The Influence of Blanching on Mass Transfer Characteristics during Osmotic Dehydration of Bilimbi Fruit

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ABSTRACT

The effect of preprocessing like blanching was studied in comparison to non-blanching treatment to obtain mass transfer characteristics during osmotic dehydration of bilimbi fruit in sucrose solution system. Half-ripe bilimbi fruits were selected for investigation. The raw materials were separated into two groups: blanched and unblanched ones. Blanching treatment was carried out in boling water for 1 min. The two groups were then immersed in 70 °brix sucrose solution at ambient temperature (30± 3 °C) for 3000 min without stirring. The ratio of raw materials to solution was 2:1. pH was initially adjusted to 3.5. Samples for both solid and liquid phase were taken at different period in order to determine water loss, solid gain, acid loss, corresponding diffusivities, as well as shrinkage. It was found that blanching in boiling water for 1 min not only led to higher rate of water loss, soluble solid gain, and acid loss but also higher rate of shrinkage of the raw materials in comparison to those of non-blanching treatment. Apparent diffusivities for water, soluble solid and acid were found higher for the blanched materials. It was summarized that preprocessing like blanching should be carried out before the dehydration process in order to soften the fruit texture for better diffusion, nevertheless fruit shrinkage or volume reduction should be improved.

Keywords: Averrhoa bilimbi, bilimbi fruit, blanching, osmotic dehydration, mass transfer, shrinkage, volume reduction, diffusivity

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INTRODUCTION

Averrhoa bilimbi, commonly known as bilimbi, cucumber tree or tree sorrel, is native to tropical Asia (Bilimibi-Wikipedia, the free encyclopedia, 2006; Bilimbi-*Averrho bilimbi* a.k.a. Cucumber tree, 2006). The plant originated seemingly from the Moluccas, Indonesia, however it is commonly found in Southeast Asian countries (Bilimbi-*Averrho bilimbi*, 2006). Bilimbi fruit has been widely used in traditional medicine for treatment of scurvy, bilious cold, whooping cough, hypertension (Goh *et al*., 1995; Abas *et al*., 2006) and treatment of stomachache (Tan *et al*., 2005). The fruit's form ranges from ellipsoid to almost cylindrical while its length is 4-10 cm (Bilimbi-definition, 2006).

Bilimbi fruit is generally regarded as too acid for eating raw (Alves *et al*., 2005; Pino *et al*., 2004), however, ripe fruit are frequently added to curries (Bilimbi-*Averrho bilimbi*, 2006). In Malaya, it is boiled with much sugar to make a jam or acid jelly. Half-ripe fruits are salted, set out in the sun, and pickled in brine and can be thus kept for 3 months (Bilimbi-*Averrho bilimbi*, 2006).

The fruits are found highly perishable and should be processed quickly after harvested. In the traditional method, osmotic dehydration is the selected way for preservation (Bilimbi-definition, 2006). However, for industrial processing, mass transfer kinetics and process characteristics have not been reported and there is no report on the properties of the fruits related to this kind of unit operation.

Osmotic dehydration is a process of removing water using hypertonic solutions. The fruit is stabilized by lowering water activity, a_w . The solution can contain one or more solutes. It is common to use sugar as the solute. During the processing, the cell membrane works as a semi-permeable tissue and allows water to pass through faster than solutes (Alves *et al*., 2005; Pino *et al*., 2004; Raoult-Wack, 1994). Rate of mass transfer depends on a number of parameters such as temperature, concentration and composition of osmotic solution, contact time, ratio of osmotic solution to food materials, pretreatment (i.e. blanching, chemicals soaking), nature of food and its geometry (i.e. size, shape, cell structure, heterogeneity, exposed surface area), level of agitation and vacuum condition (Kaymark-Ertekin and Sultanoglu, 2000; Mavroudis *et al*., 1998).

Osmotic dehydration is used as a pretreatment of many processes to improve nutritional, sensorial and functional properties of food without changing its integrity. The method was reported to be effective even at ambient temperature, so heat damage to texture, colour and flavour of food are minimized (Sutar and Gupta, 2007). Focusing on some preprocessing like blanching, it was found that temperature of hot water was in the range of 70-100 °C with a specified time of each food before suddenly cooling. Blanching not only inactivates enzymes to prevent undesirable changes in sensory characteristics and nutritional properties but also soften vegetable tissues to remove air from intercellular spaces and permit better diffusion of soluble components (Fellows, 1990). In addition, to prevent volume reduction (shrinkage) during the dehydration process, gradual increase of concentration of immersing solution can be applied (Yuthachit, 1999; Siriwatanayothin, 1988)

To obtain diffusion properties, which were scarcely reported, this research aims to investigate and compare the effect of blanching and non-blanching on mass transfer mechanism during osmotic dehydration of bilimbi fruit at ambient temperature without stirring.

