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Osmotic dehydration kinetics of Terung Asam (*Solanum lasiocarpum* Dunal)

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Abstract

Osmotic dehydration kinetics of Terung Asam (*Solanum lasiocarpum* Dunal) under different process temperature (35-55^{o}C), sucrose concentration (40-60%) and immersion time (30-180 min) were studied. Results obtained indicated that water loss (WL) increased with sucrose concentration and temperature. Similarly, solid gain (SG) also increased with temperature elevation. The effective diffusivities calculated using Fick's model were in the range of 7.7678 x 10^{-10} to 11.6519 x 10^{-10} m^2s^{-1} for WL and 3.5462 x 10^{-10} to 8.1056 x 10^{-10} m^2s^{-1} for SG. Meanwhile, the activation energy for moisture diffusion varied from 4.900 to 7.423 $kJmol^{-1}$ and for solid diffusion from 10.440 to 14.323 $kJmol^{-1}$.

Introduction

With the increased consumer demand on healthy and natural food products, the exploration of food with great nutritional value, together with a mild processing technique that can minimize adverse modification on food quality is an intense field of research. Recently, a continuing consumer's interest in exotic food has opened the market for various native fruits and vegetables products. Among the numerous native fruits and vegetables, Terung Asam (*Solanum lasiocarpum* Dunal) has received great attention due to its high nutritional values and antioxidant properties (Voon and Kueh, 1999). Terung Asam is a popular native vegetable in Sarawak, East Malaysia and it has been granted a Geographical Indication certificate, characterized by a consistent high quality and good reputation. This vegetable is a favorite to the locals due to its distinctive sour taste (Shariah, 2013). The explorations of native plant species not only bring about the discovery of new sources of functional nutrients, but also broaden the diversity of human diet.

In recent years, osmotic dehydration (OD) has received great attention due to several advantages, for instance product quality improvement and energy efficiency (Konopacka et al., 2009). OD is a combination of dehydration and impregnation process (Torreggiani, 1993), whereby water is partially removed from a moisture rich material when it is immersed in a hypertonic aqueous solution. In oppose to most of the traditional drying methods which employ high temperature, OD can effectively remove moisture under mild or ambient temperature. In addition to reduce energy consumption, this low temperature water removal process also remarkably improves the nutritional and sensory properties of the food (Tortoe, 2010). Besides that, the dehydrated products could also have longer shelf life due to the low water content and low water activity.

OD is very much beneficial to a wide range of fruits and vegetables (Khin *et al*., 2006; Falade *et al*., 2007; Lee and Lim, 2011; Yadav *et al*., 2012). It is well recognized that both the rate of osmosis and the quality of dehydrated product are affected by several processing parameters such as the concentration of osmotic solution, process temperature, product to solution mass ratio, duration of osmotic process and the size of material (Derossi *et al*., 2011). Numerous studies have been carried out to understand the mass transfer during the OD of foods because it shows a paramount importance for a successful application of osmotic process. Among the numerous empirical models studied, Fick's law is the most important model for the determination of the mass transfer during the drying processes of food. Even though some of the assumptions of Fick's law are considered unrealistic, but numerous findings reported that Fick's law can

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well fit the experimental drying curves. Therefore, the use of Fick's law to study the dehydration kinetics of food under different operative conditions was appropriate (Derossi *et al*., 2011). Despite the various studies on OD of fruits and vegetables, to date, there has been no study on the OD of Terung Asam. Hence, this study would focus on investigating the effect of process variables on the kinetics of OD of Terung Asam.

Materials and Methods

Sample and solution preparation

The fresh Terung Asam and the commercial food grade sucrose were purchased from a local market. Terung Asam with a similar ripening degree (through visual inspection, where the color of fruit becomes fully orange) and size (average height of 8 ± 1 cm, diameter 8 ± 1 cm and weight 280 ± 10 g) were selected in order to maximize the uniformity of the raw material. The moisture content and the soluble solid content were in the range of 90 to 95% (wet basis) and 6 to 7°Brix respectively. The Terung Asam was cut into rectangular slabs (30 mm length x 10 mm width x 5 mm thick) and the osmotic solution was prepared into specific concentration by dissolving the sucrose in distilled water on a weight-to-weight basis.

