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Elias Eyembe Lobe

University of Bamenda

Divine Bup Nde (✉ divinende@lsu.edu)

University of Bamenda

Sonchieu Jean

University of Bamenda

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Kinetics and Modeling of Osmotic Dehydration of Plantain (*Musa paradisiaca*) using a Low-calorie Sugar

Elias Eyembe Lobe^{1,2}, Divine Bup Nde^{1*}, Sonchieu Jean³

¹ Department of Nutrition, Food and Bio-resource Technology, College of Technology, University of Bamenda, Cameroon

²Department of Food Technology, National Polytechnic University Institute (NPUI), Mile 7 Nkwen, Bamenda, Cameroon. lobeeyembe@gmail.com

³Department of Social Economy and Family Management, Higher technical Teachers Training College, University of Bamenda, Cameroon

*Corresponding author present address: Department of Chemistry, Louisiana State University, divinende@lsu.edu

Abstract

The study was aimed at evaluating the influence of process variable on mass transfer parameters; water loss (WL) and solute gain (SG) on osmotic dehydration of plantain (*Musa paradisiaca*) in low calorie sugar solution. Fully matured unripe plantain fruits of the ‘False Horn’ cultivar were peeled and sliced into thicknesses of 2.5, 5 and 10mm. The slices were immersed in the commercial low-calorie sugar solution of concentrations 12.5, 25 and 50% and varying sample /solution ratio (1:5, 1:10 and 1:20) at room temperature (27±2). To investigate the effect of temperature, plantain slices of thickness 5mm were immersed in low calorie sugar solution of concentration 12.5 and sample/solution ratio 1:20 at temperatures 30, 40 and 50°C. The water WL and SG of the slices under the different experimental conditions were measured at various time intervals (10, 20, 40, 60, 80, 100, 120 and 140min). The kinetics of the osmotic dehydration was modeled using the Azuara, Peleg and Page models. Plantain slice of thickness 5mm, low-calorie sugar solution concentration of 50% at temperature 40°C, and a sample/solution ratio of 1:20 was judged best for osmotic treatment of plantains in low-calorie sugar solution. The Peleg model best described the dehydration kinetics with the highest R^2 (>0.999) and the least RMSE.

Key words: Osmotic dehydration, modeling, Water loss, Solid gain, *Musa paradisiaca*

1. Introduction

In recent years, considerable amount of attention has been paid to osmotic dehydration technique for the preservation of fruits and vegetables due to its potential to keep sensory and nutritional properties similar to fresh ones (Ganjloo et al., 2011). In osmotic dehydration, the potential difference between the osmotic pressure of fresh material and the surrounding solution provides a driving force for the withdrawal of water from cells into the solution (Rastogi et al., 2002). Mass transfer during osmotic process consists of two major simultaneous counter-current flows of water and solutes. There is also negligible amount of flow of natural solutes present in the cells into the osmotic solution (Rastogi and Raghavarao, 2004). The effect of several factors like solution concentration, temperature, immersion

time, sample thickness and shape, solution to sample ratio and applied pretreatments on kinetics of mass transfer have been extensively investigated (More and Khodke, 2019; Gribova et al., 2021; Panades et al., 2008).

Studies have been reported on the use of sucrose as an osmotic agent for osmotic dehydration of carrot, eggplant and beetroot (Junqueira et al., 2021), Litchi (Bera and Roy, 2015), kiwifruit (Jabrayili et al., 2016). The increasing interest in designing new low-calorie and minimally processed foods, the replacement of sugar in traditional processed products and the study of osmotic dehydration kinetics with the use of alternative carbohydrates have become popular over the years. Nowadays, it is important to find new alternatives to sucrose solutions, which can be used in this process. This is because the consumption of foods with regular sugar is thought to be at the origin of several life-threatening ailments such as diabetes, hypertension and coronary diseases (Cichowska et al., 2020 and Sethi and Kaur, 2019). Nowadays, it is important to find new alternative to sucrose solutions, which can be used in this process. Low calorie sugars like sugar alcohols have been used as solutes in the OD process of apples (Cichowska et al., 2019; Cichowska et al., 2020) and yacons (Mendonça et al., 2014).

The osmotic dehydration of ripe plantain using sucrose as the osmotic agent has been reported by several researchers (Durvesh and Samsher, 2015; Gallegos-Marin et al., 2016; Loa et al., 2017; Chavan et al., 2010; Haque et al., 2020). The resulting product may not be good for consumption for people with certain ailments especially diabetics because the use of sucrose coupled with the high sugar content of ripe plantain (10.42%) (Adewole and Duruji, 2010) may contribute to raising the blood sugar level and the glycemic index of the concerned. Several low-calorie sugars or artificial sweeteners are used today in zero sugar soda drinks or snack foods (Kapadiya and Aparnathi, 2017). Despite arising controversies in the use of some of these low-calorie sugars in food, there are more and more such products in the market because of the expected health benefits. Calorific values of low-calorie sugars are within the range (0–2.6 kcal/g), compared to sucrose with a calorific value of 4 kcal/g (Washburn and Nedra, 2012; Helen Turner, 2017). The glycemic index for sucrose is 65–80 compared to 0–1 for most low-calorie sugars (Redmer, 2014). Because low calorie sugars or alternative sweeteners are recommended to people with life threatening ailments such as diabetics, overweight etc. we hypothesized that it could be used as an osmotic dehydrating agent to give products of low sugar content and consequently low glycemic index.