MATERIALS AND METHODS

Sample selection and preparation

Half-ripe bilimbi fruits, green in color, were obtained from local market in Nakon Si Thammarat, Southern Thailand. The average length of raw materials was selected to be 5$\pm$1 cm and the weight of each fruit was in the range of 7 – 14 g. The fruits were cleaned in water, left dry at room temperature and further kept at 4 $^{\circ}$C with relative humidity (RH) of 60 % until used.

Establishment of some characteristics of raw materials

Density of bilimbi fruits was measured by specific gravity method using 25-ml Pyrex glass picnometer. Initial moisture content was determined by vacuum oven, at 60 $^{\circ}$C for 24 h. The color in Hunter system of fresh fruit was examined by colorflex instrument model JP 7100 F, Hunterlab. Firmness of the fruit was measured by a Texture analyzer model TA-TX 2i, Stable Microsystem, by using cylinder probe with v-shape head punched into the center of the fruit for a penetration distance of 5 mm. The velocity of the probe was 1.5 mm/s and the compression force of load cell was 50 N. Total acidity analysis as citric acid was carried out by AOAC Method (AOAC, 1990) while total soluble solid was determined by refractometry method using hand-held Refractometer, MISCO. Thirty samples of fruit were used in this experiment.

Investigation of blanching and non-blanching effect on osmotic dehydration mechanism of bilimbi fruits

Bilimbi fruits were soaked in solution containing 0.1 % w/v sodium metabisulfite and 0.7 % w/v calcium chloride for 6 h in order to inhibit browning reaction and preserve their firmness. The fruits were then separated into two groups; the first group was blanched in boiling water (100 $^{\circ}$C) for 1 min to soften fruit tissues and suddenly cooled in 4 $^{\circ}$C water . The other was not blanched. Both were further treated similarly in the following manner: Immersing in sucrose solution with an initial concentration of 70 $^{\circ}$Brix for 3000 min (50 h) at ambient temperature (30$\pm$3 $^{\circ}$C) without stirring. The initial ratio of osmotic solution to raw materials was 2:1 w/w and the initial pH of solution was adjusted to 3.5 with citric acid. Samples were taken for every 60 min for the first 300 min of immersion period and then for every 300 min later until reaching total time of 3000 min. At the end of operation, the concentration difference of solutes in syrup (the extract phase) and in solid phase was negligibly small.

The total weight of raw materials for each batch was 40 kg and each sampling weight was 30-40 g. Total sampling was 450-600 g. For each sample, both solid and liquid phases were measured for their weight and concentration. The solid samples were also determined for the dimension, moisture content and acid content in order to evaluate % water loss, % soluble solid (mainly sugar) gain, % acid loss, rate of mass transfer of each component, including shrinkage of fruit and diffusivity concerned. Shrinkage during operation was determined by observing volume change of raw materials using picnometer and water replacement method (Mavroudis *et al.*, 1998). Data were subjected to analysis of variance (ANOVA) and means were compared using Duncan's new multiple range test (DMRT). Software package SPSS 9.0 for Windows was used.

Evaluation of osmotic dehydration kinetics

Water loss ($WL\ (\%)$), soluble solid gain ($SG\ (\%)$) is calculated according to Eq. (1) and (2), respectively (Kaymak-Ertkin and Cakaloz, 1996); while acid loss ($AL\ (\%)$) is calculated by Eq. (3) (Yuthachit, 1999; Kaymak-Ertkin and Cakaloz, 1996)

$$WL\ (\%) = \frac{(W_0 \times M_0) - (W_t \times M_t)}{W_0} \times 100 \qquad (1)$$

where W_0, W_t = weight of bilimbi fruit at initial and any time t (g)

M_0, M_t = moisture content of bilimbi fruit at initial and any time t (fraction in wet basis)

$$SG\ (\%) = \frac{(W_t \times B_t) - (W_0 \times B_0)}{W_0} \times 100 \qquad (2)$$

where B_0, B_t = concentration fraction of soluble solid in bilimbi fruit at initial and any time t (°Brix, fraction in wet basis)

$$AL\ (\%) = \frac{(W_0 \times A_0) - (W_t \times A_t)}{W_0} \times 100 \qquad (3)$$

where A_0, A_t = concentration fraction of acid in bilimbi fruit at initial and any time t (fraction in g/100 g of sample)

To describe rate of mass transfer by diffusion for each component, mathematical model for ellipsoid developed by Siripatana (1997) is used as follow:

Diffusion equation of mass transfer:- For water;

$$E_w = 1 - \left(\frac{WL_t}{WL_\infty}\right) = C_1 \exp\left(-\frac{Sh}{2}\frac{(\gamma+1}{\gamma}\nu\frac{D_w t}{a^2}\right) \qquad (4)$$

