

# Mass Transfer Considerations in Osmotic Dehydration of Plantain (*Musa Paradisiaca*) Chips

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## ABSTRACT

The influence of process variables and the kinetics of water loss during osmotic dehydration of plantain (*Musa paradisiaca*) chips in sugar solutions was determined to provide information necessary for further drying and to enable processors maintain its quality. A 3 x 4 factorial in Complete Randomized Design (CRD) comprising of three sucrose concentrations 29, 33 and 41°Brix and four temperatures 40, 50, 60 and 80°C were used for the study. For each sucrose concentration, plantain slices each 20 g were immersed in sugar solutions contained in 500ml glass beaker which were maintained at 40, 50, 60 and 80°C respectively in agitated water bath while maintaining the syrup to fruit ratio at 5:1 in order to minimize errors arising from changes in syrup concentrations due to mass transfer. Osmotic dehydration kinetics of plantain slices was analyzed based on the models reported by Azoubel and Murr (AMM), and Zungarramudi and Lupin (ZLM). The analysis of variance shows a highly significant syrup concentration, temperature and interaction effect. As the temperature increased, water loss increased and residual water decreased. At all sucrose concentrations studied, water loss was observed to increase with temperature. Results of evaluation of the mass transfer characteristics during osmotic dehydration indicate that both AMM and ZLM gave high regression coefficients ranging from 0.789 to 0.997 for AMM and 0.821 to 0.996 for ZLM. The values of the mean relative deviation modulus (%E) used to evaluate the goodness of fit of the models for AMM and ZLM were generally low, less than 10% indicating that the two models gave good fit to experimental data with ZLM predicting the experimental data better than AMM. The apparent diffusivity ( $D_a$ ) values generally increased with both temperature and sucrose concentration with the values ranging between  $3.489 \times 10^{-12}$  to  $1.857 \times 10^{-6}$  m<sup>2</sup>/s.

**Keywords:** Osmotic dehydration, plantain chips, drying, quality, temperature, diffusivity, sucrose concentration, Nigeria.

## 1. INTRODUCTION

Plantain is a tropical fruit which belongs to the genus *Musa*, with about forty species, widely distributed throughout the tropics. The hard plantain is used as food in contrast to the soft sweet desert banana varieties (Kochhar, 1981). The unripe plantain is rich in starch which on ripening

converts to sugar. Plantain contains about 68.2 % water (FAO, 1986) and therefore deteriorates fast after harvest. In order to extend the shelf life and/or provide variety of plantain products, plantain chips are dried. Drying removes moisture from food so that bacteria, yeast and mold activities are reduced to a reasonably low level (Holdworth, 1986).

Osmotic dehydration in combination with various methods of thermal drying is reported by Lewicki and Lenart (1992), Grabowski and Marcote (2001) and Alakali et al., (2006) as energy efficient drying technology. Such a hybrid technology is particularly advantageous because a significant fraction of moisture can be removed non-thermally with simultaneous infusion of desirable solutes. A review by Torregiani (1993) indicated that osmosed products maintained significant proportion of their fresh qualities and that color, flavor and texture of air, freeze or vacuum dried fruits and vegetables could be improved by osmotic pretreatment.

Osmotic dehydration is achieved by immersing fruits in sucrose solution and vegetable in chloride solution of high osmotic pressure (Expedito et al., 1996). This gives rise to two simultaneous counter current flows: water flows from the material to the solution followed by a simultaneous transfer of solutes from the solution to the food material by diffusion. Osmotic dehydration is an unsteady state diffusion process which can be described by Fick's second law of diffusion in equation 1 (Torregiani, 1993; Crank, 1999; Azoubel and Murr, 2002; Alakali, 2004).

$$\frac{\partial M}{\partial t} = D \frac{\partial^2 M}{\partial x^2} \quad (1)$$

where, M = moisture content/mean solid content after time t, t = time, x = thickness, D = diffusion coefficient for moisture in solids (m<sup>2</sup>/s)

The diffusion coefficient based on equation (1) serves as the drying rate. The values of D have been reported under different osmotic dehydration conditions by earlier researchers (Alakali et al., 2006; Azoubel and Murr, 2002; Expedito et al., 1996). The objectives of this work are to determine the influence of process variables and the kinetics of water loss during osmotic dehydration of plantain chips.