On the other hand, studies on the kinetics and mathematical modeling of OD process of plantain using low-calorie sugars (LCS) are scarce (Alakali et al., 2008). Kinetics and mathematical modeling of mass transfer during OD process gives valuable information on the understanding of the mechanisms, composition of dehydrated material and operational design. Empirical models such as Peleg, Azuara and Page models having parameters with physical meaning have been widely used to model the rate of dehydration of different plant-based materials (Ganjloo et al., 2011; Langari and Movagharnejad, 2015; Azoubel et al., 2004). However, in literature, the suitability of these equations to model the dehydration rate of plantain is scarce. The aim of this study was to evaluate the effect of temperature, solution concentration, thickness and sample /osmotic solution ratio on mass transfer during OD process using an LCS as the osmotic dehydrating agent and to access the predictive capacity of Peleg, Azuara and Page's equations for the OD process.

2. Materials and Methods

2.1. Preparation of Plantain

Fresh fully matured and unripe plantain fruits (*Musa paradisiacal* L.) of the false horn variety were bought from a local farmer in Bamenda, North West region of Cameroon and transported to the food technology laboratory at National Polytechnic University Institute (NPUI) Bamenda. The plantain samples were kept under laboratory temperature (25- 27°C) and used within 24 hours for the experiments. The plantain fruits were washed with distilled water, peeled and sliced into 2.5, 5, and 10 mm thickness using a stainless-steel knife. The thicknesses of the slices were measured with vernier calipers. Osmotic solutions of different concentrations of a commercial LCS (12.5, 25 and 50 %) were prepared by dissolving the required quantity in distilled water.

2.2. Osmotic dehydration procedure

To evaluate the effect of process parameters on the mass transfer of the OD process, 3 different concentrations of the solution (12.5, 25 and 50%) and slices of thickness (2.5, 5, and 10 mm) were used in the study. The plantain slices were immersed in 200 ml beakers containing the respective solutions in the ratio 1:10 (w/v). The beakers were allowed to stand at room temperature (25 ±2°C) and at varied time intervals (10, 20, 40, 60, 80, 100, 120 and 140min). The effect of sample solution ratio (1:5, 1:10 and 1:20) was evaluated at ambient temperature (25±2°C), with slices of thickness 5mm in 12.5% solution concentration. The influence of temperature (30, 40 and 50°C) on mass transfer was investigated with slices of thickness 5mm in 12.5% LCS concentration. and material to solution ratio of 1:10 (w/v). After each experiment, samples were washed with distilled water and gently blotted using a tissue to remove the excess water and the weight taken using an electronic balance (0.01 precision KD-CN 1107260) to evaluate the change in mass.

2.3. Determination of mass transfer parameter

The initial moisture content of raw fresh plantain and OD plantain slices after each contact time was determined by drying in an electro thermal oven (Model DHG SearchTech Instruments, Germany) at 105°C until constant weight (AOAC, 2000). The water loss (WL) and solid gain (SG) were determined according to the method described by Zhelyazkov et al., (2020) using equations 1 and 2 respectively.

$$WL (\%) = \frac{W_i X_i - W_f X_f}{W_i} \times 100 \dots\dots\dots \text{Equation 1}$$

$$SG (\%) = \frac{W_f X_{stf} - W_i X_{sti}}{W_i} \times 100 \dots\dots\dots \text{Equation 2}$$

Where WL and SG are moisture and solid gain respectively, W_i and W_f are respectively the initial and final weights of samples in grams for a given run; X_i and X_f are initial and final moisture content for a given run, respectively and X_{sti} and X_{stf} are the initial and final solid content for each run.

2.4. Mathematical Modeling

The Peleg, Azuara and Page's models were tested using kinetic data from different experiments on temperature effect (Table 1). These models are frequently used in the literature to describe the drying kinetics of some foods and vegetables.

Table 1: List of different drying models used

No	Model	Model equation	Reference
1	Peleg	$X = X_0 + \frac{t}{K_1 + K_2 t}$	Ganjloo et al., (2011) and Azoubel et al., (2004)
2	Azuara	$XG = \frac{\beta i t XG_{\infty}}{1 + \beta i t}$	Ganjloo et al., (2011); Bera and Roy (2015)
3	Page	$W_{a \text{ or } s} = \exp(-At^B)$	Azoubel et al., (2004), Ganjloo et al., (2011)

In order to evaluate the constants K_1, K_2, A, B and βi in the respective models, the equations were expressed in linear forms as follows:

Peleg's model:

$$\frac{t}{x - x_0} = K_1 + K_2 (t) \quad \text{Eq.3}$$

X is the amount of water or solids at time t , X_0 is the initial amount of water or solids, t is the time, and k_1 and k_2 are Peleg constants.

Page's Model was linearized to

$$\ln(-\ln W) = B \ln t + \ln A \quad \text{Eq. 4}$$

where W represents the water lose or solid gain at time t ; A and B are Page constants

While the Azura was simplified to

$$\frac{t}{WLt} = \frac{1}{WL_{\infty}} (t) + \frac{1}{\beta_1 WL_{\infty}} \quad \text{Eq. 5}$$

$$\frac{t}{SGt} = \frac{1}{SG_{\infty}} (t) + \frac{1}{\beta_2 SG_{\infty}} \quad \text{Eq. 6}$$

WLt and SGt are the average percentage of water loss and solid gain at any time, WL_{∞} and SG_{∞} are the moisture loss and solid gain fraction at equilibrium, β_1 and β_2 are the constants related to the rate of water lose and the rate of

solid diffusion into the product respectively. The moisture loss and solid gain fraction at the equilibrium time (β_1 and β_2) were obtained from the slopes and intercepts of plots of equations 5 and 6.