For soluble solid;

$$E_s = 1 - \left(\frac{SG_t}{SG_\infty}\right) = C_1 \exp\left(-\frac{Sh}{2}\frac{(\gamma+1}{\gamma}\nu\frac{D_s t}{a^2}\right) \qquad (5)$$

For acid;

$$E_a = 1 - \left(\frac{AL_t}{AL_\infty}\right) = C_1 \exp\left(-\frac{Sh}{2}\frac{(\gamma+1}{\gamma}\nu\frac{D_a t}{a^2}\right) \qquad (6)$$

Hence, general form is shown below.

$$E = C_1 \exp\left(-\frac{Sh}{2}\frac{(\gamma+1}{\gamma}\nu\frac{Dt}{a^2}\right) \qquad (7)$$

Then diffusion rate of mass transfer for each component can be described in general form as;

$$\frac{d(1-E)}{dt} = C_1\left(-\frac{Sh}{2}\frac{(\gamma+1}{\gamma}\nu\frac{Dt}{a^2}\right) \qquad (8)$$

Where $E = E_w, E_s, E_a$ = dimensionless parameter for water, solid, and acid according to Equation (4), (5), and (6), respectively

WL_t, WL_∞ = water quantity diffused from solid phase at any time t and at infinite (value in percentage)

SG_t, SG_∞ = soluble solid quantity infused to solid phase at any time t and at infinite (value in percentage)

AL_t, AL_∞ = acid quantity diffused from solid phase at any time t and at infinite (value in percentage)

D_w, D_s, D_a = diffusivity of water, soluble solid and acid (m^2/s)

t = contact time (s)

C_1 = parameter depending on initial condition of solute concentration distribution in solid phase

Sh = Sherwood number

γ = equilibrium extraction factor

ν = shape factor of solid

a = characteristic length (m)

Equation (4), (5) and (6) can be rewritten in a form as follow:

$$\frac{WL_t}{WL_\infty} \text{ or } \frac{SG_t}{SG_\infty} \text{ or } \frac{AL_t}{AL_\infty} = 1 - C_1 \exp(-Bt) \quad (9)$$

$$B = \left(-\frac{Sh}{2}\frac{\gamma+1}{\gamma}\nu\frac{D}{a^2}\right) \quad (10)$$

where $WL_t/WL_\infty, SG_t/SG_\infty$ and AL_t/AL_∞ is fraction loss of water, fraction gain of soluble solid (mainly sugar) and fraction loss of acid, respectively.

Effective diffusivity evaluation

Diffusivities of each component were calculated from diffusion rate equation (equation (8)), proposed by Siripatana (1997), which was derived based on Fick's second law of solution. Once slope of the graph between $d(1-E)/dt$ and t was determined; diffusivity was thus shown by following relation:-

$$D = -(slope)\frac{2}{Sh}\frac{\gamma}{(\gamma+1)}\frac{a^2}{\nu} \quad (11)$$

Sherwood number was calculated by similar approached used by Luikov (1969), thus the generalized following equation can be applied for all geometries (Siripatana, 1997).

$$Sh = 2g(\alpha,\eta,Bi)\left[u(\alpha,\eta) - \frac{\nu(\alpha,\eta)}{\alpha} + \frac{w(\alpha,\eta)}{\alpha^2}\right] \quad (12)$$

where $u(\alpha,\eta) = 2.460 + 0.3770\eta$

$\nu(\alpha,\eta) = 0.4015 + 0.248\eta$

$w(\alpha,\eta) = 0.0270 + 0.03531\eta$

And $g(\alpha, Bi) = \left(\dfrac{1}{1+\dfrac{p}{Bi^k}}\right)$

where

$$p = 2.293 - \frac{0.4036}{\alpha} + \left(0.2409 - \frac{0.1237}{\alpha}\right)\eta$$

$$k = 1.069 + 0.0404\eta$$

$$\eta = \nu - 1$$

Here, draft of extraction (α) is γ (equilibrium extraction factor) in batch system. Equation (12) has maximum error of 10% for Biot number (Bi) > 1 and $\alpha > 0.3$, although usually the errors are within 5% for most cases. Nevertheless, For $Bi < 1$ and $\alpha > 0.3$, the following simpler relation is recommended (Siripatana, 1997).

$$Sh = 2(2.0591 + 0.41309\nu)\left(1 + \frac{2.0011 + 0.3215\nu}{Bi^{(1.0177+0.02762\nu)}}\right)^{-1} \quad (13)$$

Shape factor (ν) is 1 for slab, 2 for long cylinder, and 3 for sphere. Equation (12) and (13) can also be used for anomalous shape.

RESULTS AND DISCUSSION

Some characteristics of raw materials: Bilimbi fruits

Half-ripe bilimbli fruits which are in appropriate harvesting period for osmotic dehydration were selected for the investigation. Corresponding properties are shown below in Table 1.

