# The Influence of Operating Temperature on Mass Transfer Characteristics during a Diffusion Process in Bilimbi Fruit

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## ABSTRACT

The effects of operating temperature on an osmotic sucrose solution with a selected concentration pattern (30-50-70 °Brix) on mass transfer characteristics during the diffusion process in bilimbi fruits in a dehydration system were investigated. Half-ripe bilimbi fruits were used. In the pretreatment step, all fruits were blanched in boiling water for 1 min to soften the fruit for better diffusion. The osmotic solutions were prepared without agitation. For each temperature level, bilimbi fruits were firstly immersed in a 30 °Brix sucrose solution for 3,000 min, then a 50 °Brix for 3,000 min, and finally a 70 °Brix for 3,000 min. The ratio of solution to raw materials was 2:1 and the pH was adjusted to 3.5 before each step. Samples from both solid and liquid phases were taken out at different periods in order to determine water loss, soluble solid gain, acid loss, corresponding diffusivities, as well as shrinkage. It was found that an operating temperature of 40 °C yielded the lowest mass transfer characteristics *i.e.* water loss and its rate, soluble solid gain and its rate, and acid loss and its rate while there was nearly no difference in the values obtained at 50 and 60 °C. Nevertheless, at the highest concentration and at all temperatures, though the water loss (%) and the acid loss (%) still increased upon time the soluble solid gain (%) decreased. The phenomenon was similar to what happened in mechanical squeezing. This result corresponded to continuous shrinking, which was clearly observed during dehydration. For bilimbi fruits, the final shrinkage was found to be 80 % of the initial volume. The final shrinkage value and also the rate of shrinkage for each period were lowest at 40 °C with no difference at 50 and 60 °C. Higher concentrations like 50 and 70 °Brix did not lead to a higher rate of water loss, soluble solid gain and acid loss; on the contrary it lowered these values. In addition, for all experiments, the diffusivity for each component *i.e.* water, soluble solids, and acid decreased as the concentration was increased (30-50-70 °Brix). Seemingly for blanched materials at higher concentrations, strong

interactions among components were observed. The results lead to a conclusion that blanched materials in a system without agitation were accompanied by shrinkage, by a squeezing-like phenomenon. The concentration effect not only dominated the temperature effect but also stabilized the rate of mass transfer especially at the operating temperatures of 50 and 60 °C.

**Keywords:** *Averrhoa bilimbi*, bilimbi fruit, temperature effect, shrinkage, osmotic dehydration, diffusion rates, volume change, diffusivity

## INTRODUCTION

Osmotic dehydration is a water removal process based on immersing food such as edible parts of plant materials into a concentrated osmotic solution having higher osmotic pressure and lower water activity [1]. Water loss occurs simultaneously with the infusion of solutes [2]. It is common to use sugar (sucrose), salt (sodium chloride), or combination of both as selective solutes. The sweetness of sucrose limits its application to vegetables while salt has been found satisfactory in the concentration range of 10 to 15 % [2,3]. If the infusion is focused, shrinkage should also be controlled especially for food materials.

Main process variables like concentration and the composition of the osmotic solution, temperature, immersion time, pretreatments, agitation, nature and geometry of the food, solution to sample ratio and others have been studied extensively [2-6], especially in relation to the product quality and mass transfer mechanism. Among a number of operating parameters that affects mass transfer during the process, temperature plays an important role. At a relatively low process temperature (up to 50 °C), it improves product color and flavor retention [4,5]. High process temperatures favor solids uptake and results in higher water loss [7,8]. It was reported that higher temperatures cause an increase in diffusion coefficients, a decrease in viscosity of the sucrose solution [7], swelling and plasticizing of cell membranes [4,5]. Nevertheless, the role of shrinkage was not mentioned.

*Averrhoa bilimbi*, a plant which is a native to tropical Asia, was selected for this investigation. Bilimbi fruits have been consumed as food and used as a traditional medicine for centuries [9]. In medication, bilimbi fruit and leaf extracts have been widely used for the treatment of scurvy, bilious cold, whooping cough, hypertension [6,10], stomach aches [11], and diabetes [12]. Its antioxidant activities have been clearly shown [1,12,13].

Bilimbi fruit is frequently added to curries for acidic taste or boiled with much sugar to make a jam or acid jelly. In Malaysia, half-ripe fruits are salted, set out in the sun, and pickled in brine [14]. Osmotic dehydration by immersing in a sucrose solution is not a general way for preservation. In addition, mass transfer characteristics are still

not established. Reports of mass transfer during a diffusion process like osmosis for bilimbi fruit are scarcely found.

This research follows our previous work, where the important pretreatment like blanching effect was already reported and a concentration pattern on dehydration was shown [15]. The aim of this study is to report the influence of temperature which is an important operating parameter on the mass transfer characteristics in bilimbi fruit during the dehydration process in a sucrose solution. The raw material characteristics, in addition, are reported as shown in **Table 1** [15].

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

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

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

## MATERIALS AND METHODS

### Sample Selection and Preparation

Half-ripe bilimbi fruits, green in color, were obtained from a local market in Nakhon Si Thammarat, Southern Thailand. The average length of the 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 to dry at room temperature and kept at 4 °C at a relative humidity (RH) of 60 % until used.

Sucrose sugar, commercial food grade, was used in the osmotic solution. The preparation was done by dissolving sugar in hot water to the required concentrations of 30, 50 and 70 °Brix.