Osmotic dehydration process

The Terung Asam slices were subjected to OD over a range of temperature (35, 45 and 55°C) and sucrose concentration (40, 50 and 60% w/w). The samples were fully immersed in the osmotic solution. The sample to solution ratio was fixed at 1:5 (w/w) based on the preliminary trial, with a constant agitation of 80 rpm to avoid localized dilution of sucrose solution. The desired temperature was achieved by holding the beakers in a temperature controlled shaking incubator (Thermo Electron Corporation, USA). The samples were taken from the osmotic solution after 30, 60, 90, 120, 150 and 180 min of immersion. These samples were rinsed quickly with distilled water to remove adhering sugar, blotted gently with an absorbent paper and weighed (Lee and Lim, 2011). The moisture content of the samples was determined gravimetrically by drying the sample in an oven for 24 hours at 105°C following the AOAC method 934.01 (AOAC, 2000). All experiments were carried out triplicate and the average value was taken for analysis.

Determination of water loss and solid gain

The water loss (WL) and solid gain (SG) were determined based on the following equations (Eren and Kaymak-Ertekin, 2007):

$$WL\ (\%) = \frac{m_i z_i - m_f z_f}{m_i} \times 100 \qquad (1)$$

$$SG\ (\%) = \frac{m_f s_f - m_i s_i}{m_i} \times 100 \qquad (2)$$

where, m_i and m_f are the initial and final weight of sample (g) respectively, z_i and z_f are the initial and final mass fraction of water (g water/g sample) and s_i and s_f are the initial and final mass fraction of total solids respectively (g total solids/g sample).

Determination of water and solid diffusivities

The diffusion coefficient of water *(D_{ew})* and solute *(D_{es})* were estimated based on the solution of Fick's second law. Different analytical solutions of Fick's second law have been given by Crank (1975). The analytical solution of Fick's equation for slab geometry is expressed as:

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2} \times \exp\left[(2n+1)^2\frac{\pi^2 D_{ew} t}{4L^2}\right] \quad (3)$$

While for solute gain

$$SR = \frac{S_t - S_e}{S_0 - S_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2} \times exp\left[(2n+1)^2\frac{\pi^2 D_{es} t}{4L^2}\right] \quad (4)$$

where MR and SR are the moisture ratio and solid ratio respectively, D_{ew} and D_{es} are the effective moisture and solute diffusivities ($m^2 s^{-1}$) respectively, t is time (s), L is slab thickness (m), M_t is moisture of sample after time t, M_0 is moisture of sample prior to OD (g water/g dry solid), M_e is moisture of sample at equilibrium (g water/g dry solid), s_t is solid content of sample after time t, s_0 is solid content of sample prior to OD and s_e is solid content of sample at equilibrium (g).

For long dehydration time, the solution (Eq. 3) is simplified to the first term:

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\exp\left(-\frac{D_{ew}\pi^2 t}{4L^2}\right) \quad (5)$$

Eq. (5) can be represented in a linear form according to Eq. (6):

$$\ln MR = \ln\left(\frac{8}{\pi^2}\right) - D_e\left(\frac{\pi}{2L}\right)^2 t \qquad (6)$$

The water diffusivity can be determined by plotting ln MR versus time (Brennan, 1994). Similarly, solid diffusivity can be determined by plotting ln SR versus time.