Table 1 *Some physical and chemical properties of bilimbli fruits (Averrhoa bilimbi)*

Compositions	$\overline{X} \pm SD$
Moisture content (% wet basis)	86.95±0.91
Total acidity as citric acid (%w/w)*	1.53±0.92
Soluble solid (^{o}Bx)	5.80±0.57
Hardness (N)	7.72±1.48
Density (kg/m^3)	992.50±0.63
Color value:	
L	49.75±1.12
a	-3.18±0.32
b	27.63±1.36

*value calculated on the basis of g of acid per 100 g of raw materials.

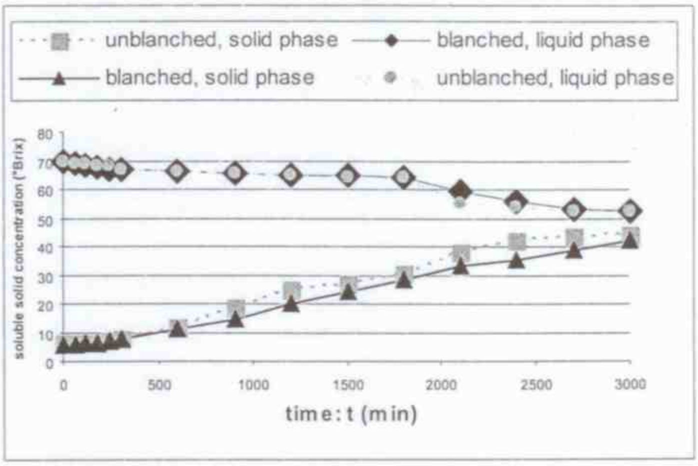
The effect of blanching on osmotic dehydration mechanism of bilimbi fruits Characteristics of soluble solid concentration between blanched and unblanched fruits immersing in 70 ^{o}Brix solution

Soluble matters (mainly sucrose) in solid and liquid phase of the blanched and unblanched materials were shown in Fig. 1 (a). It was found that the solid concentration in solid phase of the blanched materials were lower than those of the unblanched, corresponding to what obtained in liquid phase where the values were higher ($p<0.05$). Concentration differences between solid and liquid phase of the unblanched materials were obviously higher than those of the blanched, and at the immersion time of 3,000 min, they were less than 10% (Figure 1b). This information can be used to specify the time when the dehydration process should be ended.

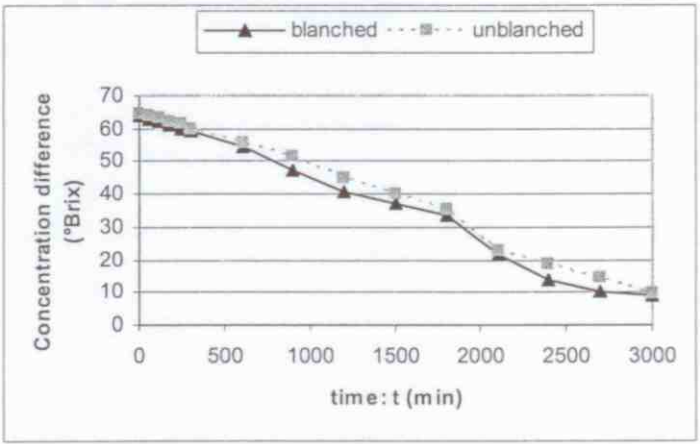
Mass transfer characteristics between blanched and unblanched fruits

Water loss of blanched materials were higher than that of unblanched ones until the immersion time closed to 3,000 min, where there was no difference between the two groups (Figure 2a). Rates of water loss (g of water remained at time t per g of equilibrium water at infinite time per min) for blanched materials were also found higher. The highest value (2.5×10^{-3} g/g.min) obtained at immersion time of about 270 min for blanched samples (Figure 3a), which marked the time where cell plasmolysis completely took place. The similar curve of water loss rate is also found in other work for apricot fruits (Khoyi and Hesari, 2007).

Considering soluble solids, the blanched materials contained less amount of sugar components than that of the unblanched ones (Figure 2b), the unexpected results. We suggested that this may be due to the higher shrinkage of the fruits (Figure 4a), which causes higher internal stress and thus occludes the sugar molecules.Nevertheless, the rate of sugar gain was found slightly higher for the blanched materials (Figure 3b) and reached the highest value (1.1×10^{-3} g/g.min) at the immersion time of about 750 min. The results also shown that, to attain the highest rate of sugar gain, the processing time was longer in comparison to that of water loss (Figure 3a compared with 3b). The reason is that molecular weight of sucrose is much higher than that of water (Rodrigues et al., 2003; Rastogi and Raghavaroa, 2004).