### Blanching Pretreatment

Bilimbi fruits were soaked in a solution containing 0.1 % (w/v) sodium metabisulfide and 0.7 % (w/v) calcium chloride for 6 h in order to inhibit browning and preserve their firmness. The fruits were then drained for 10 min, blanched in boiling water for 1 min to soften the fruit tissues and suddenly cooled in water at 4 °C.

**Operating Temperatures during Submersion in Sucrose Solution and a Stage-Wise Concentration Pattern**

Treatments are as follows:-

Treatment 1: Operating Temperature of 40 °C - Conc. Pattern 30-50-70 °Brix,

Treatment 2: Operating Temperature of 50 °C - Conc. Pattern 30-50-70 °Brix,

Treatment 3: Operating Temperature of 60 °C - Conc. Pattern 30-50-70 °Brix.

Each treatment was carried out as follows:-

The fruits were firstly immersed in a 30 °Brix sucrose solution in a temperature-controlled water bath at a selected temperature without stirring. The initial ratio of osmotic solution to raw materials was 2:1. The pH was adjusted to 3.5 with citric acid. Samples were taken out every hour for the first 300 min of immersion and then for every 300 min until the total time of 3,000 min was reached.

After that, all the fruits were drained on a screen for 10 min and then immersed into a 50 °Brix solution for another 3,000 min. Samplings were carried out in a similar way as mentioned above. Finally, the dehydration step was done in a similar way, changing the osmotic concentration to 70 °Brix.

For each step of concentration, the total weight of raw materials was 40 kg and each sampling weight was 30 - 40 g. Total sampling was 450 - 600 g. This was replicated twice.

Each sample of both solid and liquid phase was measured for their weight, soluble solute (refractometry with an Abbe refractometer) and acid concentration (titration with 0.01 N NaOH). The solid samples were also measured for their dimensions, moisture content (drying in a hot air oven) and acid content (titration) in order to evaluate % water loss, % soluble solid (mainly sugar) gain, % acid loss, rate of mass transfer of each component, including shrinkage of the fruit and shrinking rate.

Initial volume and shrinkage was determined using a picnometer and water replacement method [16]. Shrinkage was calculated by observing the volume changes of raw materials during operation time in comparison with the initial volume.

**Statistical Analysis**

Data were subjected to analysis of variance (ANOVA) and means were compared using Duncan's new multiple range test (DMRT), using SPSS 9.0 for Windows.

**Evaluation of Osmotic Dehydration Kinetics**

Water loss $\{WL\ (\%)\}$, soluble solids gain $\{SG\ (\%)\}$ are calculated according to Eq. (1) and (2), respectively [17], while acid loss $\{AL\ (\%)\}$ is calculated by Eq. (3) [17,18].

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

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

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

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

where $B_0$, $B_t$ are the concentration fraction of soluble solids in bilimbi fruit at initial and any time t (°Brix, fraction in wet basis).

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

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

To describe the rate of mass transfer by diffusion for each component, a mathematical model for ellipsoids developed by Siripatana [19] is used as follows: For water loss;

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

For soluble solid gain;

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

For acid transfer;

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

Hence, a general form is shown below.

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

Thus, the diffusion rate of mass transfer for each component can be described in a general form as;

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

where $E = E_w, E_s, E_a$ are the dimensionless parameters for water, soluble solids, and acid according to Eq. (4), (5) and (6), respectively.

$WL_t, WL_\infty$ are the quantity of water diffused from the solid phase at any time $t$ and at infinity (%)

$SG_t, SG_\infty$ are the quantity of soluble solid infused into the solid phase at any time $t$ and at infinity (%)

$AL_t, AL_\infty$ are the quantity of acid diffused from solid phase at any time $t$ and at infinity (%)

$D_w, D_s, D_a$ are the diffusivity of water, soluble solids and acid (m²/s)

$t$            is the contact time (s)

$C_1$           is the parameter depending on the initial solute concentration distribution in the solid phase

$Sh$          is the Sherwood number

$\gamma$            is the equilibrium extraction factor

$v$            is the shape factor of the solid

$a$            is the characteristic length (m)

Eq. (4), (5) and (6) can be rewritten in a form as follows:

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

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

where $WL_t/WL_\infty$, $SG_t/SG_\infty$ and $AL_t/AL_\infty$ are the fractional loss of water, gain of soluble solids (mainly sugar) and loss of acid, respectively.


## RESULTS AND DISCUSSION

**Raw Materials: Bilimbi Fruits**

Half-ripe bilimbi fruits in appropriate harvesting condition for osmotic dehydration, were selected for the investigation. Its properties have previously been reported [15].


**The Effect of Operating Temperatures on the Diffusion Mechanism of Osmotic Dehydration**

**Mass Transfer Characteristics**

Results of water loss and its rate, soluble solid gain and its rate, and acid loss and its rate are shown in **Figures 1a** and **2a**, **Figures 1b** and **2b** and **Figures 1c** and **2c**, respectively. For each osmotic concentration and all operating time periods, the lowest

water losses (**Figure 1a**) and their corresponding rates (**Figure 2a**) were observed at 40 °C while there were no significant differences at 50 and 60 °C ($p > 0.05$). The soluble solid gains (**Figure 1b**) and there corresponding rates (**Figure 2b**) were also low at 40 °C. In addition, the acid losses at 40 °C, showed the highest loss for the first period (30 °Brix, 3,000 min) (**Figure 1c**). However, the corresponding rates were still the lowest for all operating times (**Figure 2c**).