Determination of activation energy

Activation energy is determined by fitting Dew and D_{es} to the Arrhenius type equation:

(7)

where D_{eff} is effective diffusivity (m^2s^{-1}), D_0 is constant diffusivity of the Arrhenius equation (m^2s^{-1}), Ea is activation energy ($Jmol^{-1}$), T is temperature (K) and R is universal gas constant (8.3143 $JK^{-1}mol^{-1}$). A straight line with slope ($-E_a/R$) can be obtained by plotting ln D_{eff} against 1/T. The activation energy can be determined from the slope.

Statistical analysis

Data obtained were analyzed by one way analysis of variance (ANOVA) using IBM SPSS Statistics Version 23 software. Post hoc analysis was performed using Tukey test at $p < 0.05$.

Results and Discussion

Water loss and solid gain

Results obtained revealed that the water loss (WL) increased rapidly during the first hour of osmosis followed by a slower rate close to the end of the process. The large osmotic driving force between the dilute sap of Terung Asam slices and the surrounding hypertonic solution promoted the rapid removal of water from the Terung Asam into the osmotic medium during the initial phase of the osmotic process. Conversely, the reduction of osmotic driving potential and compaction of the surface cell layer of Terung Asam had resulted in a slower mass transfer rate at the later stage of the process. Figure 1 demonstrates that the increase of sucrose concentration promoted the water removal due to the increased osmotic driving force. This result corroborates the findings of Haj Najafi *et al.* (2014) for the OD of red pitaya. Furthermore, temperature elevation also promoted the WL of Terung Asam slices (Figure 2). The enhanced WL under elevated temperature was due to the increased rate of diffusion and reduction of solution viscosity which improved the water transfer characteristics on the product surface. On the other hand, improved membrane permeability under high temperature also facilitated the water removal from Terung Asam slices into the sucrose solution. A similar observation was reported for the OD of watermelon (Falade *et al*., 2007) and cucumber (Dermesonlouoglou *et al.*, 2008).

Similar to the WL, solid gain (SG) also showed an increasing trend at the beginning of the osmotic process, then gradually slowed down towards the end of the process due to the reduction of osmotic driving potential. On the other hand, the formation of high solids subsurface layers due to the massive uptake of solute at the initial stage of osmosis also resulted in low succeeding water and solute transfer rates (Dermesonlouoglou *et al.*, 2008). Unlike the previously reported findings on pomegranate arils (Mundada *et al.*, 2011) and red pitaya (Haj Najafi *et*