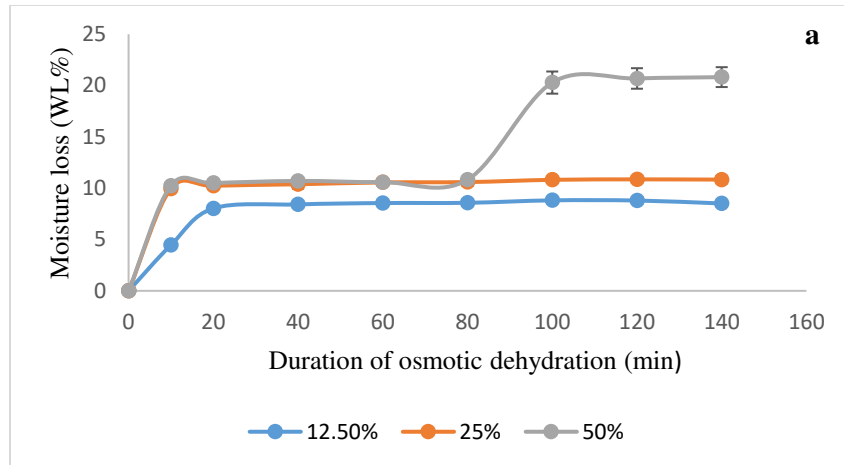
2.5. Statistical analysis

Analysis of variance (ANOVA) on Stargraphics Centerion version XVII.II. was used to test significant differences between means. Duncan multiple range test was used to detect differences between means. The fitting of the mathematical functions (Peleg, Azuara, and page) to the experimental points was on using Sigma plot (Version 14.5 Systat Software Inc.). The determination coefficient (R^2) and the root mean square error ($RMSE$) were used to evaluate the goodness of fit of the model. The best model was that with the highest R^2 , and the least $RMSE$. Graphs were plotted using Microsoft Excel 2007.

3. Results and Discussions

3.1. Effect of concentration on moisture loss and solid gain

Figure 1 and Figure 2 show the moisture loss and solid gain as affected by concentration of osmotic solution at different slice thickness. In general, there was increased moisture loss and solid gain associated with increased concentration of osmotic solution at all slice thickness. This observation could be because an increase in solute concentration accentuates the osmotic pressure gradient between the fruit and the solution, hence establishing an enhanced driving force for mass transfer. There was an observed sudden and pronounced WL at 100, 60 and 20 min for the 50% concentration for the 2.5, 5 and 10mm slices. Yadav et al. (2012) made a similar observation and explained that increased concentration showed its pronounced effect on WL after a long time. Meanwhile for SG, there was no significant difference ($P < 0.05$) at concentration 25 and 50% concentrations especially for the 5 and 10mm slice thickness (Figures 2 a and b).



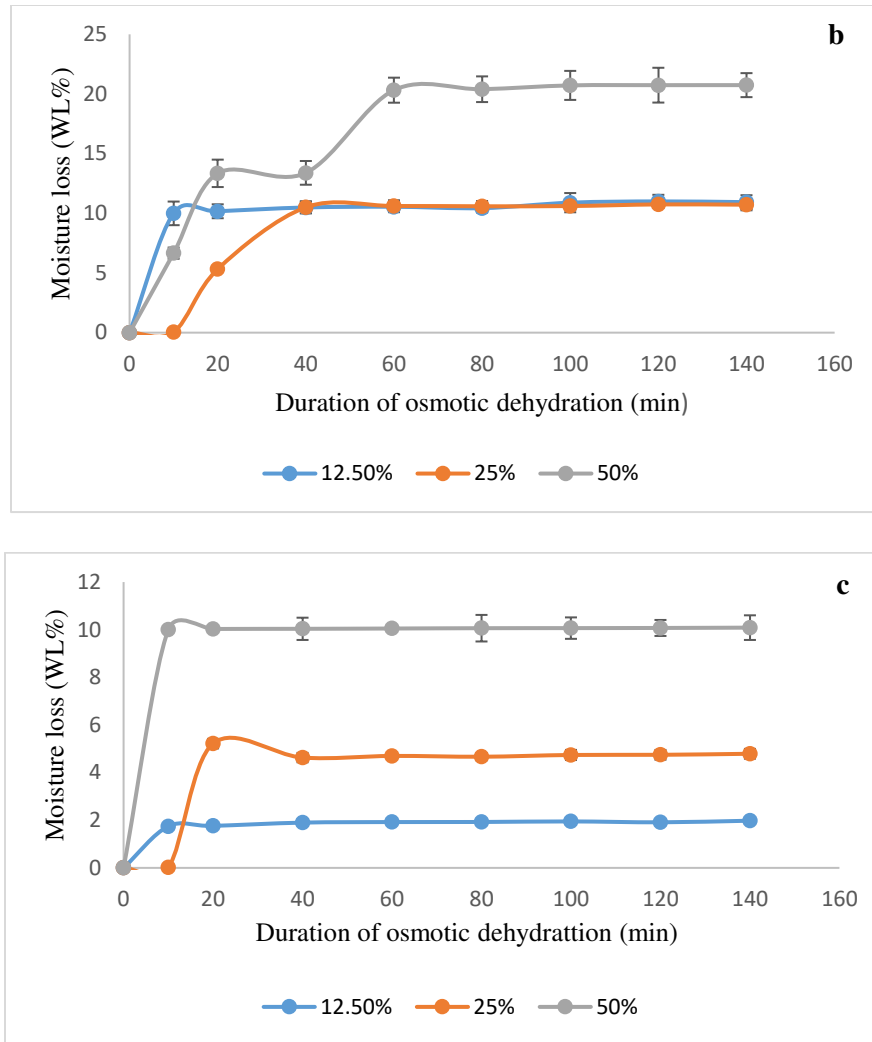


Fig. 1 Effect of solution concentration on moisture loss during osmotic dehydration of plantain
(a) 2.5mm (b) 5 mm and (c) 10mm slice thickness

The results also demonstrated that water loss (Figure 1) and solid gain (Figure 2) were higher at initial stages of osmosis and finally slowed down and became stable in later stages. These results corroborate with findings of Jalali et al., (2008) and Md Salim et al., (2016) on osmotic dehydration of banana and broccoli stalk slices respectively. Md Salim et al. (2016) explained that the higher water removal from the sample during the early stage of the process reduces concentration gradient between the solution and the sample and subsequently decreases the driving force, thus lowering the mass transfer rate.