## 2. MATERIALS AND METHODS

### 2.1 Materials

Ten (10) kg of ripe and firm plantain (*Musa paradisiaca*) were purchased from Wurukum market in Makurdi, Nigeria. The fruits were transported to the laboratory in jute bags. The fruits were thoroughly washed to remove adhering foreign materials and kept in a household refrigerator until required for experiment.

## 2.2 Osmotic Dehydration

The plantain fruits were peeled and cut into 10mm thick slices of 20 g each using stainless steel knife. A 3 x 4 factorial in Complete Randomized Design (CRD) experimental design comprising of three sucrose concentrations of 29, 33 and 41°Brix and four temperatures of 40, 50, 60 and 80°C were used to study mass transfer during osmotic dehydration of plantain slices in sugar solutions. For each sucrose concentration, plantain slices each 20 g were immersed in sugar solutions contained in 500 ml glass beaker which were maintained at 40, 50, 60 and 80°C respectively in agitated water bath (Model Cambridge Ltd CB 25 Q2). The syrup to fruit ratio was maintained at 5:1 as recommended by Silveira et al. (1996) in order to minimize errors arising from changes in syrup concentrations due to mass transfer. At regular intervals of half hour in the first two hours and intervals of two hours in the remaining time, slabs were removed from the solution, blotted to remove surface liquid and weighed using electronic balance (Mettler, P163). The experiment was terminated when equilibrium weight was attained. Each experiment was replicated three times.

## 2.3 Kinetic Analysis

Osmotic dehydration kinetics of plantain slices was analyzed based on the models reported by Azoubel and Murr (2002) and Zungarramudi and Lupin (1980). According to Azoubel and Murr (2002), water loss during osmotic dehydration can be determined based on mass balance as shown in equations 2-5:

$$WL = WL_{\infty} - WR \quad (2)$$

where,

WL = water loss (g H<sub>2</sub>O/100 g sample) at time, t

WL<sub>∞</sub> = water loss at equilibrium (g H<sub>2</sub>O/100 g sample)

WR = residual water at time, t (g H<sub>2</sub>O/100 g sample)

According to the authors, since WR decrease as WL increase, there exists a relationship between the two parameters represented by K, the rate of water loss:

$$K = WL/WR \quad (3)$$

Assume the rate of water loss is only a function of time, K is related to time, t and a constant, S as follows:

$$K = St \quad (4)$$

Substituting equations 2 and 4 into 3 and rearranging, we obtain

$$WL = \frac{St(WL_{\infty})}{1 + St} \quad (5)$$

To predict WL at time (t), it is necessary to know the values of S and  $WL_{\infty}$ . This was calculated by linear regression using experimental data for WL and the linear form of equation 5 as shown in equation 6:

$$\frac{t}{WL} = \frac{1}{SWL_{\infty}} + \frac{t}{WL_{\infty}} \quad (6)$$

$1/WL_{\infty}$  is obtained from the slope of the plot of  $t/WL$  versus t and  $1/SWL_{\infty}$  from the intercept. Consequently S was determined and the water loss calculated from equation 5 as a function of time. Thereafter, residual water as a function of time was determined using equation 7.

$$WR(t) = WL_o - WL \quad (7)$$

where  $WL_o$  = initial amount of water (g).

According to Zungarramudi and Lupin (1980) residual water as a function of time can be predicted using equation 8:

$$WR(t) = WL_o \exp(-K_w t) + WL_{\infty} [1 - \exp(-K_w t)] \quad (8)$$

where  $K_w$  is the rate of water loss.

The validity of equations 7 and 8 for predicting residual water during osmotic dehydration of plantain slices was evaluated. The goodness of fit of Azoubel and Murr (2002) and Zungarramudi and Lupin (1980) models as applied to experimental data was evaluated using the mean relative deviation modulus (%E). Values of %E were calculated using equation 9:

$$E = \frac{100}{n} \sum_{i=1}^n \left| \frac{V_o - V_p}{V_o} \right| \quad (9)$$

where  $V_o$  and  $V_p$  are observed and predicted values respectively. Values of E less than or equal to 10% are considered to fit the experimental data satisfactorily (Azoubel and Murr, 2002).

Based on equation 1, Crank (1999) proposed an equation for diffusion coefficient of solutes in contact with an infinite amount of solution. Its solution for small values of t according to Azoubel and Murr (2002) is

$$\frac{WL}{WL_{\infty}} = 6 \left( \frac{D_a t}{\pi L^2} \right) \quad (10)$$

where  $D_a$  = apparent diffusivity ( $m^2/s$ ), L = thickness of sample (m).