The temperature of 40 °C provided the lowest values of mass transfer characteristics in bilimbi fruit ($p < 0.05$) while no difference was observed at 50 and 60 °C ($p > 0.05$). This phenomenon was markedly seen at high concentrations like 50 °Brix (3,000 - 6,000 min) and 70 °Brix (6,000 - 9,000 min). In theory, a higher temperature should cause a higher rate of mass transfer [20], especially the rate of water loss [1,7,21]. This is true at temperatures lower than 50 °C where pectin substances were not degraded [18]. At temperatures higher than 50 °C like 60 or 70 °C, temperature not only influenced cell structure and semi-permeable properties of the cell wall [20,21] but also blocked mass transfer of water and soluble solids due to pectin-degraded substances formed in plant tissues [18,21]. For potatoes and apples, water permeability and sugar transport suffered sharp changes at processing temperatures beyond 40 °C [22-24].

For bilimbi fruit, pectin content was not determined, yet there was no evidence that the pectin degradation had a significant effect on the mass transfer behavior at 40 °C. The reason is that the soluble solid gains for 40 °C were still significantly less than those at 50 and 60 °C ($p < 0.05$) (**Figure 1b**).

According to our pretreatment, raw materials were blanched in hot water (100 °C) for 1 min. This may cause damage to the cell structure and affect the diffusion mass transfer [25]. If the cell structure collapsed and semi-permeability of the cell wall was destroyed, there is no time of cell plasmolysis [26,27]. Hence, the operating temperature has less influence on diffusion characteristics. That is the reason why there was nearly no difference on mass transfer between the operating temperatures 50 and 60 °C.

In all cases, sugar uptake results in the development of a concentrated solids layer under the surface of the product, upsetting the osmotic pressure gradient across the product-medium interface and decreasing the driving force for water flow [26]. Osmotic solids block the surface layers of the product, making an additional resistance to mass exchange [28].

Our results thus lead to a conclusion that cell structure could be damaged due to thermal destruction and the concentration effect not only dominated the temperature effect but also stabilized the rate of mass transfer in a system without agitation.

It is interesting to note that at the highest concentration (70 °Brix), although water loss and acid loss still increased upon time (6,000 - 9,000 min) (**Figures 1a** and **1c**), but the soluble solid gain decreased for all temperatures (**Figure 1b**). In fact, at 40 °C, the soluble solid gain decreased since the operating time was short at 3,000 min. These characteristics are similar to a slow squeezing, corresponding to continuous fruit shrinking over time (**Figure 3a**).