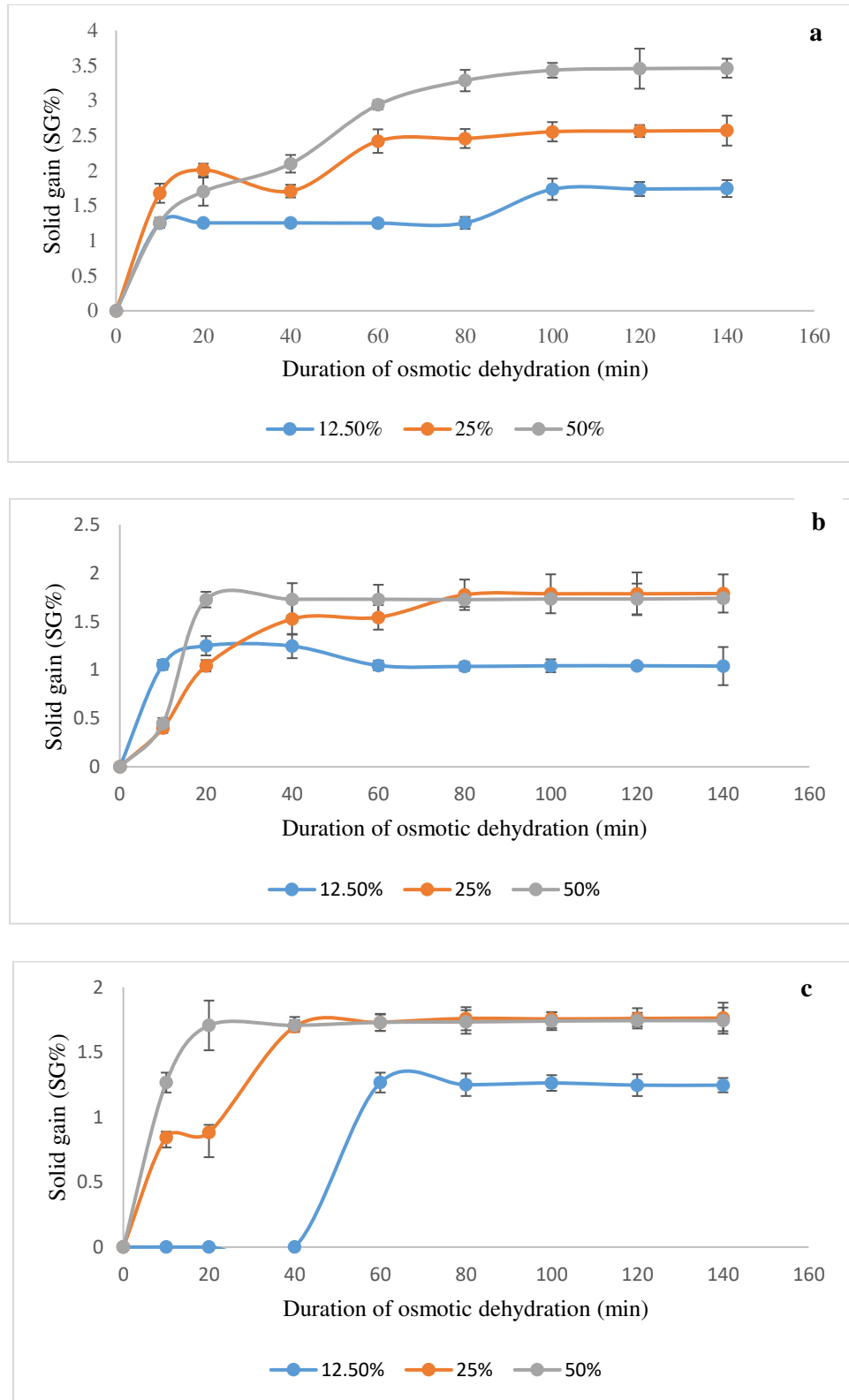
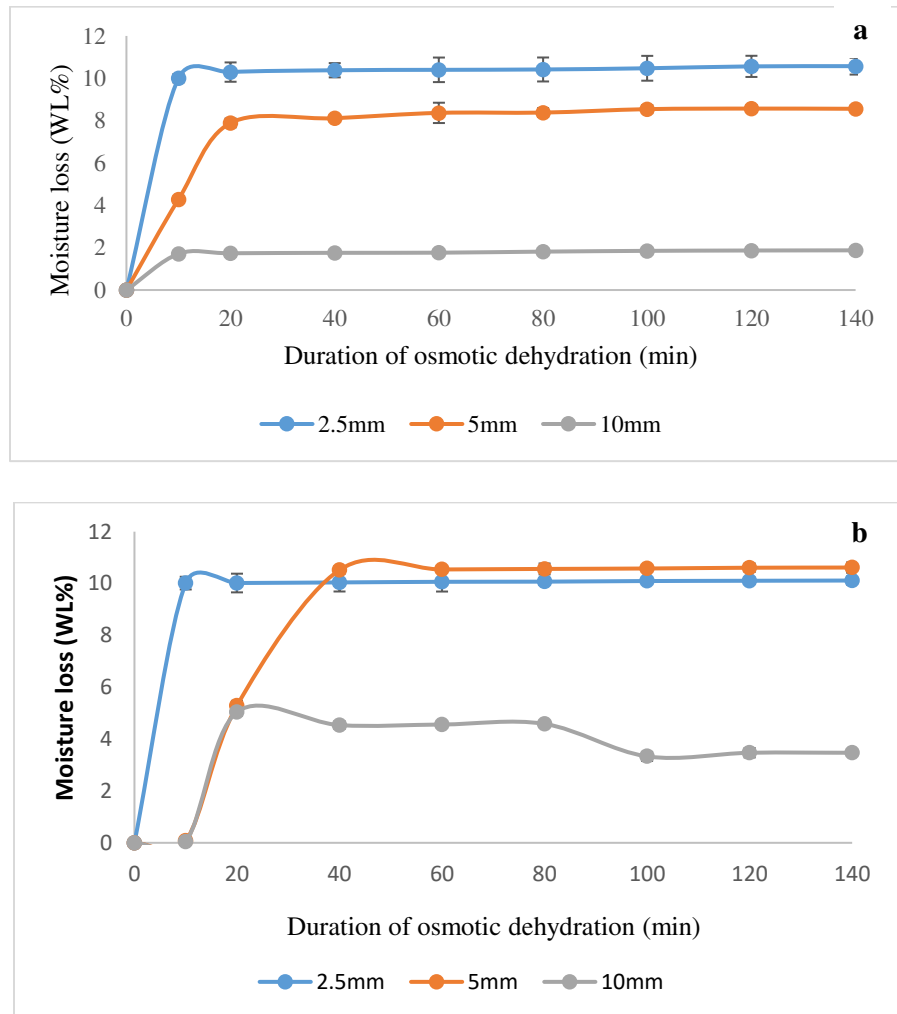