Equation 10 is used when water loss from a material is directly proportional to the square root of time (Silveira et al. 1996). From equations 10 and 5, an expression for  $D_a$  at different times is

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$$D_a(t) = \frac{\pi t}{36} \left[ \left( \frac{SL}{1+St} \right) \left( \frac{WL_{\infty}^p}{WL_{\infty}^o} \right) \right]^2 \quad (11)$$

where,

$WL_{\infty}^p$  = predicted water loss and

$WL_{\infty}^o$  = observed water loss from experiment.

### 3. RESULTS AND DISCUSSION

#### 3.1 Effect of Temperature and Sucrose Concentration

The mean residual water at equilibrium for various syrup concentrations and temperatures is shown in Table 1 while the analysis of variance (ANOVA) table is summarized in Table 2.

Table 1. Mean water loss at equilibrium

| Syrup concentration<br>°Brix | Mean water loss (g H <sub>2</sub> O/100 g sample)* |        |        |        |
|------------------------------|----------------------------------------------------|--------|--------|--------|
|                              | Temperature, °C                                    |        |        |        |
|                              | 40                                                 | 50     | 60     | 80     |
| 29                           | -15.767                                            | -7.933 | 2.100  | 6.300  |
| 33                           | 3.800                                              | 7.100  | 12.100 | 15.100 |
| 41                           | 15.200                                             | 18.233 | 23.533 | 43.100 |

\*Values are mean of three replications

#### *Fishers Least Significant Difference (F-LSD)*

F-LSD (P = 0.05) of the difference between two syrup concentration means = 0.1601

F-LSD (P = 0.05) of the difference between two temperature means = 0.1849

Table 2. Summary of ANOVA on effect of syrup concentration and temperature on mean water loss of plantain chips

| Source of variation | Degrees of freedom | Water loss, gH <sub>2</sub> O/100g sample | 5%   | 1%   |
|---------------------|--------------------|-------------------------------------------|------|------|
| Treatment           | 11                 |                                           |      |      |
| Syrup concentration | 2                  | 6.932x10 <sup>4</sup> **                  | 3.40 | 5.61 |
| Temperature         | 3                  | 1.96x10 <sup>4</sup> **                   | 3.01 | 4.72 |
| Interaction         | 6                  | 1901.36**                                 | 2.51 | 5.67 |
| Error               | 24                 |                                           |      |      |

\*\*Highly significant (P=0.01)

As the temperature increased, water loss increased and residual water decreased. The analysis of variance (Table 2) shows a highly significant ( $p \leq 0.05$ ) syrup concentration, temperature and

interaction effect. A two-tailed F-LSD test at 5% level of significance shows that residual water at equilibrium is statistically different between all syrup concentration levels. Also at each syrup concentration level, statistical difference for water loss was observed between all temperature levels. At all sucrose concentrations studied, water loss was observed to increase with temperature, however, at sucrose concentration of 41°Brix, there was a very rapid increase in water loss at 80°C compared to 60°C. Table 1 also shows that at constant sucrose concentration, the mean water loss was highest at 80°C and significantly different from 40, 50 and 60°C. The results further show that for every 10°C change in the process temperature, water loss values were significantly different ( $p \leq 0.05$ ) as indicated by the difference between two temperature means of 0.1849. These results followed the same trend as reported by Tregunno and Golf (1996), Azuara et al. (1996) and Alakali et al. (2006) for apples, potatoes and mango. Residual water curves for osmosed plantain chips at different temperatures and constant sucrose concentration (Figure 1) and sucrose concentration at constant temperature (Figure 2) also show a very strong influence of temperature and syrup concentration on the process.