(a)



(b)

Figure 1 *(a) Characteristics of total soluble solid concentration (mainly sugar with small amount of acid) between blanched and unblanched bilimbi fruits which were immersing in 70 °Brix sucrose solution (b) Concentration difference between two phase.*

Another point should be mentioned for **Figure 3b**, rate of soluble solid (sugar) gain for some points since 1950 min of immersion time were found negative. This phenomena could possibly take place. The reason is that:- although solid concentration (°Brix) still increased up on time, the weight of sampling materials substantially reduced due to a lot of water loss. In other words, rate of soluble solid gain was calculated based on equation (2), (5) and finally (8). Each point for calculation (see equation (2)) came from the product between solute concentration and weight of raw materials. This leads to a conclusion that shrinkage effect (high water loss) dominate concentration effect (high solid gain) (also see **Fig. 4a** and **4b**)

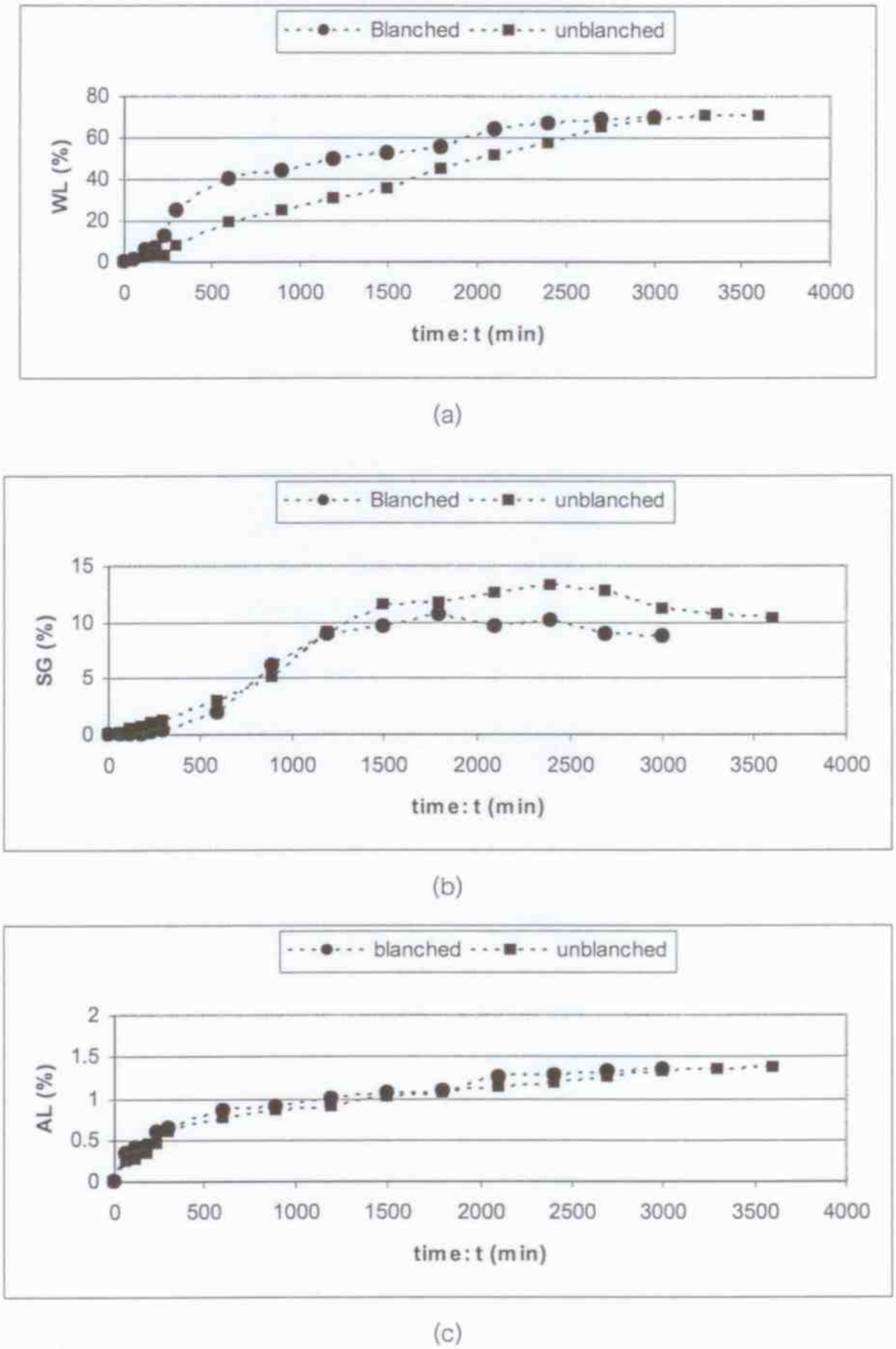
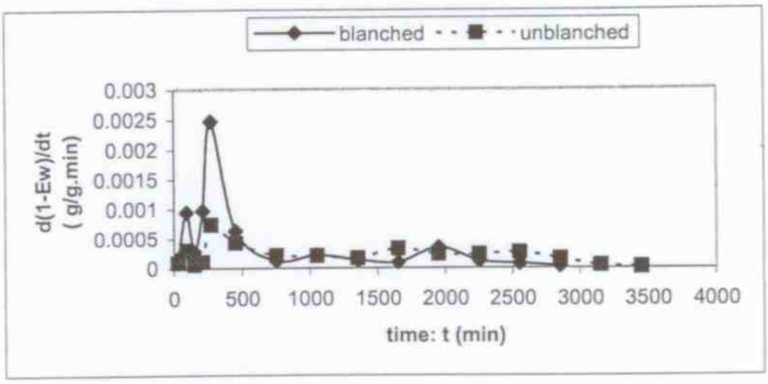
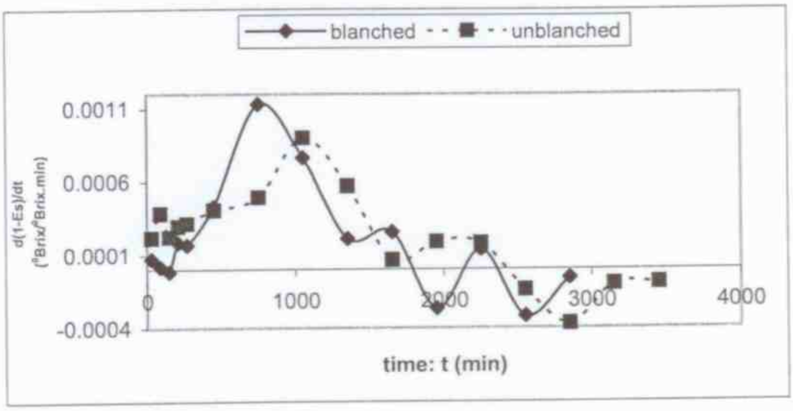