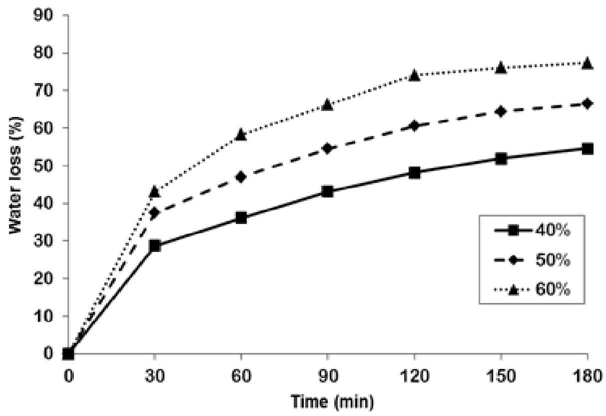

Figure 1. Water loss of Terung Asam at different solution concentrations at 55°C

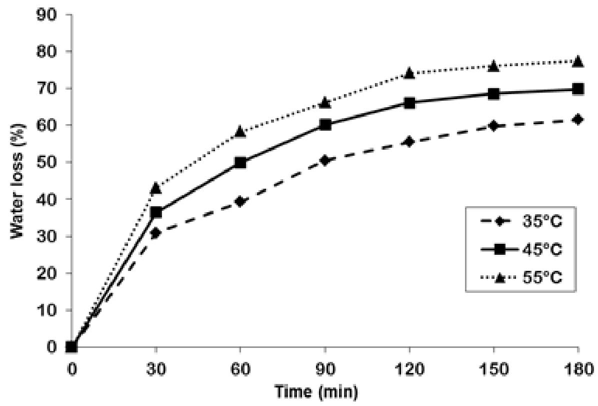

Figure 2. Water loss of Terung Asam under different temperatures at 60% sucrose

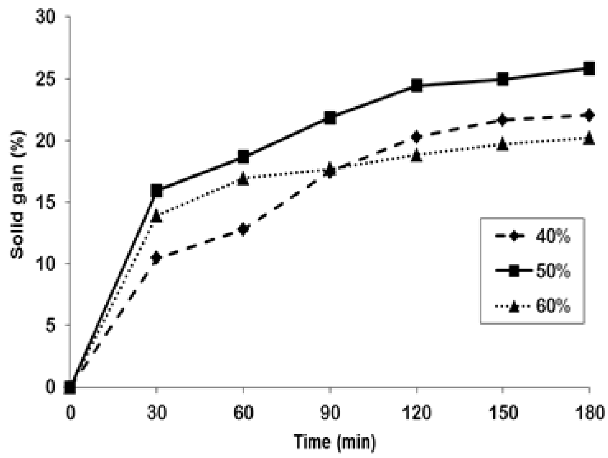

Figure 3. Solid gain of Terung Asam at different solution concentrations at 55°C

Table 1. Water and solute diffusivity at different processing conditions

Conditions		Water Diffusivity ($\times 10^{-10}$) (m^2s^{-1})	Solid Diffusivity ($\times 10^{-10}$) (m^2s^{-1})
35°C	40%	7.7678 ± 0.14 [a]	3.5462 ± 0.00 [a]
	50%	9.4566 ± 0.14 [c]	4.5594 ± 0.00 [ab]
	60%	10.1321 ± 0.00 [d]	5.5714 ± 0.14 [bc]
45°C	40%	8.6967 ± 0.15 [b]	4.5550 ± 0.43 [ab]
	50%	9.8788 ± 0.00 [d]	5.7414 ± 0.29 [bc]
	60%	11.3986 ± 0.00 [f]	7.1768 ± 0.29 [de]
55°C	40%	9.2877 ± 0.15 [c]	4.5594 ± 0.00 [ab]
	50%	10.6387 ± 0.00 [e]	6.2480 ± 0.15 [cd]
	60%	11.6519 ± 0.00 [f]	8.1056 ± 1.16 [e]

Mean value with identical alphabet within the same column indicates insignificant difference ($p > 0.05$)

al., 2014), this study found that increase of solution concentration might not always enhance the SG during OD. As shown in Figure 3, samples treated with 50% sucrose exhibited the highest solute uptake, while those treated with 60% sucrose recorded the lowest value. The declined of SG at high concentration was explained by Giraldo *et al.* (2003) as case-hardening effect, where an extensive dehydration on the surface cells caused tissue shrinkage which subsequently reduced the transport properties. It is obvious that during the first hour of immersion, samples treated with 60% sucrose showed a higher SG as compared to those treated with 40% sucrose and this could be attributed to the higher initial driving force for the 60% sucrose solution. A similar trend was observed for samples treated at 35 and 45°C. In agreement with Lee *et al*. (2013), the SG increased significantly when the process temperature rose from 35 to 55°C. As mentioned on WL section, temperature elevation might increase the rate of diffusion, hence accelerated the solute uptake. Additionally, the membrane swelling and plasticizing effect also increased the membrane permeability to sucrose molecules, resulted in higher diffusion of sucrose into the Terung Asam slices.

Water and solute diffusivity

The water diffusivities obtained in this study varied from 7.7678 x 10^{-10} to 11.6519 x 10^{-10} m^2s^{-1} and the solute diffusivities from 3.5462 x 10^{-10} to 8.1056 x 10^{-10} m^2s^{-1} (Table 1). These values were in the range of the values (10^{-12} to 10^{-8} m^2s^{-1}) reported by Mendoza and Schmalko (2002) for the OD of papaya. Meanwhile, the reported diffusion coefficients for apricots dehydrated in sucrose solution were in the range of 6.08 x 10^{-10} to 4.06 x 10^{-9} m^2s^{-1} (Khoyi and Hesari, 2007) and cherry tomato from 4.40 x 10^{-10} to 1.77 x 10^{-9} m^2s^{-1} in the combination of sucrose-salt solution (Azoubel and Murr, 2004).