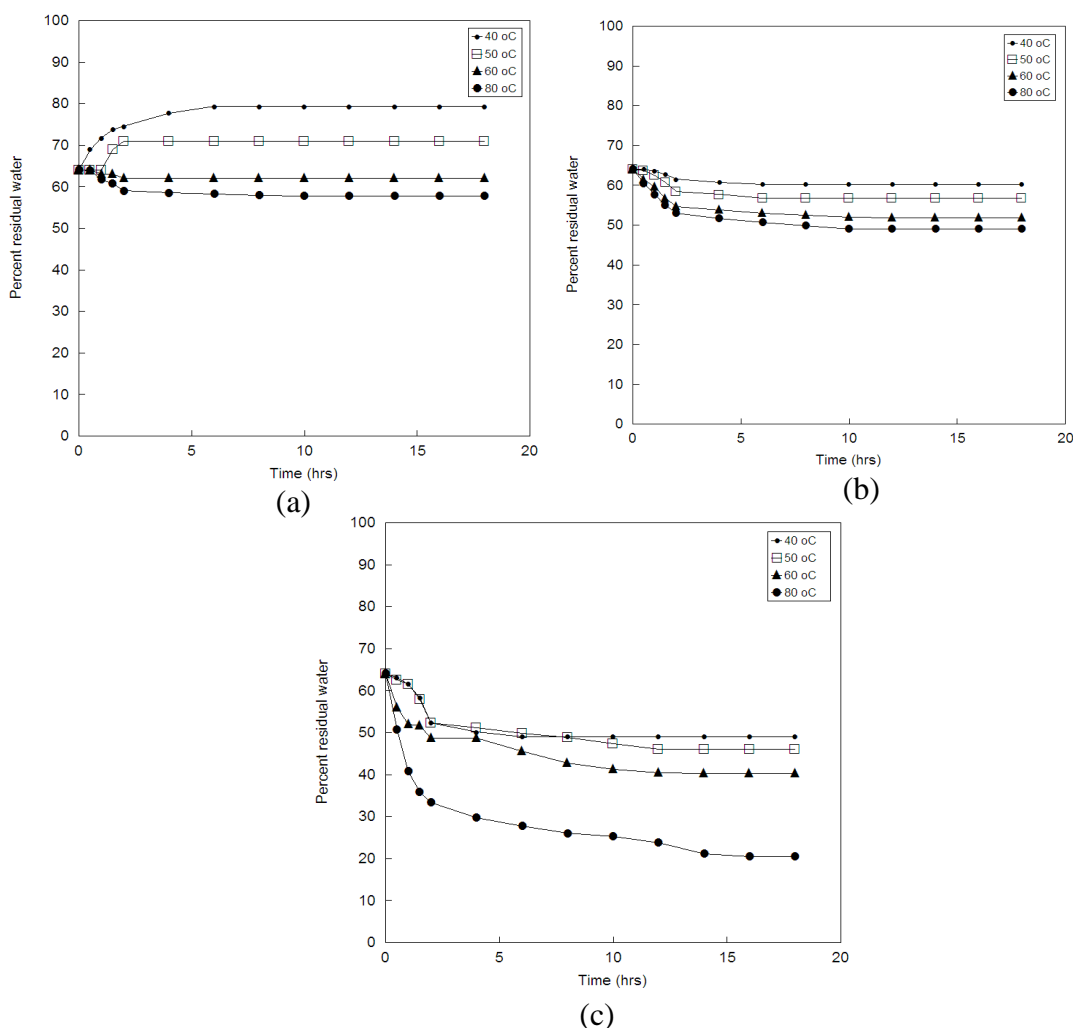


Figure 1. Effect of temperature on residual water at syrup concentrations of (a) 29°Brix, (b) 33°Brix and (c) 41°Brix

Figure 1 and Table 1 show that high osmotic dehydration temperatures favor the rate of moisture loss. At high temperatures, water molecules gain kinetic energy, hence high degree of freedom and mobility, which promote escape from the constituent resulting to increased water loss (Expedito et al., 1996, Azoubel and Murr, 2002; Alakali et al., 2006). According to Torregiani (1993), increase in temperature during osmotic dehydration could also cause tissue modification making them more permeable, thereby favouring the phenomenon of mass transfer.