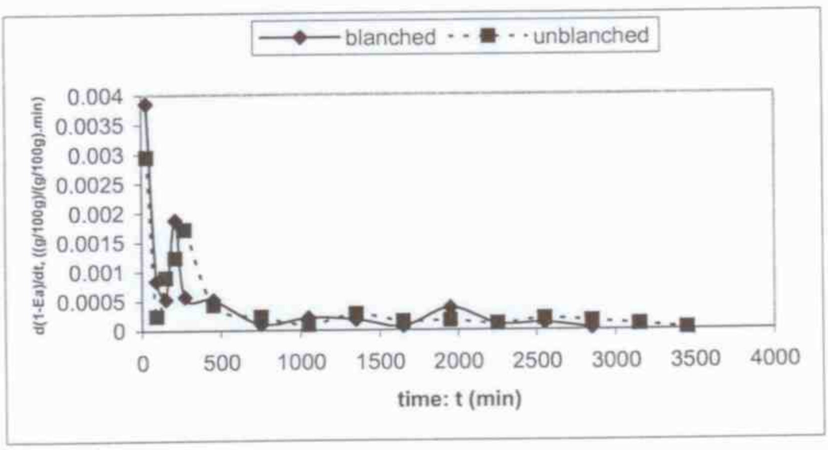
Figure 2 *(a) Water loss (WL (%)) , (b) Soluble solid gain (SG (%)), and (c) Acid loss (AL (%)) during osmotic dehydration in 70 °Brix sucrose solution for blanched and unblanched bilimbi materials.*



(a)



(b)



(c)

Figure 3 *(a) Rate of water loss [d(1-Ew)/dt], (b) Rate of soluble solid gain [d(1-Es)/dt], and (c) Rate of acid loss [d(1-Ea)/dt] during osmotic dehydration in 70 °Brix sucrose solution for blanched and unblanched bilimbi fruits.*

The acidity loss of blanched materials is a little higher than that of unblanched ones (Figure 2c), rate of acid loss is found nearly no difference, however (Figure 3c). The reason can be explained that acid content in the fruit is not high enough to obtain clear result and blanching time for 1 min does not give significant effect on that loss in comparison to water loss and sugar gain. Similar results for acid characteristics is also found in Yuthachit's work (1999). According to her work, the experiments were conducted by using mango as raw materials. It was found that, not only the quantity of water loss, sugar gain and acid loss of blanched materials were higher than those of unblanched ones; rate of water loss, sugar gain and acid loss were also higher. A little contrast to our experiments is that the quantity of sugar gain of blanched materials was lower than the unblanched.