Fig. 2 Effect of solution concentration on solid gain (SG) during osmotic dehydration of plantain (a) 2.5mm (b) 5 mm and (c) 10mm slice thickness

3.2. Effect of thickness on moisture loss and solid gain

Figures 3a, b, and c show the effect of plantain slice thickness on moisture loss while figures 4a, b and c depict the effect on solid gain. The percentage moisture loss decreased significantly with increased slice thickness; 10% in 2.5mm to 4.5% in 5mm and 1.7% in 10 mm at 12.5% solution concentration. However, the final moisture loss was not significantly different for 5 and 10mm at higher concentrations. Solid gain (Figure 4a, b and c) was significantly higher at all concentration for the 2.5 mm thick slice compared to 5 and 10 mm... The results are similar to those of Paradkar and Sahu, (2018), More and Khodke (2019), Haque et al. (2020) for osmotic dehydration of plantain slices, Kolawole et al. (2007) and Rastogi et al. (2002). All authors reported a decrease in the rate of water loss and solids gain with increase in slice thickness. According to Kolawole et al. (2007) this may be due to the width ratio and the increase of surface area in contact with the osmotic solution. Rastogi et. al. (2002) explained that the thicker solid, dehydrated more slowly because the length of the diffusion path is greater compared to the smaller pieces.



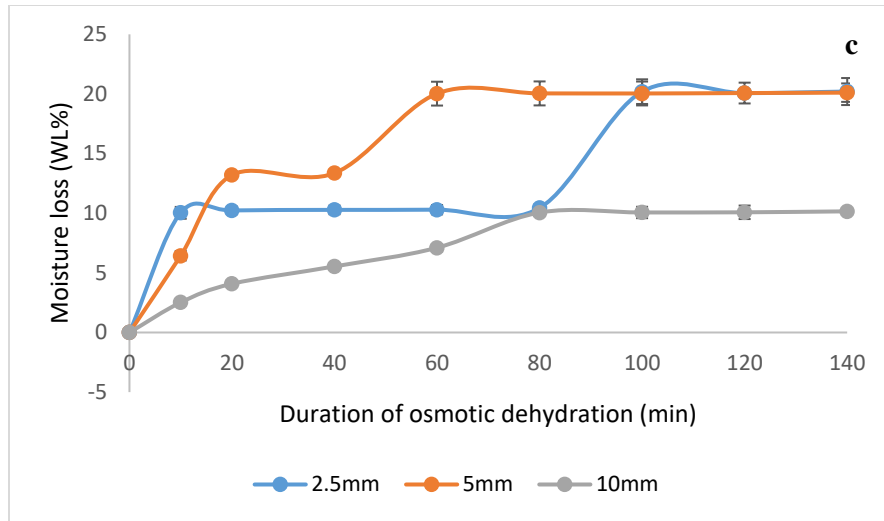
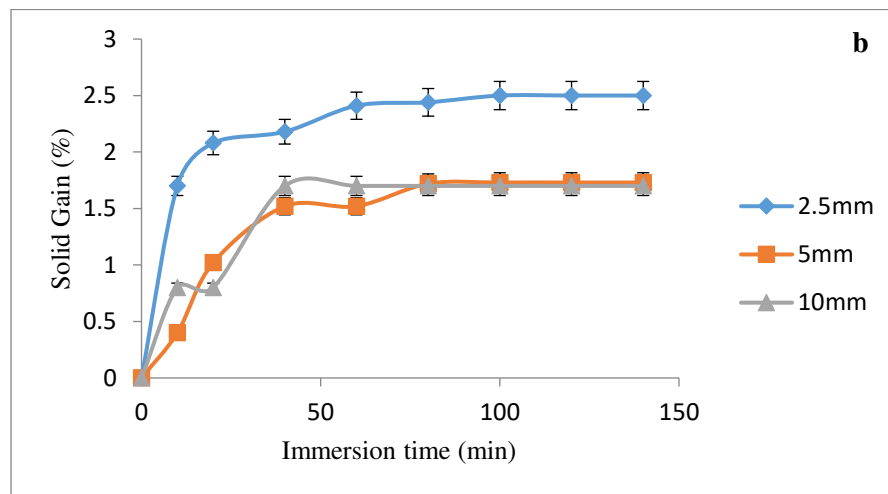
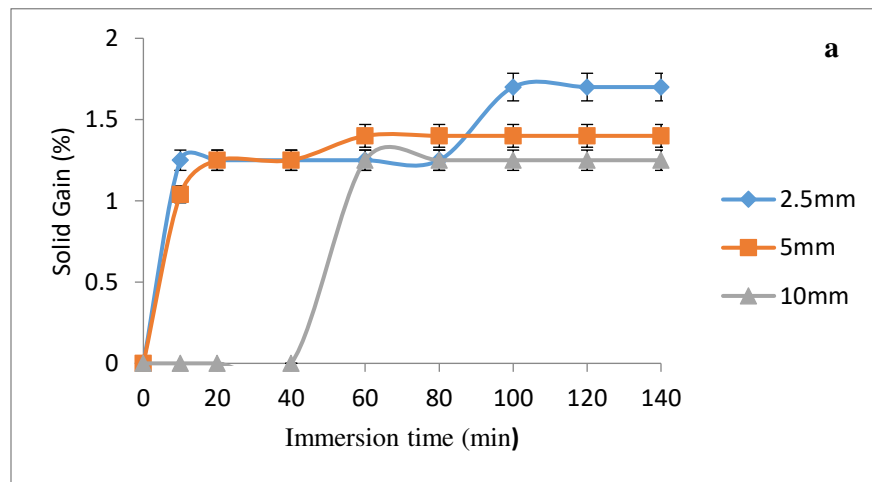