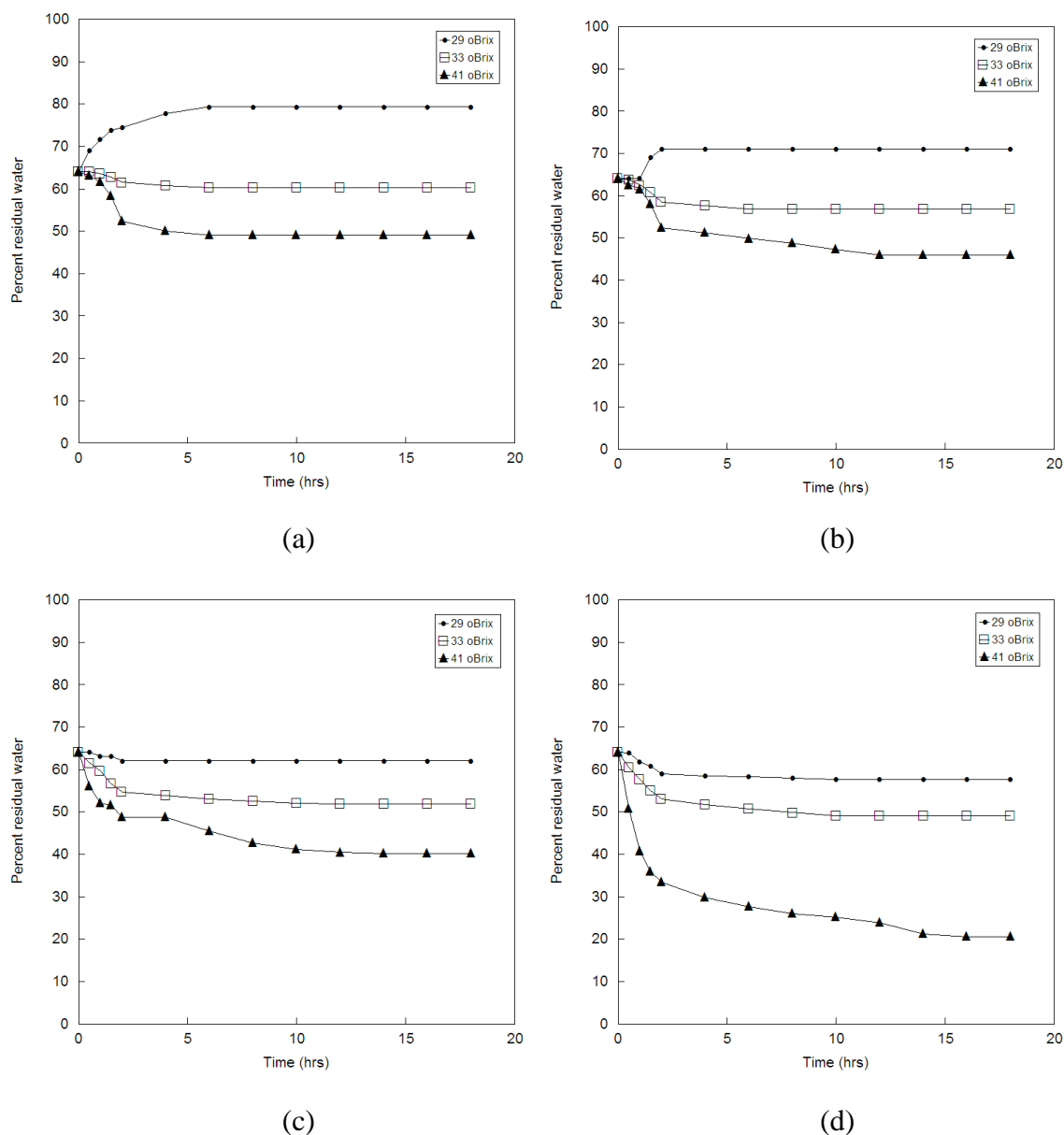


Figure 2. Effect of syrup concentration on residual water at temperatures of (a) 40 °C, (b) 50°C, (c) 60 °C and (d) 80°C

Both percent residual water (Figure 2) and mean water loss (Table 1) show that at constant temperature, residual water decreased and water loss increased as sucrose concentration increased. Water loss at 41°Brix was higher and significantly different ( $p \leq 0.05$ ) from 33 and 29°Brix. Increase in water loss due to increase in syrup concentration could be due to increase in osmotic concentration gradient between the syrup and the plantain chips. Apart from the effect of osmotic gradient, by increasing the syrup concentration, permeability of water through the tissues of the material increases due to tissue modification and selectivity thereby favoring water loss. Hang et al. (1990), Bolin and Huxsoll (1983) and Islam and Flink (1982) reported increase in water loss due to increase in syrup concentration.

Results obtained also indicate that the optimum conditions for osmotic dehydration of plantain chips are 41°Brix and 80°C during which the maximum water loss occurred. At 40°C and 29°Brix as well as 40°C and 33°Brix, there was water uptake instead of water loss from the chips (Figures 1 and 2). This indicates that at low sucrose concentration  $\leq 33^\circ\text{Brix}$  and temperature  $\leq 50^\circ\text{C}$ , osmotic dehydration of firm ripe plantain is not feasible, and at sucrose concentrations less than 41°Brix and temperatures less than 80°C, the process may not be economical as very low water loss is achieved.