Shrinkage characteristics between blanched and unblanched fruits

Shrinkage of agricultural products is commonly found when osmotic dehydration in highly concentrate solution was subjected (Mavroudis *et al*., 1998; Lazarides and Mavroudis, 1996). Unavoidable volume change occurs due to the results of the water transfer out of fruit tissues (Vaccarezza and Chirife, 1975). According to Figure 4a, shrinkage of blanched materials is obviously higher that that of unblanched ones (i.e 66.1 % in comparison to 61.2 % at 3,000 min). The explanation is that blanching increased the destruction of semipermeability of the cell membranes, leading to large amount of water loss (Vaccarezza and Chirife, 1975). In addition, rate of shrinkage (in average value) was found a little higher for blanched materials ($p<0.01$) (Figure 4b).

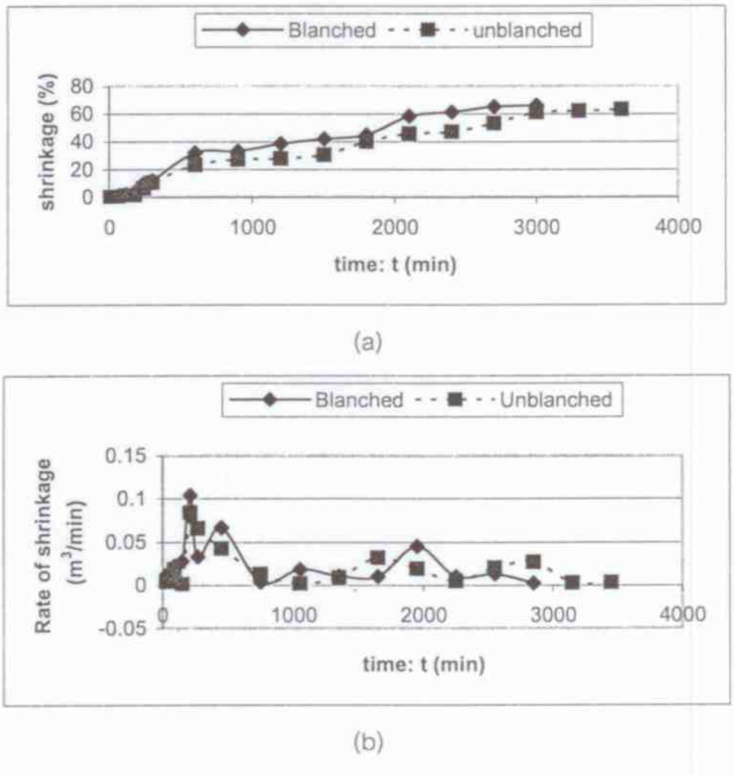


Figure 4 *(a) Shrinkage characteristics (% volume change), and (b) Rate of shrinkage between blanched and unblanched bilimbi fruits which were immersing in 70 °Brix sucrose solution for 50 h at room temperature using a ratio of raw materials to solution for 1:2*

Apparent diffusivity estimation for blanched and unblanched materials

Considering that solid materials were in cylindrical shape (shape factor=2.06), apparent diffusivity for each component was calculated according to Equation (11). Although shrinkage continuously occurs upon time, average volume and then average characteristic length were used for calculation. Biot number was selected for system without agitation and Sherwood number was calculated to be 1.55. The results shown that diffusivity of water, soluble solid (mainly sucrose), and acid for blanched materials were higher than that for unblanched ones (Table 2). Each value directly related to internal tissue structure of fruit material (Yuthachit, 1999). This result can be explained that heat treatment softens fruit tissues and then destroys the cell membrane integrity, which is the resistance to component diffusion (Vaccarezza and Chirife, 1975).

For future work, gradual increase of concentration of immersing solution (stage-wise process) will be studied due to the reason that, in some report (Yuthachit, 1999), volume reduction (shrinkage) was improved for a certain degree.

Table 2 *Apparent diffusivity of each component for blanched and unblanched bilimbi fruits.*

Condition	Diffusivity ($\times 10^{-10}$ m^2/s)					
	water	r^2	soluble solid	r^2	acid	r^2
Blanched	11.06	0.9279	11.06	0.8190	18.44	0.9639
Unblanched	7.44	0.9559	7.44	0.7934	9.30	0.9872

r^2: regression coefficient

CONCLUSION

It was found that blanching increased mass transfer characteristics of bilimbi fruit like water loss, soluble solid gain and acid loss. In addition, blanching not only leads to higher rate of water loss, soluble solid gain, and acid loss but also higher shrinkage (volume reduction) and rate of shrinkage of the raw materials in comparison to those of non-blanching treatment. The apparent diffusivity for each component like water, soluble solid, and acid were according compared and these values were found higher for the blanched materials. Although blanching leads to higher rate of shrinkage, it still needs to be done to soften the fruit tissues and better diffusion. However it was recommended that the method to protect shrinkage from blanching should be concerned and further investigated in order to preserve the fruit quality.