Fig.3Effect of slice thickness on moisture loss during osmotic dehydration (a) 12.5% concentration (b) 25% concentration and (c) 50% concentration



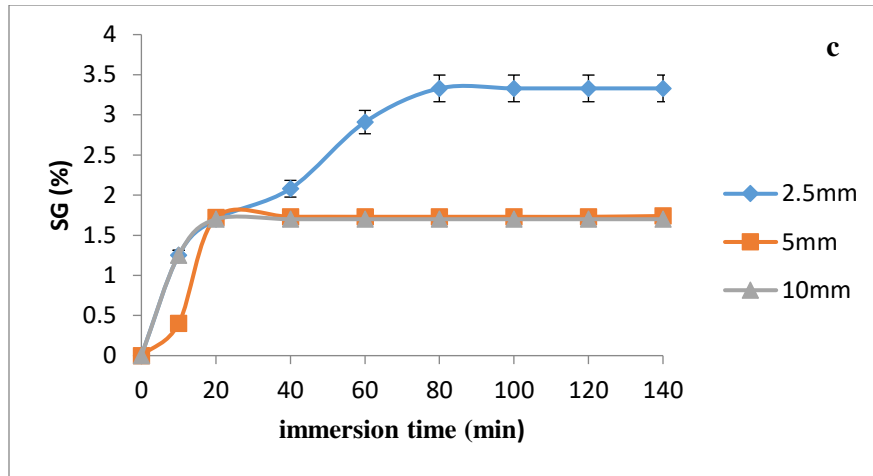


Fig.4Effect of slice thickness on solid gain during osmotic dehydration(a) 12.5% concentration (b) 25% concentration and (c) 50% concentration

3.3. Effect of plantain / sugar solution ratio on moisture loss and solid gain

Figure 5 (a and b) represents the effect of sample /solution ratio (1:5 to 1:20 w/v) on moisture loss and solid gain of plantain slices during osmotic dehydration. Moisture loss from plantain slices increased with increase in sample/ solution ratio with about double the value recorded at 1:20w/v compared to that at lower ratios. There was no significant difference ($P < 0.05$) in moisture loss between sample/solution ratios 1:5 and 1:10. On the other hand, there was a decrease in SG with an increase in sample/solution ratio even though no significant difference was observed between 1:10 and 1:20 ratios. This observed trend in moisture loss corroborate with that reported by Akbarian et al., (2013). The authors reported that an increase in osmotic sample mass/solution ratio resulted in an increase in both the solid gain and moisture loss of the osmotic dehydrated samples. As dehydration progresses, the osmotic solution becomes increasingly diluted and the driving force for further release of water drops, thus there is low WL and SG at low solution to sample (Ramya and Jain, 2016). Thus, 1:20 ratio represents the suitable sample /solution ratio for OD of plantain in the low-calorie sugar solution.