### 3.2 Kinetics of Osmotic Dehydration

Mass transfer characteristics during osmotic dehydration of plantain chips were evaluated using Azoubel and Murr (2002) and Zungarramudi and Lupin (1980) models. Table 3 shows the regression parameters of Azoubel and Murr (2002) model (AMM) while Table 4 shows the regression parameters of the Zungarramudi and Lupin (1980) model (ZLM). Both models gave high regression coefficients ranging from 0.789 to 0.997 for AMM and 0.821 to 0.996 for ZLM.

Table 3. Regression and derived parameters of Azoubel and Murr (2002) model

| Syrup concentration<br>°Brix | Parameters      | Temperature, °C         |                         |                        |                        |
|------------------------------|-----------------|-------------------------|-------------------------|------------------------|------------------------|
|                              |                 | 40                      | 50                      | 60                     | 80                     |
| 29                           | n               | 13                      | 13                      | 13                     | 13                     |
|                              | R <sup>2</sup>  | 0.996                   | 0.998                   | 0.973                  | 0.996                  |
|                              | A               | -0.641                  | -0.051                  | 0.489                  | 0.185                  |
|                              | S               | 0.004                   | 0.007                   | 0.882                  | 0.789                  |
|                              | B               | -0.060                  | -0.139                  | 0.437                  | 0.146                  |
|                              | WL <sub>∞</sub> | -16.667                 | -7.194                  | 2.320                  | 6.863                  |
|                              | D <sub>a</sub>  | 3.489x10 <sup>-12</sup> | 6.878x10 <sup>-11</sup> | 1.715x10 <sup>-6</sup> | 1.857x10 <sup>-6</sup> |
| 33                           | n               | 13                      | 13                      | 13                     | 13                     |
|                              | R <sup>2</sup>  | 0.900                   | 0.789                   | 0.997                  | 0.997                  |
|                              | A               | 0.532                   | 0.483                   | 0.106                  | 0.076                  |
|                              | S               | 0.402                   | 0.216                   | 0.704                  | 0.800                  |
|                              | B               | 0.222                   | 0.102                   | 0.074                  | 0.061                  |
|                              | WL <sub>∞</sub> | 4.510                   | 9.580                   | 13.400                 | 16.310                 |
|                              | D <sub>a</sub>  | 5.664x10 <sup>-8</sup>  | 1.417x10 <sup>-7</sup>  | 1.047x10 <sup>-6</sup> | 1.413x10 <sup>-6</sup> |



| Syrup concentration<br>°Brix | Parameters      | Temperature, °C        |                        |                        |                        |
|------------------------------|-----------------|------------------------|------------------------|------------------------|------------------------|
|                              |                 | 40                     | 50                     | 60                     | 80                     |
| 41                           | n               | 13                     | 13                     | 13                     | 13                     |
|                              | R <sup>2</sup>  | 0.868                  | 0.923                  | 0.993                  | 0.997                  |
|                              | A               | 0.216                  | 0.214                  | 0.073                  | 0.027                  |
|                              | S               | 0.231                  | 0.190                  | 0.572                  | 0.831                  |
|                              | B               | 0.050                  | 0.047                  | 0.038                  | 0.022                  |
|                              | WL <sub>∞</sub> | 20.00                  | 24.570                 | 26.596                 | 48.248                 |
|                              | D <sub>a</sub>  | 1.134x10 <sup>-7</sup> | 1.177x10 <sup>-7</sup> | 5.713x10 <sup>-7</sup> | 1.493x10 <sup>-6</sup> |

n = number of observations, R<sup>2</sup> = regression coefficients, A = intercept, S=constant, B = gradient, WL<sub>∞</sub> = predicted water loss at equilibrium, D<sub>a</sub> = apparent diffusivity (m<sup>2</sup>/s)

