Optimization of osmotic dehydration of papaya followed by air-drying

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Abstract

Papayas are a fragile fruit; characteristic that limits large-scale exportation from the producing centers to countries in temperate regions. Loss of fruit ranges from 10% to 40% and could be reduced if papayas were dried. The process of osmotic dehydration followed by air-drying was studied and modeled for papaya preservation, so it could be optimized. The developed model has been validated with experimental data and simulations have shown how the operating conditions affect the process. An optimization was done using the model in order to search for the best operation condition that would reduce the total processing time.

Keywords: Papaya; Optimization; Osmotic dehydration; Drying

1. Introduction

Papaya (*Carica papaya*) is an important fruit crop grown widely in tropical and subtropical lowland regions. The fruit is nutritive, rich in vitamins A and C and presents good organoleptic characteristics. Its fragility, however, is a characteristic that limits large-scale exportation to countries in temperate regions. Brazil is one of the main producers of the fruit and the total post harvest loss is estimated from 10% to 40% of total production making the preservation of papayas an interesting field of study.

Water removal from fruit and vegetables by drying is one of the oldest forms of food preservation known to man and is the most important process to preserve food. Water, being one of the main food components, has a decisive direct influence on the quality and durability of foodstuffs through its effect on many physico-chemical and biological changes. Water removal is the main task while preserving food (Lenart, 1996) reducing the moisture contents to a level, which allows safe storage over an extended period of time. Dried foods also present low storage and transportation cost when compared to the fresh ones (Okos, Narsimham, Singh, & Witnauer, 1992).

Conventional air-drying is a simultaneous heat and mass transfer process, accompanied by phase change (Barbanti, Mastrocola, & Severine, 1994) and is a high cost process. A pre-treatment, such as osmotic dehydration, can be used in order to reduce the initial water content, reducing total processing and air-drying time. Osmotic dehydration is a useful technique that involves product immersion in a hypertonic aqueous solution leading to loss of water through the cell membranes of the product and subsequent flow along the inter-cellular space before diffusing into the solution (Sereno, Moreira, & Martinez, 2001). For fruit dehydration, sucrose solutions with concentrations from 50° to 70 °Brix have been used (Lerici, Pinnavaia, Dalla Rosa, & Bartolucci, 1985). The osmotic process has received considerable attention as a pre-treatment so as to reduce energy consumption and improve food quality (Jayaraman & DasGupta, 1992; Karathanos, Kostaropoulos, & Sarava-

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Nomenclature

A_i	surface area of phase i (m^2)	ρ	density (g/m^3)
C_i^j	mass concentration of j in phase i (g/m^3)		
D	effective diffusivity (m^2/h)	*Subscripts*	
H	moisture content (g_{water}/g)	eq	equilibrium
K_m	effective mass transfer coefficient ($1/h\ m^2$)	FR	fruit
M	mass (g)	OS	osmotic solution
M_S	mass (dry basis) (g)	ODD	osmotic dehydration device
R	drying rate at the constant-rate period ($g/h\ m^2$)		
t	time (h)	*Superscripts*	
V_i	volume of phase i (m^3)	S	sucrose
α	shrinking factor of the fruit	W	water
δ	height of the fruit (m)		

cos, 1995; Torreggiani, 1993). Besides reducing the drying time, the osmotic dehydration as a pre-treatment also inhibits enzymatic growing, retains natural color (without sulphite addition) and retains volatile aromas during the subsequent drying (Pokharkar, Prasad, & Das, 1997).

In this work, the osmotic dehydration of papaya followed by air-drying in a fixed bed was studied. Experimental data were collect and used to obtain the mass transfer coefficients for osmotic dehydration and diffusion coefficients for the air-drying step. The integrated process was modeled and optimized in order to achieve the operating condition that minimizes total processing time. Although several works on osmotic dehydration and air-drying of fruits have been published lately (Agnelli, Marani, & Mascheroni, 2005; Alves, Barbosa, Antonio, & Murr, 2005; Babalis & Belessiotis, 2004; Corzo & Gómez, 2004; Demirel & Turhan, 2003; Doymaz, 2004; Fito, 1994; Karim & Hawlader, 2005; Togrul & Pehlivan, 2004; Tsamo, Bilame, Ndjouenkeu, & Nono, 2005) few have considered the integrated process and its optimization.