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REFERENCES

Bilimbi-Wikipedia, the free encyclopedia. Available at: http://en.wikipedia.org/wiki/Bilimbi, accessed June 2006.

Bilimbi-*Averrhoa bilimbi* a.k.a Cucumber Tree, Bilimbing. Available at: http://www.tradewindsfruit.com/ bilimbi.html, accessed June 2006.

Bilimbi - *Averrhoa bilimbi*. Available at: http://www.hort.purdue.edu/newcrop/morton/ bilimbi.html, accessed June 2006.

SH Goh, CH Chuah, JSL Mok, and E Soepadmo. 1995. Malaysian medicinal plants for the treatment of cardiovascular diseases. Pelanduk, Malaysia. 63.

F Abas, NH Lajis, DA Israf, S Khozirah, and YU Kalsom. 2006. Antioxidant and nitric oxide inhibition activities of selected Malay traditional vegetables. *Food Chemistry*. 95: 566-573.

BKH Tan, CH Tan, and PN Pushparaj. 2005. Anti-diabetic activity of the semi-purified fractions of *Averrhoa bilimbi* in high fat diet fed-streptozotocin-induced diabetic rats. *Life Sciences*. **76**: 2827-2839.

Bilimbi:-Definition. Available at: http://www.answer.com/topic/bilimbi, accessed June 2006.

DG Alves, JL Barbosa Jr., GC Antonio, and FEX Murr. 2005. Osmotic dehydration of acelora fruit (*Malpigghia punicifolia* L.). *Journal of Food Engineering*. **68**: 99-103.

JA Pino, R Marbot, and A Bello. 2004. Volatile components of *Averrho bilimbi* L. fruit grown in Cuba. *J.Essent. Oil Res*. **16**: 241-242.

F Kaymak-Ertekin and M Sultanoglu. 2000. Modelling of mass transfer during osmotic dehydration of apples. *Journal of Food Engineering*. **46**: 243-250.

AL Raoult-Wack. 1994. Recent advances in the osmotic dehydration of foods. *Trends in Food Science & Technology*. **5**: 255-260.

NE Mavroudis, V Gekas, and I Sjöholm. 1998. Osmotic dehydration of apples. Effects of agitation and raw material characteristics. *Journal of Food Engineering*. **35**: 191-209.

PP Sutar and DK Gupta. 2007. Mathematical modeling of mass transfer in osmotic dehydration of onion slices. *Journal of Food Engineering*. **78**: 90-97.

PJ Fellows. 1990. Food processing technology-Principles and practice. Ellis Horwood Limited. England. 505p.

P Yuthachit. 1999. The development of process for mango glace production. Master of Science Thesis in Food Technology (*in Thai*). Prince of Songkla University, Hadyai, Songkla, Thailand.

S Siriwatanayothin. 1988. Study on mass transfer in the infusion process of papaya fruits. Master thesis of Food Engineering (*in Thai*). Department of Food Engineering. King Mongkut Institute of Technology Thonburi, Bangkok,Thailand.

AOAC 1990. *Official method of analysis of the asscoication of official analytical chemist*. 15th ed. Verginia: The Association of official analytical chemists, Inc., USA.

NE Mavroudis, V Gekas, and I Sjöholm. 1998. Osmotic dehydration of apples. Shrinkage phenomena and the significance of initial structure on mass transfer rates. *Journal of Food Engineering*. **38**: 101-123

F Kaymak-Ertekin and T Cakaloz. 1996. Osmotic dehydration of peas: I. Influence of process variables on mass transfer. *Journal of Food Processing and Preservation*. **20**: 87-104.

C Siripatana. 1997. Solute diffusion in fruit, vegetable and cereal processing I: Simplified solutions for diffusion in anomalous shapes. *Songklanakarin J. Sci. Technol*. **19**: 77-88.

Luikov. 1969. The theory of heat diffusion. Academic Press. New York.

MR Khoyi and J Hesari. 2007. Osmotic dehydration kinetics of apricot using sucrose solution. *Journal of Food Engineering*. **78**: 1355-1360.

ACC Rodrigues, RL Cunha, and MD Hubinger. 2003. Rheological properties and colour evaluation of papaya during osmotic dehydration processing. *Journal of Food Engineering*. **59**: 129-135.

NK Rastogi and KSMA Raghavaroa. 2004. Increased mass transfer during osmotic dehydration of γ-Irradiated potatoes. *Journal of Food Science*. **69(6)**: 250-259.

HN Lazarides and NE Mavroudis. 1996. Kinetics of osmotic dehydration of a highly shrinking vegetable tissue in a salt-free medium. *Journal of Food Engineering*. **30**, 61-74.

LM Vaccarezza and J Chirife. 1975. On the mechanism of moisture transport during air drying of sugar beet root. *Journal of Food Science*. **40**, 1