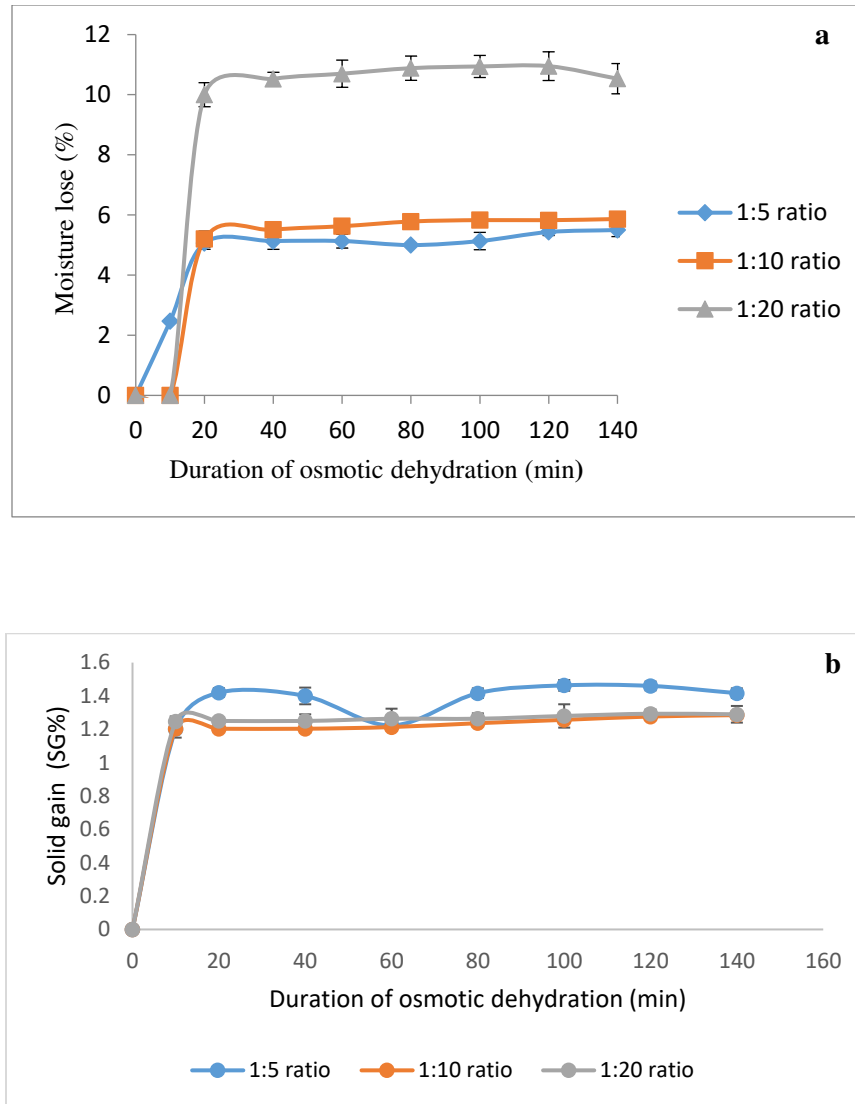


Fig.5Effect of sample /solution ratio on (a) moisture loss (b) Solid gain during osmotic dehydration of plantain slices at concentration 12.5% and slice thickness 5mm

3.4. Effect of temperature on moisture loss and solid gain

Figure 6 (a and b) illustrates the effect of temperature on moisture loss and solid gain during osmotic dehydration of plantain. It was observed that the moisture loss (WL) increased with increased temperature in the first 1h showed no significant difference between 30 – 40°C within this period. However, above the 1h, moisture loss at 40°C was significantly higher compared to loss at 50 and 30°C. On the contrary, solid gain (SG) increased significantly with increase in temperature all through the experimental period.

This corroborates with findings by Islam (2019) and Jalali et al. (2008) who reported increased moisture loss and SG with increased temperatures during osmotic dehydration of papaya and banana slices respectively. The

researchers indicated that, higher temperatures decrease the viscosity of the osmotic solution and external resistance to mass transfer rate at the sample surface thus, facilitating the outflow of water. On their part, Singh and Gangwar, (2020) working on osmotic dehydration of carrot slices associated increase moisture loss at higher temperatures to rise in fruit membrane permeability which promotes swelling and plasticization of cell membrane, and better water transfer characteristics on the product surface due to lower viscosity of the osmotic medium. Regarding the decreased moisture loss observed at 50°C, Gallegos-Marín et al. (2016) made similar observation on the influence of OD on the structural properties of plantain. The authors attributed this decrease WL at higher temperature (above 40°C) to increased density (reduced porosity) of samples, due to rapid solute impregnation and starch gelatinization. They explained that starch swelling in amorphous areas due to water absorption, reduces water outlet, in addition to the solute barrier which prevented the flow of water and consequently reduced WL at higher temperature. Osmotic solution temperature of 40°C could be retained as the best temperature.