Table 4. Regression parameters of Zungarramudi and Lupin (1980) model

| Syrup concentration<br>°Brix | Parameters     | Temperature, °C |       |       |       |
|------------------------------|----------------|-----------------|-------|-------|-------|
|                              |                | 40              | 50    | 60    | 80    |
| 29                           | n              | 13              | 13    | 13    | 13    |
|                              | R <sup>2</sup> | 0.946           | 0.744 | 0.856 | 0.936 |
|                              | K              | 0.362           | 0.572 | 0.622 | 0.503 |
|                              | SE             | 0.040           | 0.179 | 0.018 | 0.058 |
| 33                           | n              | 13              | 13    | 13    | 13    |
|                              | R <sup>2</sup> | 0.933           | 0.931 | 0.970 | 0.996 |
|                              | K              | 0.378           | 0.459 | 0.547 | 0.559 |
|                              | SE             | 0.052           | 0.059 | 0.037 | 0.033 |
| 41                           | n              | 13              | 13    | 13    | 13    |
|                              | R <sup>2</sup> | 0.915           | 0.948 | 0.821 | 0.843 |
|                              | K              | 0.443           | 0.300 | 0.063 | 0.623 |
|                              | SE             | 0.065           | 0.031 | 0.063 | 0.025 |

n = number of observations, R<sup>2</sup> = regression coefficients, K = rate constant, SE = asymptotic standard error

Figures 3 and 4 show typical plots of the observed and predicted residual water during osmotic dehydration of plantain chips for ZLM and AMM respectively. A close relationship between the experimental and predicted residual water was observed. Table 5 shows the values of the mean relative deviation modulus (%E) used to evaluate the goodness of fit of the models. The values of %E for AMM and ZLM were generally low. This indicates that the two models gave good fit to experimental data. The %E values of ZLM were generally lower than AMM. This indicates that ZLM predicted the experimental data better than AMM. According to Azoubel and Murr (2002), values of %E less than or equal to 10% indicate good fit to experimental data, and the lower the %E the better the model for predictive purposes.

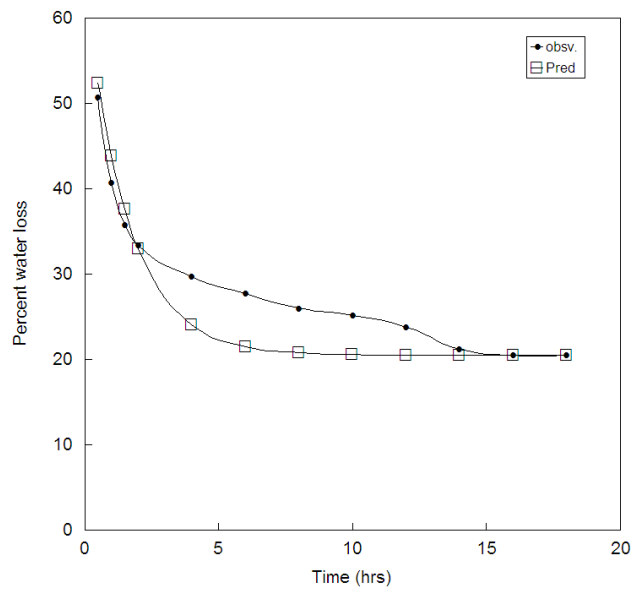


Figure 3. Typical plot of observed and predicted residual water at 41°Brix and 80°C using ZLM

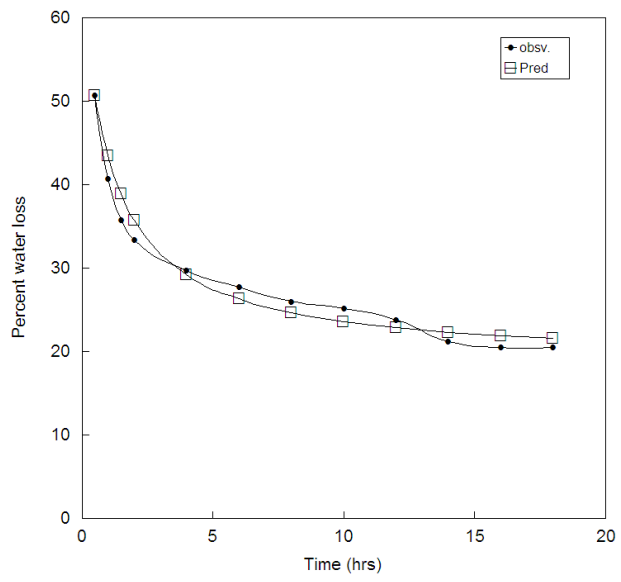


Figure 4. Typical plot of observed and predicted residual water at 41°Brix and 80°C using AMM