The soluble solid gain (% SG) was calculated based on Eq. (2) proposed by Monsalve-Gonzalez and co-workers [17]. In experiments with apples, the soluble solid gain increased over time due to low weight reduction by water loss, with a little shrinkage [17] which is in contrast to our experiments where a high weight reduction took place. Thus for bilimbi fruit, the soluble solids content (°Brix) increased over time and when the weight reduction due to water loss began to dominate the soluble solid gain, the % SG curve declined which contradicts what is normally expected (**Figure 1b**).
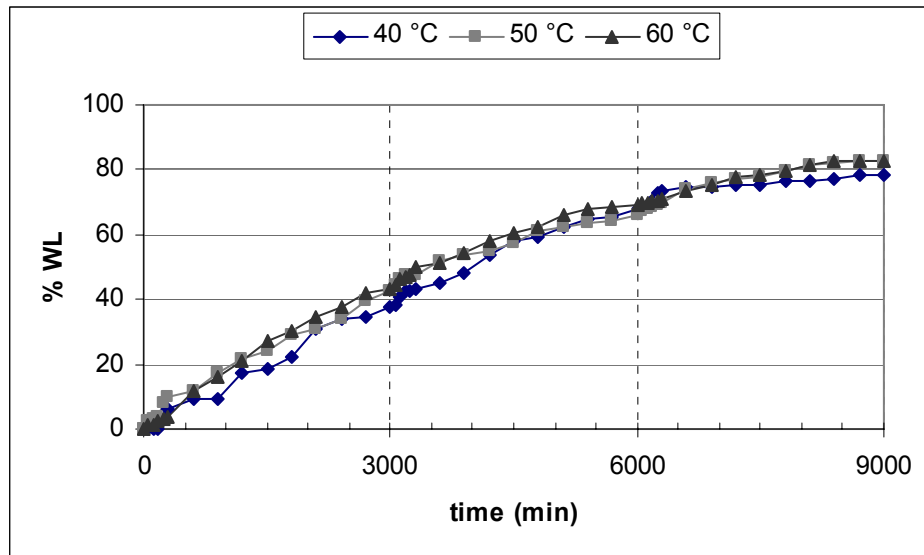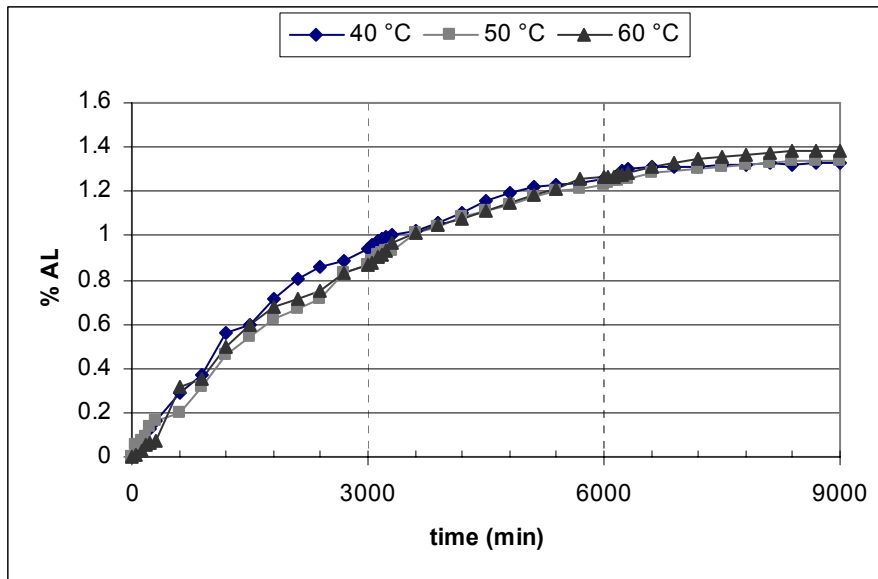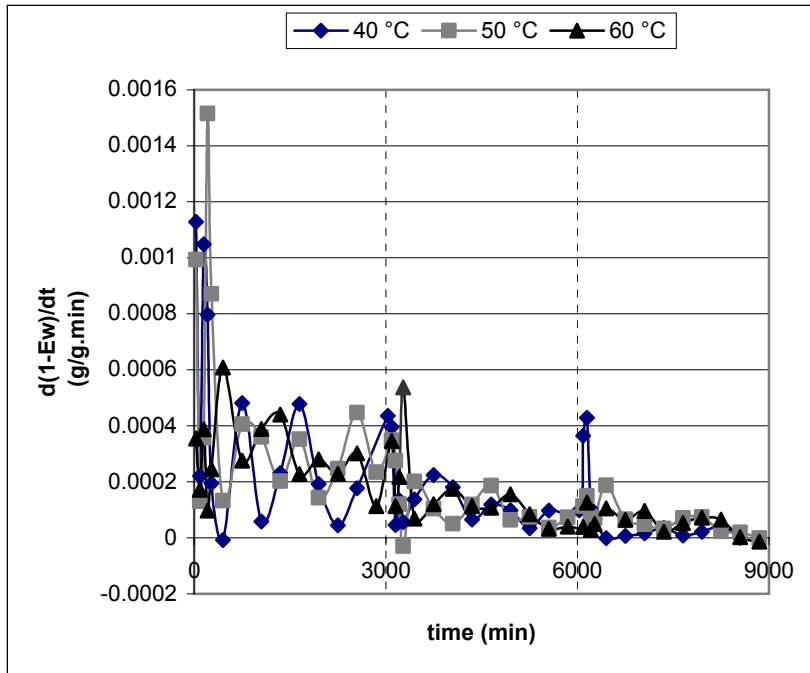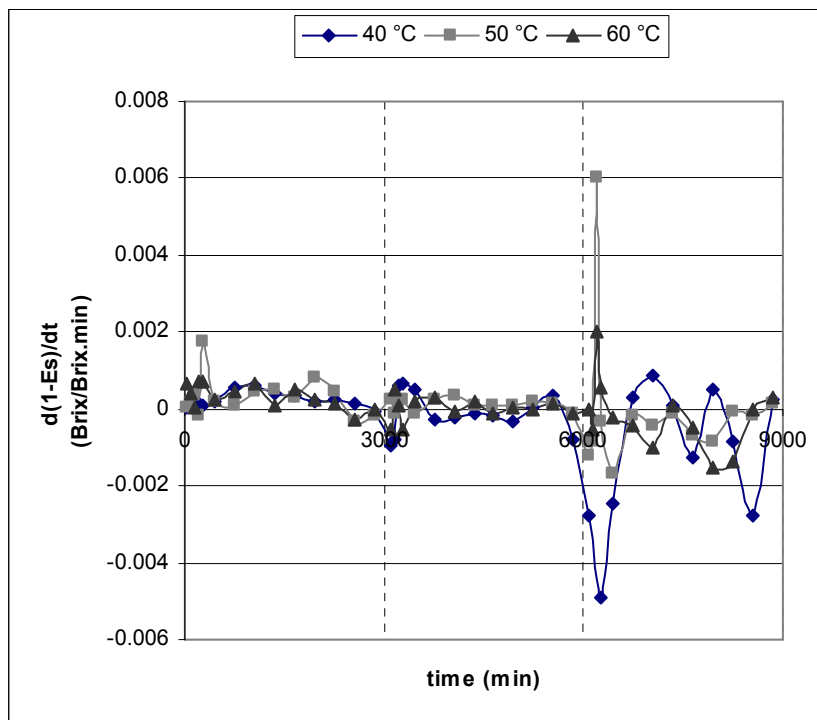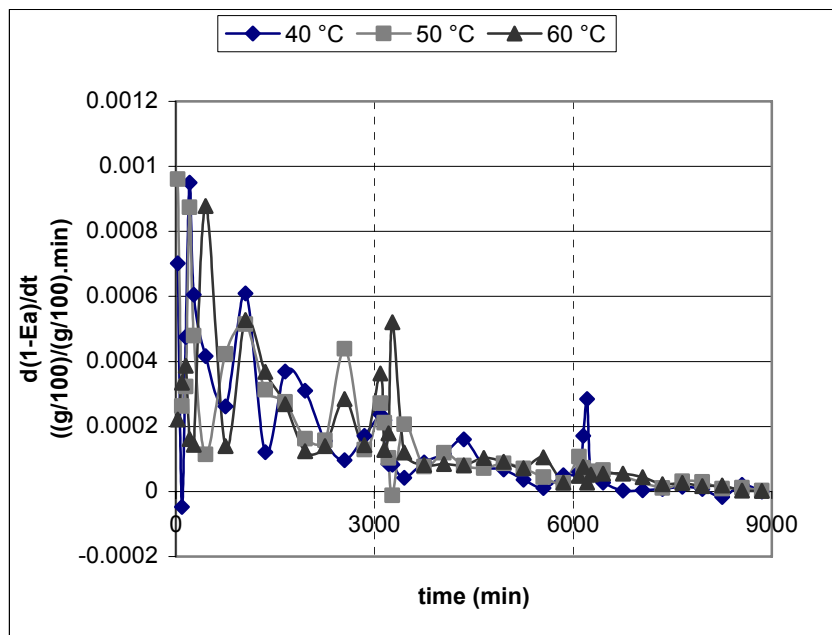