Table 2. Activation energy for water and solid diffusivity

Sucrose concentration (% w/w)	Activation energy ($kJmol^{-1}$)	
	Water diffusivity	Solid diffusivity
40	7.423 ± 1.25 [b]	10.440 ± 0.00 [a]
50	4.900 ± 0.64 [a]	13.076 ± 0.96 [b]
60	5.810 ± 0.00 [ab]	14.323 ± 0.57 [b]

Mean value with identical alphabet within the same column indicates insignificant difference ($p > 0.05$)

In this study, the highest water diffusivity was observed when OD was carried out using 60% sucrose at 55°C ($p<0.05$). However, similar water diffusivity could also be obtained at 45°C with the same sucrose concentration ($p>0.05$). In compliance with the trend reported in a wide range of fruits and vegetables, the effective water diffusivity was generally increased along with the increase of process temperature. High temperature enhanced moisture diffusion within the product and improved the water transfer characteristic on the surface of Terung Asam slices by lowering the osmotic solution viscosity. The water diffusivity was found to increase significantly ($p<0.05$) when the sucrose concentration increased from 40 to 60%, due to the elevated osmotic pressure gradient. Abraao *et al.* (2013) reported similar results for their studies on pumpkin.

Similar to water diffusivity, OD treatments carried out with 60% sucrose concentration at both 45°C and 55°C (Table 1) resulted in the highest solute diffusivity ($p<0.05$). Increase of sucrose concentration from 40 to 60% would increase the solute diffusivity at 55°C, however, this trend was not observed at 35°C and 45°C. Moreover, this study also discovered that increase of temperature did not increase the solute diffusivity in 40% sucrose ($p>0.05$), but a significant increase was observed in 60% sucrose ($p<0.05$). Results obtained indicate that appropriate combination of sucrose concentration and process temperature is essential to achieve efficient diffusivity during OD process.

Activation energy

The activation energy values obtained in this study ranged from 4.900 to 14.323 $kJmol^{-1}$ (Table 2), which were lower than the values (38.9 to 41.7 $kJmol^{-1}$) reported by Abraao *et al.* (2013) during the OD of pumpkin. These differences may most probably attribute to the small sample size employed in this study. Falade *et al*. (2007) also reported that the activation energy for water removal and solute uptake of watermelon reduced along with the reduction in slab thickness. As shown in Table 2, increase of sucrose concentration reduced the activation energy for water diffusivity ($p<0.05$), however no significant difference was found between 50 and 60% sucrose ($p>0.05$). High sucrose concentration led to low energy consumption due to the high osmotic driving force.

This work demonstrated that the activation energy for solute diffusivity during OD treatment with 50% and 60% sucrose were higher than 40% ($p<0.05$). On the other hand, it was evident that solute diffusion consumed higher energy as compared to water diffusion. This may most probably attribute to the difference between the molecular weight of water and sucrose. Water with low molecular weight could diffuse more easily as compared to the larger sucrose molecule (Lazarides *et al.*, 1997), hence solute uptake consumed more energy than water removal.

Conclusion

Results obtained showed that the process temperature, sucrose concentration and immersion time significantly affected the kinetics of mass transfer during the OD of Terung Asam. A combination of high temperature and high sucrose concentration enhanced the water removal, but did not promote the solute uptake. Increase of sucrose concentration facilitated the water diffusivity by reducing the activation energy, while increasing the activation energy for solute diffusivity ($p<0.05$). The activation energy for solute diffusion was higher than water diffusion due to the high molecular weight of sucrose.

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