Table 5. Summary of mean relative deviation modulus (%E)

| Syrup concentration<br>°Brix | Models | Temperature, °C |       |       |       |
|------------------------------|--------|-----------------|-------|-------|-------|
|                              |        | 40              | 50    | 60    | 80    |
| 29                           | ZLM    | 3.38            | 7.63  | 0.212 | 0.254 |
|                              | AMM    | 12.780          | 6.236 | 0.336 | 0.752 |
| 33                           | ZLM    | 0.332           | 0.625 | 0.739 | 0.740 |
|                              | AMM    | 0.492           | 1.559 | 0.807 | 0.729 |
| 41                           | ZLM    | 1.893           | 3.900 | 3.344 | 9.465 |
|                              | AMM    | 3.487           | 2.320 | 2.450 | 5.160 |

ZLM = Zungarramudi and Lupin (1980) Model; AMM = Azoubel and Murr (2002) Model

The applicability of Ficks unsteady state diffusion model was verified based on the report of Alakali et al. (2006) and Silveira et al. (1996). According to the authors, for Fickian diffusion processes, the plot of  $WL/WL_{\infty}$  vs  $t^{0.5}$  gives a straight line. Since Figure 5 gave straight lines; consequently, apparent diffusivity ( $D_a$ ) was calculated using equation 11 based on Ficks second law of diffusion. The apparent diffusivity values (Table 3) generally increased with temperature and sucrose concentration. This was expected since water loss increased with both temperature and sucrose concentration. Azoubel and Murr (2002) and Alakali et al. (2006) observed similar trends in cherry tomatoes and mango slabs respectively. According to the authors, the kinetic energy of molecules of water increased at high temperatures resulting in increased rate of diffusion. Similarly, increase in sucrose concentration increases osmotic gradient and hence the driving force and rate of diffusion of molecules of species.

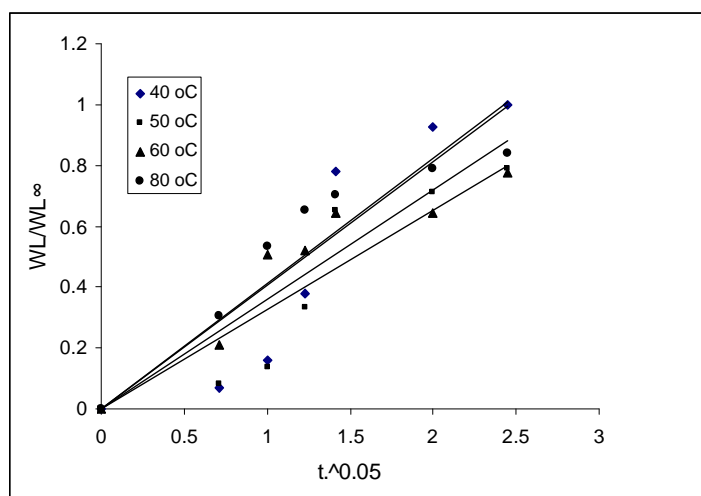


Figure 5. Typical plot of  $WL/WL_{\infty}$  vs  $t^{0.05}$  at 41°Brix and 80°C

The apparent diffusivity ranged between  $3.489 \times 10^{-12}$  to  $1.857 \times 10^{-6}$  m<sup>2</sup>/s. The apparent diffusivities corresponding to 29°Brix and 40°C, 29°Brix and 50°C were particularly very low (Table 3). It was observed that at these conditions, there was a reverse in osmotic gradient. Water diffused into the material giving negative water uptake values. This can be explained to be due to low osmotic concentration of the syrup at 29 and 33°Brix relative to the plantain, coupled with low kinetic energy of the water molecules at the low temperatures (40 and 50°C). This combined effect favored movement of water from the syrup to the plantain as opposed to what was observed at high syrup concentrations and temperatures.

#### 4. CONCLUSIONS

The following conclusions can be made based on the study:

- (a) Syrup concentration and temperature has a highly significant effect ( $p \leq 0.05$ ) on water loss in plantain chips. The rate of water loss in the plantain chips increased as both temperature and syrup concentration increased.
- (b) The optimum condition for osmotic dehydration of plantain chips was found to be 80°C and 41°Brix.
- (c) Both ZLM and AMM satisfactorily predicted the experimental data with ZLM having the best fit.
- (d) Apparent diffusivity of plantain chips increased with both temperature and syrup concentration.

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