(a)
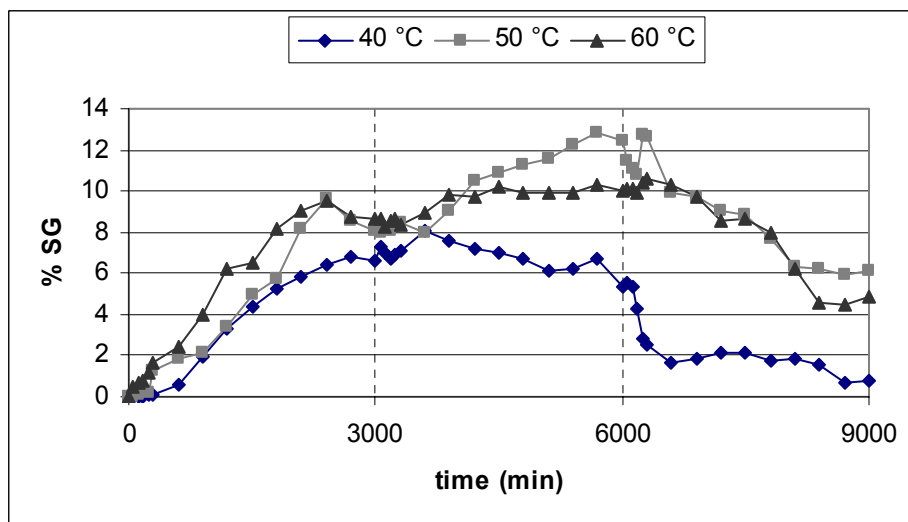


(b)

(c)

**Figure 1** (a) Water loss {WL (%)}, (b) soluble solid gain {SG (%)} and (c) acid loss {AL (%)} during osmotic dehydration of blanched bilimbi fruits at different operating temperatures at a selected concentration pattern of 30-50-70 °Brix.

(a)



(b)

(c)

**Figure 2** (a) Rate of water loss [d(1-Ew)/dt], (b) Rate of soluble solids gain [d(1-Es)/dt] and (c) Rate of acid loss [d(1-Ea)/dt] during osmotic dehydration for blanched bilimbi fruits at different operating temperatures at a selected concentration pattern of 30-50-70 °Brix.

**Shrinkage Owing to Different Operating Temperatures**

Shrinkage is a result of volume change due to internal mass transfer [28], through the diffusion mechanism and osmotic pressure gradient in this case. A higher concentration causes a higher shrinkage [28,29]. Our previous results [15], have shown that preprocessing like blanching should be still carried out in order to soften fruit texture and permit better diffusion, nevertheless, a stepwise process needs not to be applied if the quality improvement is focused since this does not improve volume reduction during the dehydration.

In fact, the 3 concentration-immersion steps aim to reduce weight loss (or shrinkage) which is generally opposite to the purpose of the dehydration [15,18]. If water loss was the main interest, the very high shrinkage of bilimbi fruit makes it a very good candidate for osmotic dehydration treatment. Yet, for food materials, general appearance is still a key problem, especially for consumer acceptability.

For bilimbi fruits, the gradual increase in the osmotic solution did not inhibit the shrinkage of raw materials or keep up general characteristics; the longer the osmotic period, the higher the shrinkage obtained [15]. The results found contrast those which have been reported for mango [18] and garcinia fruits [30]. For mango, the volume reduction could be inhibited by 17 - 27 % if a stage-wise process of 30-50-70 °Brix was

applied, in comparison to a system where materials were immersed in a 70 °Brix solution [18]. For garcinia fruits no volume reduction was reported [30]. This can be explained by the fact that the bilimbi fruits have much lower hardness (textural property) than mango and garcinia fruits. Bilimbi's hardness was found to 7.72 N [15] approximately 11 times lower than that of garcinia (85.14 N [31]). In addition, no difference in mass transfer characteristics between a stage-wise process of 30-40-50-60-70 °Brix and 30-50-70 °Brix was observed for garcinia [30].

To investigate and clearly scrutinize the temperature effects on dehydration without stirring, a stage-wise process of 30-50-70 °Brix was still applied. The results are shown in **Figure 3a** for shrinkage characteristics (% volume change) and **Figure 3b** for its corresponding rate.

