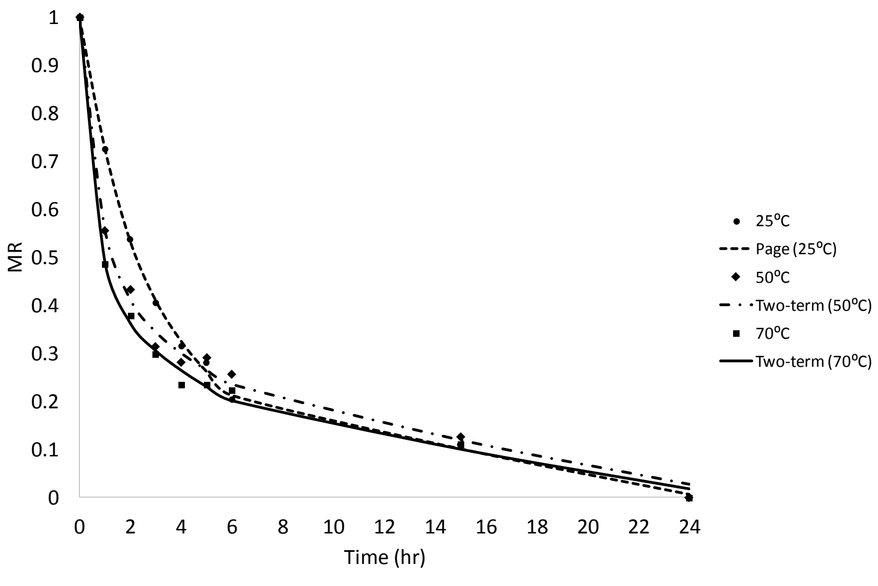

Figure 3 Prediction of experimental moisture ratio using semi-theoretical models.

It can be observed that Page model predicted well the dehydration process at 25 ℃ by having the highest R^2, lowest $\chi^2$and lowest RMSE values. However, the Two-term model was selected for dehydration process at 50 ℃ and 75℃ (Figure 3) based on similar criteria. Good prediction of the experimental data can be observed from the R^2 values determined at 0.9942 - 0.9986 in all the chosen models. Typically, mathematical model with multiple coefficients and constants are better in predicting the experimental data but care must be taken as this could increase the χ^2 value.

Table 2 Coefficients and constants of thin layer drying models.

Model	Coefficients and constants	R^2	χ^2	RMSE
(25℃)				
Newton	k=0.2863	0.9955	5.66×10^{-4}	2.22×10^{-2}
Henderson-Pabis	a=0.9789 k=0.2789	0.9953	5.62×10^{-4}	2.05×10^{-2}
Page	k=0.3361 n=0.8671	0.9986	1.67×10^{-4}	1.12×10^{-2}
Logarithmic	a=0.9661 b=0.0153 k=0.2883	0.9955	6.26×10^{-4}	1.98×10^{-2}
Two-term Model	a=0.4249 b=0.5774 g=0.1694 k=0.5773	0.9981	1.74×10^{-4}	9.32×10^{-2}
(50℃)				
Newton	k=0.3434	0.9291	8.57×10^{-3}	8.66×10^{-2}
Henderson-Pabis	k=0.3000	0.9226	8.07×10^{-3}	7.78×10^{-2}
Page	k=0.5866 n=0.5266	0.9901	1.02×10^{-3}	2.76×10^{-2}
Logarithmic	a=0.8342 b=0.1054 k=0.4249	0.9326	8.08×10^{-3}	7.11×10^{-2}
Two-term Model	a=0.4804 b=0.5195 g=1.3652 k=0.1186	0.9942	0.89×10^{-3}	2.12×10^{-2}
(70℃)				
Newton	*k=0.4075*	0.9231	9.66×10^{-3}	$9.20 \times 10\text{-}^{2}$
Henderson-Pabis	a=0.8980 k=0.3551	0.9136	9.34×10^{-3}	8.37×10^{-2}
Page	k=0.7031 n=0.4780	0.9944	0.58×10^{-3}	2.10×10^{-2}
Logarithmic	a=0.8247 b=0.1377 k=0.6216	0.9353	7.88×10^{-3}	7.02×10^{-2}
Two-Term Model	a=0.4550 b=0.5446 g=1.7576 k=0.1361	0.9967	0.51×10^{-3}	1.59×10^{-2}

3.3 Effective moisture diffusivity

Table 3 shows the effective moisture diffusivity values estimated from the Fick's second law equation. The values ($1.58\text{-}1.84 \times 10^{-10}$ m^2/s) are in the order of magnitude typically found in most fruit products [18]. The increased values of effective moisture diffusivities are in accordance with rising dehydration temperatures due to increase in vapour pressure inside the samples [19].

Table 3 Effective moisture diffusivities.

Temperature (℃)	Effective moisture diffusivity (m^2/s)
25	1.58×10^{-10}
50	1.60×10^{-10}
70	1.84×10^{-10}

Equation 18 shows the Arrhenius temperature dependency of effective moisture diffusivities (D_e) with dehydration temperatures. The activation energy (E) and pre-exponential factor (D_o) determined are 2.8 kJ/mol and 4.8×10^{-10} m^2/s, respectively. The activation energy is defined as the minimum energy barrier to initiate the diffusion process during dehydration. This equation can be used to estimate the effective moisture diffusivity within temperature range of 25℃-70℃ for osmotic dehydration process of kedondong.

$$D_e = 4.8 \times 10^{-10} exp^{-2.8/RT} \quad (18)$$

4. Conclusions

Results from the osmotic dehydration studies showed that temperature of the osmotic solutions increased the moisture losses and solute gain due to increasing permeability of the fruit membranes and reducing viscosity of the osmotic agent which in turn favour the mass transfer process between the fruit and the solution. Mathematical modelling showed that Page model was able to predict well the dehydration kinetics for 25℃, while the Two-term model was able to predict well for 50 ℃ and 70 ℃. Effective moisture diffusivities were estimated in the order of magnitude 1.58×10^{-10}- 1.84×10^{-10} m^2/s within temperature range of 25-70℃ with activation energy 2.8 kJ/mol.

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