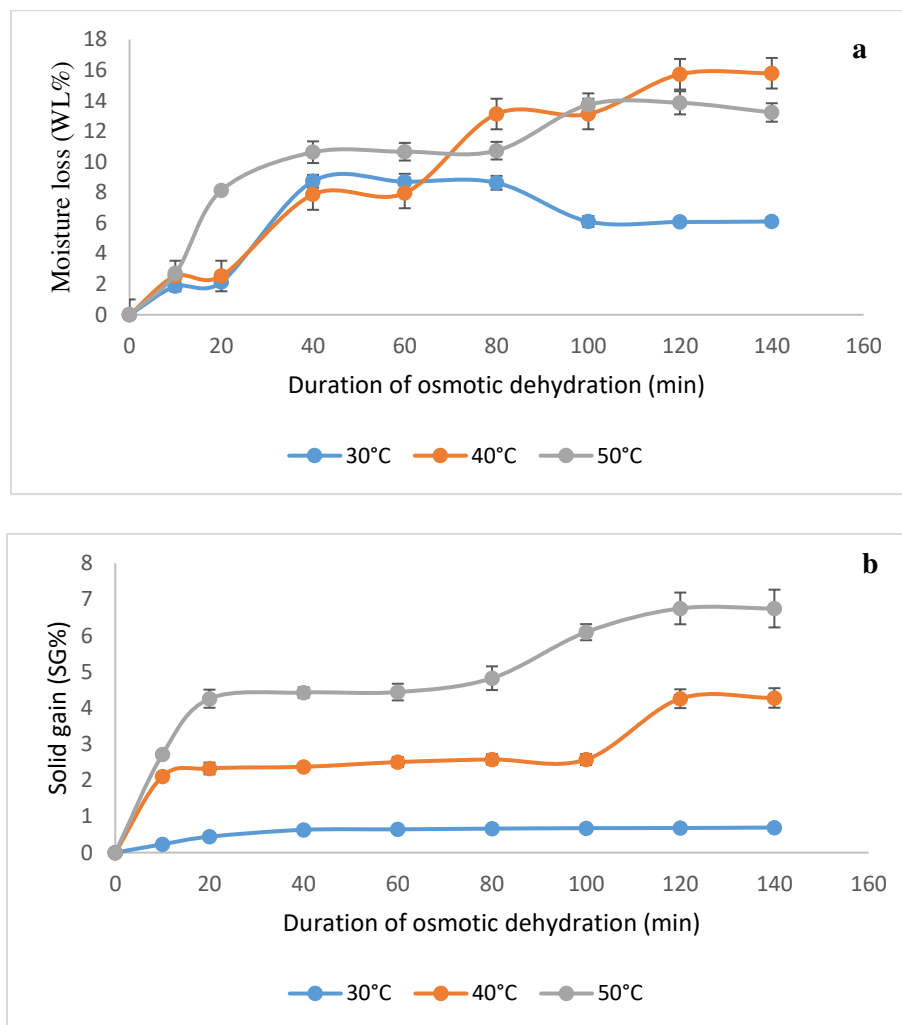


Fig. 6 Effect of temperature on (a) moisture loss and (b) Solid gain during osmotic dehydration of plantain at concentration 12.5% and slice thickness 5mm

3.6. Mathematical modeling of water loss and solid gain during OD process

In this study, the Peleg, Azuara and Page equations were used to evaluate osmotic dehydration kinetics of plantain slices. Parameters of the three equations calculated from the plots of data obtained at 30, 40 and 50°C, plantain slices/osmotic solution ratio 1:20, slice thickness of 5mm, and 12.5% solution concentration are shown in table 1. Regression coefficients (R^2) and Root Mean Square Errors (RMSE) were used to check the validity of the models. R^2 values from the PELEG model were very close to unity while the corresponding RMSE values were all less than 0.065 which was an indication of the model ability to adequately describe the osmotic dehydration process of plantains with the low-calorie sugar.

Table 1: Parameters for the equations used to model the kinetic data for the osmotic dehydration of plantain

AZURA Model								
Weight Loss					Solid Gain			
Temp (°C)	β_1	WL_{∞}	R^2	RMSE	β_2	SG_{∞}	R^2	RMSE
30	0.013	14.08	0.841	1.042	0.052	0.812	0.988	5.979
40	0.005	41.67	0.511	1.073	0.031	4.42	0.764	5.537
50	0.026	18.18	0.942	0.601	0.029	9.708	0.935	1.689
PELEG Model								
	K_1	K_2	R^2	RMSE	K_1	K_2	R^2	RMSE
30	0.040	-0.017	0.999	0.017	0.005	-0.030	1	0.0009
40	0.110	-0.020	0.997	0.046	0.077	-0.033	0.998	0.065
50	0.056	-0.019	0.999	0.019	0.120	-0.037	0.998	0.065
PAGE Model								
	A	B	R^2	RMSE	A	B	R^2	RMSE
30	-0.206	0.503	0.890	0.153	4.468	-0.539	0.9100	0.147
40	-0.316	0.457	0.915	0.121	-0.384	0.234	0.691	0.136
50	-0.652	0.302	0.743	0.154	-1.520	0.124	0.882	0.068

The Peleg constant K_1 relates to the initial mass transfer coefficients for SG and WL. The parameter K_2 describes the rate of SG and WL at the equilibrium stage of osmotic dehydration process. The K_1 parameter for WL of the Peleg's model increased with solution temperature from 30 to 40°C and then decreased at 50°C. Cichowska et al.(2018)reported that the $1/K_1$ of the Peleg's model, describes the initial dehydration rate. was highest at 30°C followed by dehydration rate at 50°C and then decreased at 40°C, as reflected in the values of K_1 (Table2). Suggesting that initial rate of mass transfer (WL) decreased up to 40° and then increased thereafter. Cichowska et al. (2018)also indicated that the lower the K_2 parameter, the higher the water removal at equilibrium.

The trend for K_1 parameter for SG increased steadily with elevation in temperatures meanwhile there was an observed decreased in K_2 values with temperature. Ganjloo et al. (2011) reported decreased K_1 values for WL and

SG with increased temperature for Peleg model in seedless guava (*Pisidium guajava* L.). This implies initial rate of SG decreased with increased temperature while the equilibrium SG increased with increasing temperature.

4. Conclusion

Low calorie sugar was successfully used to carry out the osmotic dehydration of raw plantain slices with results comparable to those obtained with salt and sucrose solutions. All parameters tested slice thickness, solution concentration, sample /solution ratio, and temperature had significant effects on Water loss and Solid gain. Peleg's model fits best the experimental data due to high R^2 values (>0.999) and low RMSE values. Plantain slice of thickness 5mm, low-calorie sugar solution concentration of 50% at temperature 40°C, and a sample/solution ratio of 1:20 was judged best for osmotic treatment of plantains in low-calorie sugar solution.

Author Contribution LOBE ELIAS: Conceptualization, methodology, investigation, writing of original draft. DIVINE BUP: Conceptualization, methodology, investigation, supervision, writing of original draft.

SONCHIEU JEAN: Conceptualization, methodology, investigation, supervision, writing of original draft.

Declarations

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Competing Interests The authors declare no competing interests.

Data availability statement All the data that support the findings of this study are available with the authors and can be made available upon reasonable request.

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