Shrinkage of the fruit at the end of each step (30-50-70 °Brix) of each treatment was found as follows: (1) Treatment I (40 °C): 28.95 %, 65.55 % and 79.40 %, respectively; (2) Treatment II (50 °C): 35.55 %, 58.35 % and 80.22 %, respectively; and (3) Treatment III (60 °C): 36.73 %, 63.6 7% and 81.02 %, respectively. It was shown that the shrinkage (**Figure 3a**) and its corresponding rate (**Figure 3b**) at 40 °C was lower than that at 50 and 60 °C due to lower water loss (**Figure 1a**). Nevertheless, no significant difference in these values was found at 50 and 60 °C (**Figure 3b**). In addition, for all operating periods, the higher concentration leads to a little declination in the rate of mass transfer. The result thus confirmed that the bilimbi fruit which was blanched at high temperature led to destruction of the cell structure and consequently the concentration effect dominating the temperature effect.
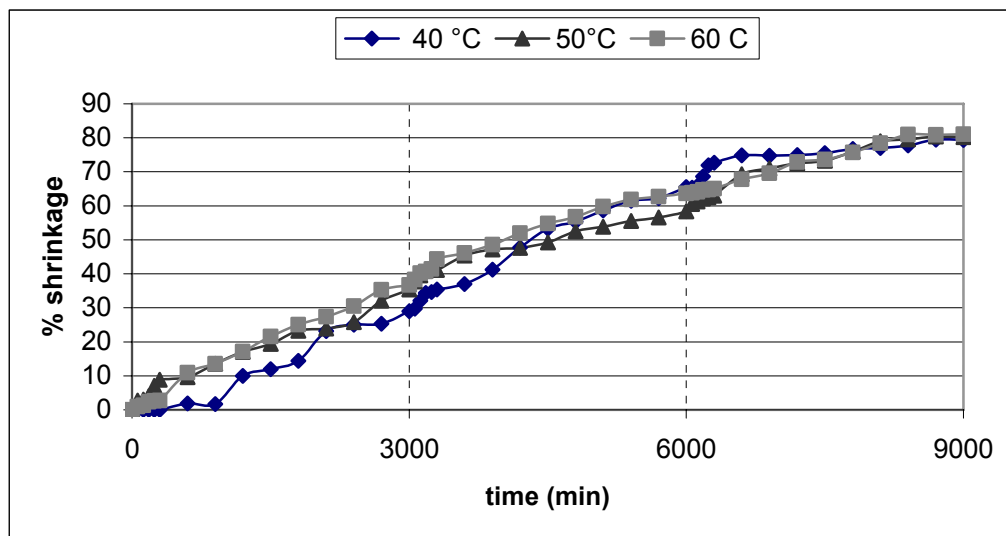


(a)
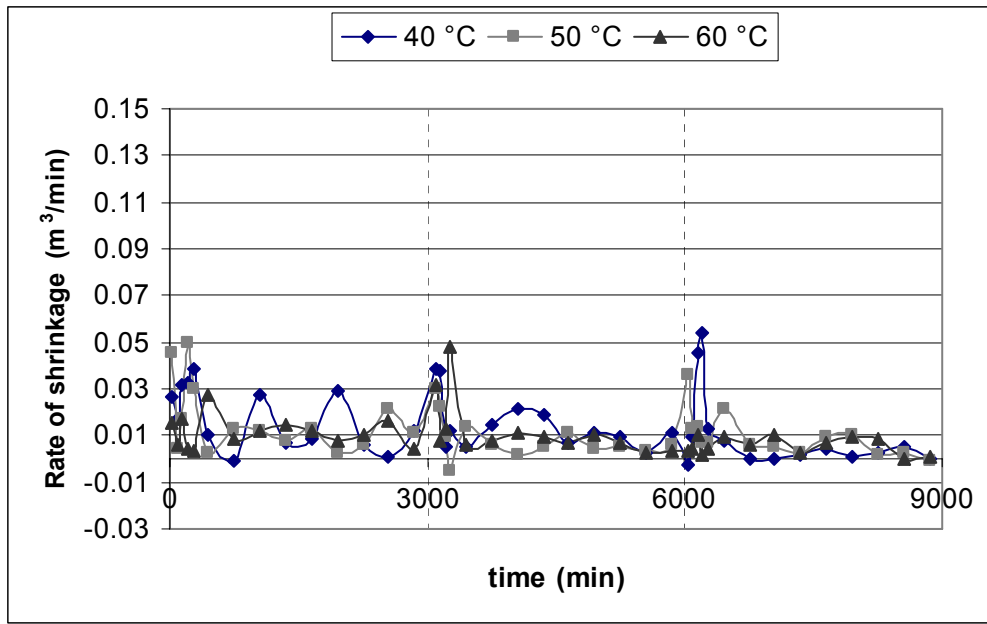
(b)

**Figure 3** (a) Shrinkage characteristics of bilimbi fruit (% volume change) and (b) Rate of shrinkage (volume change in m$^3$/min) during osmotic dehydration for blanched bilimbi fruits at different operating temperatures at a selected concentration pattern of 30-50-70 °Brix.

**Effective Diffusivity Evaluation**

Diffusivities of each component were calculated from Eq. (8), which was derived based on Fick's second law of solution, proposed by Siripatana [19]. Once the slope of the graph between $d(1-E)/dt$ and $t$ was determined; diffusivity was thus shown by the following relationship:-

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

The Sherwood number ($Sh$) was calculated by a similar approach used by Luikov [32], thus the following generalized equation can be applied for all geometries [19].

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

where
$$u(\alpha,\eta) = 2.460 + 0.3770\eta$$
$$v(\alpha,\eta) = 0.4015 + 0.248\eta$$
$$w(\alpha,\eta) = 0.0270 + 0.03531\eta$$

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

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

$k = 1.069 + 0.0404\eta$

$\eta = v - 1$

Here, draft of extraction ($\alpha$) is $\gamma$ (equilibrium extraction factor) in a batch system. Eq. (12) has a maximum error of 10 % for Biot number ($Bi$) > 1 and $\alpha$ > 0.3, although usually the errors are within 5 % for most cases.

The shape factor ($v$) is 1 for a slab, 2 for a long cylinder, and 3 for a sphere. Eq. (12) and (13) can also be used for anomalous shapes [19]. For our study the cylinder shape was assumed for all calculations. The Biot number was selected for a system without agitation and the Sherwood number was calculated to be 1.55.

Effective diffusivities ($D$) were calculated based on an average volume and a characteristic length. The values found are reported in **Table 2**. It was observed that the concentration of osmotic solutions greatly influence the diffusivity. In addition, according to our results, it's not easy to conclude that higher temperature lead to higher diffusivities. We postulate that blanching is responsible for this due to destruction of the cell structure. In cooperation with the high concentration effect, higher concentration obviously causes lower diffusivity (**Table 2**). The reason may also be due to interactions among the components [33], *i.e.* water, solids, and acid. It was also reported that the use of highly concentrated viscous sugar solutions also hindered contact between the food material and osmotic solution, causing a reduction in the mass transfer rates [33].

Another point should be mentioned. In some work, it was claimed that increasing temperature increased water loss and soluble solid gain due to the increasing diffusion coefficients and the decreasing viscosity of the sucrose solution [7], however, a degree of shrinkage was not mentioned.

Cell structure and its damage have effects on the rates of mass transfer and hence diffusivities [25,34]. Different plant cells or tissues respond in a particular way to osmotic stress. Composition-structural profiles developed in the tissue during the osmotic process have a great impact on physical and chemical properties and kinetics [25]. Changes in shrinkage during osmotic dehydration are strongly associated with the mechanism governing the rate of mass transfer [28], that of squeezing due to osmotic pressure and the soft texture of the material.

In our experiment, a lot of shrinkage was found, especially up to 80 % of initial volume. This phenomenon is quite similar to that in some vegetables like potatoes [28] and strawberries [35]. We postulate that, at selected operating variables, for blanched bilimbi fruit in the system without agitation, the high concentration of the osmotic solution stabilized the operating temperature effect. The flux due to squeezing overcame the flux due to diffusion. In addition, kinetic values like diffusivities were also influenced by raw material shrinkage and a certain degree of cell structure damage. The diffusion mechanism seems somewhat dominated by the squeezing-like phenomenon.

For future work, the blanching effect should be deeply investigated, agitation should be conducted and pectin content should be also determined since this also influences mass transfer.

**Table 2** Effective diffusivity of components during dehydration of bilimbi fruits at different operating temperatures using a selected immersing concentration pattern of osmotic solutions without agitation.

| Treatment No. | Osmotic solution (°Brix) | Shrinkage (% of volume change) | Diffusivity* ($\times 10^{-9}$ m$^2$/s) | | |
|---|---|---|---|---|---|
| | | | Water | Soluble solids (mainly sucrose) | Acid |
| I:  40 °C | 30 | 28.95$^a$ | 3.94$^b$ | 5.52$^{ab}$ | 6.31$^a$ |
| | 50 | 65.55$^b$ | 2.83$^{bc}$ | N/A** | 2.83$^{bc}$ |
| | 70 | 79.40$^c$ | 1.50$^c$ | N/A** | 2.17$^c$ |
| II: 50 °C | 30 | 35.36$^{ab}$ | 4.85$^{ab}$ | 4.04$^b$ | 4.85$^b$ |
| | 50 | 58.35$^b$ | 4.70$^{ab}$ | 2.61$^c$ | 4.18$^b$ |
| | 70 | 80.22$^c$ | 2.66$^{bc}$ | N/A** | 2.66$^{bc}$ |
| III: 60 °C | 30 | 36.73$^{ab}$ | 6.41$^a$ | 7.21$^a$ | 7.21$^a$ |
| | 50 | 63.67$^b$ | 3.88$^b$ | 3.88$^b$ | 4.28$^b$ |
| | 70 | 81.02$^c$ | 2.14$^c$ | N/A** | 1.88$^c$ |

Note: * Diffusivities were calculated based on an assumed cylindrical solid shape.
       ** Not available due to the squeezing-like effect.
        The same alphabet for each column implied non-significant difference ($p > 0.05$).

## CONCLUSIONS

The investigation of operating temperature on the mass transfer characteristics during osmotic dehydration of bilimbi fruits without agitation were carried out at a selected immersing-concentration pattern of osmotic sucrose solutions (30-50-70 °Brix). It was found that, for each component (water, soluble solid and acid) at the same period, the operating temperature of 40 °C yielded the lowest value for mass transfer characteristics *i.e.* water loss and its rate, soluble solid gain and its rate, and acid loss and its rate; while there was no significant difference in these values at 50 and 60 °C. At the highest concentration for all temperatures, water loss (%) and acid loss (%) increased over time while soluble solid gain (%) decreased. The results found are similar to a squeezing-like phenomenon and correspond to continuous shrinking during dehydration. For bilimbi fruits, the high shrinkage was found to be 80 % of the initial volume. The shrinkage value and the corresponding rate were lowest at 40 °C while no difference was observed at 50 and 60 °C. Higher concentrations did not lead to higher rates of water loss, soluble solids gain and acid loss. On the contrary, it led to lower mass transfer values. The diffusivity for each component like water, soluble solids, and acid decreased as their concentrations increased. It is postulated that at higher concentrations for blanched bilimbi fruits in a system without agitation, strong interactions among components are established. The results lead to the conclusion that the blanched bilimbi materials for which osmotic dehydration and simultaneous shrinkage (squeezing-like phenomenon) occur over time, the concentration effect (30-50-70 °Brix) not only dominates the temperature effect but also stabilizes rate of mass transfer, especially at 50 and 60 °C.

## ACKNOWLEDGMENTS

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# บทคัดย่อ

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**อิทธิพลของอุณหภูมิทำงานต่อคุณลักษณะการถ่ายโอนมวลระหว่างกระบวนการแพร่ในผลตะลิงปลิง**

งานวิจัยนี้เป็นการศึกษาผลของอุณหภูมิทำงาน ณ รูปแบบความเข้มข้นของสารละลายออสโมติกของน้ำตาล
ซูโครสที่เลือกใช้ (30-50-70 องศาบริกซ์) ต่อคุณลักษณะการถ่ายโอนมวลระหว่างกระบวนการแพร่ในระบบทำแห้งผล
ตะลิงปลิง การทดลองเลือกใช้ผลตะลิงปลิงชนิดกึ่งสุกโดยขั้นตอนการเตรียมวัตถุดิบนั้นผลตะลิงปลิงจะถูกลวกในน้ำ
เดือดเป็นเวลา 1 นาทีเพื่อให้เนื้อสัมผัสอ่อนตัวให้การแพร่ดีขึ้น ระบบออสโมติกดำเนินการโดยปราศจากการกวนและ
เขย่า ทั้งนี้ ณ แต่ละอุณหภูมิทำงานที่ศึกษาคือ 40 50 และ 60 องศาเซลเซียส ผลตะลิงปลิงจะถูกนำมาแช่ในสารละลาย
น้ำตาลซูโครสเข้มข้น 30 องศาบริกซ์ เป็นเวลา 3,000 นาที จากนั้น 50 องศาบริกซ์ เป็นเวลา 3,000 นาที และ 70 องศา
บริกซ์ เป็นเวลา 3,000 นาที ตามลำดับ สัดส่วนของสารละลายต่อวัตถุดิบที่ใช้คือ 2 ต่อ 1 โดยน้ำหนัก โดยค่า pH เริ่มต้น
ของสารละลายในแต่ละขั้นตอนการแพร่เป็น 3.5 ทั้งนี้ในระหว่างกระบวนการทดลองได้มีการเก็บตัวอย่างทั้งจากเฟส
ของแข็งและของเหลวที่ช่วงเวลาต่างๆ เพื่อตรวจวัดการสูญเสียน้ำ การได้รับของแข็งละลาย การสูญเสียกรด สัมประสิทธิ์
การแพร่และการหดตัวของผลตะลิงปลิง ผลการทดลองพบว่า อุณหภูมิทำงานที่ 40 องศาเซลเซียสให้คุณลักษณะการถ่าย
โอนมวลต่ำสุดโดยพิจารณาจาก การสูญเสียน้ำและอัตราการสูญเสียน้ำ การได้รับของแข็งละลายและอัตราการได้รับ
ของแข็งละลาย การสูญเสียกรดและอัตราการสูญเสียกรด ในขณะที่พบว่าไม่มีความแตกต่างของคุณลักษณะดังกล่าว
ระหว่างอุณหภูมิ 50 และ 60 องศาเซลเซียส อย่างไรก็ตาม ณ ที่ความเข้มข้นสูงสุดของแต่ละอุณหภูมิทำงาน ถึงแม้การ
สูญเสียน้ำและการสูญเสียกรดเพิ่มขึ้นเมื่อเทียบกับเวลา แต่การได้รับของแข็งละลายกลับลดลง ปรากฏการณ์นี้คล้ายคลึง
กับสิ่งที่เกิดขึ้นในระบบบีบอัดแบบเชิงกลและยังสอดคล้องกับการหดตัวของวัตถุดิบอย่างต่อเนื่อง ในทุกปฏิบัติการ
พบว่าค่าการหดตัวสุดท้ายของผลตะลิงปลิงเป็น 80 เปอร์เซ็นต์โดยประมาณเมื่อเทียบกับปริมาตรเริ่มต้น โดยที่การหดตัว
และอัตราการหดตัวของแต่ละขั้นตอนการแพร่มีค่าต่ำสุดที่ 40 องศาเซลเซียสและ ไม่แตกต่างกันที่ 50 และ 60 องศา
เซลเซียส ทั้งนี้ ณ อุณหภูมิเดียวกัน การเพิ่มความเข้มข้นของสารละลายน้ำตาลจากระดับ 30 ไปยัง 50 และ 70 องศาบริกซ์
ตามลำดับ ไม่ได้ทำให้อัตราการสูญเสียน้ำ อัตราการได้รับของแข็งละลายและอัตราการสูญเสียกรดเพิ่มขึ้น แต่กลับทำให้
คุณลักษณะดังกล่าวลดลง นอกจากนี้พบว่า ค่าสัมประสิทธิ์การแพร่ของแต่ละองค์ประกอบอันได้แก่ น้ำ ของแข็งละลาย
และกรด มีค่าลดลงเมื่อระดับความเข้มข้นของน้ำตาลเพิ่มขึ้น ผลการทดลองการแพร่นำไปสู่ข้อสรุปคือ สำหรับตะลิงปลิง
ที่ผ่านการลวกและทำแห้งในระบบออสโมติก ผลของความเข้มข้นซึ่งทำให้เกิดการหดตัวคล้ายคลึงกับการบีบอัดเชิงกล
ไม่เพียงแต่ส่งอิทธิพลเหนือผลของอุณหภูมิทำงานแต่ยังทำให้เกิดการหน่วงอัตราการถ่ายโอนมวลอีกด้วย โดยเฉพาะเมื่อ
พิจารณาระหว่างอุณหภูมิทำงานที่ 50 และ 60 องศาเซลเซียส

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