2. Materials and methods

2.1. Preparation of samples

First, papayas were washed with water with chlorine (50 ppm active chlore/15 min), and then peeled and with the help of a cutting device papaya slices were produced in order to obtain cubes of same dimensions (3.0 cm average side). The slices were whitened passing saturated water vapor (100 °C for 2 min). The initial concentration of solute (°Brix) was determined by refractometry. For the refractometry, the papaya samples were crushed and homogenized in an ultra-turrax and the osmotic solution was collected using a syringe (5 mL). The soluble solids content (°Brix) was determined in a PZO WARSZAWA refratometer model RL2 NR2720 (0.0–90.0 ± 0.01% °Brix). The moisture content was determined by direct heating in a drying oven at 105 °C for 48 h according to the AOAC method 931.04 (AOAC, 1990). The initial average values for the main characteristics of the pre-processed papaya are shown in Table 1.

The osmotic solution used in each experiment was prepared by mixing food grade sucrose with the amount of distilled water. The osmotic solution pH was adjusted to 3.0 by addition of food grade citric acid, and sodium benzoate was added to stabilize the final product. The osmotic solution to fruit ratio used was maintained at 4:1 in order not to diluted the osmotic solution by water removal during the runs, which can lead to local reduction of the osmotic driving force during the process. Ten papaya cubes randomly formed each experimental group and each experiment was done in triplicate.

2.2. Osmotic dehydration

An experimental group was immersed in the osmotic solution of given concentration and temperature during a period of time. Experiments were performed with the same constant magnetic agitation. The solution was agitated continuously with a magnetic stirrer to maintain a uniform temperature throughout the experiment, thus, enhancing equilibrium conditions. The process temperature was monitored using a thermocouple and a heating plate (Fig. 1).

In the experiments made to estimate the mass transfer coefficients of the dehydration process, the samples were kept in the osmotic solution for 1.0, 2.0 and 3.0 h. After removal from the solution, the dehydrated cubes of each group were drained, blotted with absorbent paper to remove the excess solution, and weight, moisture content and °Brix were measured individually.

Table 1
Initial average values for the main characteristics of the pre-processed papayas

Characteristic	Average	SD
Moisture content (%)	87.83	0.27
Soluble solids content (°Brix)	10.10	0.14
pH	5.37	0.07
Acidity ($mg_{citric\ acid}/g_{fruit}$)	0.15	0.01

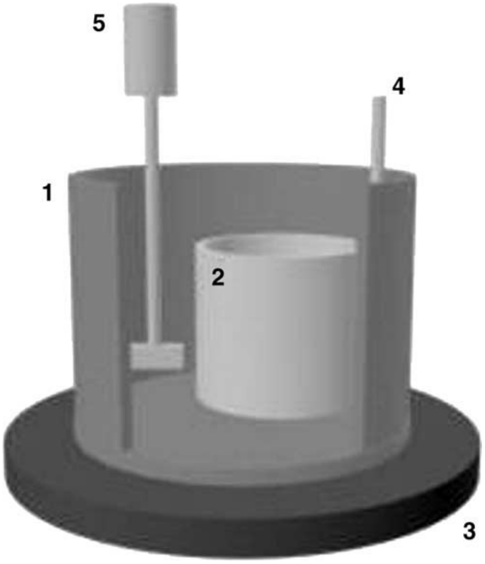

Fig. 1. Experimental setup for osmotic dehydration of papayas: (1) osmotic dehydration apparatus; (2) perforated basket with the papaya cubes; (3) heating plate; (4) thermocouple.

2.3. Air-drying

In the experiments made to study the process of osmotic dehydration followed by air-drying, the samples were kept in the osmotic solution for 3.0 h. After removal from the solution, the dehydrated cylinders of each group were drained, blotted with absorbent paper to remove the excess solution, and transferred to the fixed bed air-dryer.

The air-dryer used in the experiments was built in wood and covered with aluminum foil, having height of 1.3 m and width and length of 0.34 m. Air is injected at the base of the dryer through a 3.5 CV blower. Before entering the dryer the air is heated by electrical resistances with 2250 W (Fig. 2).

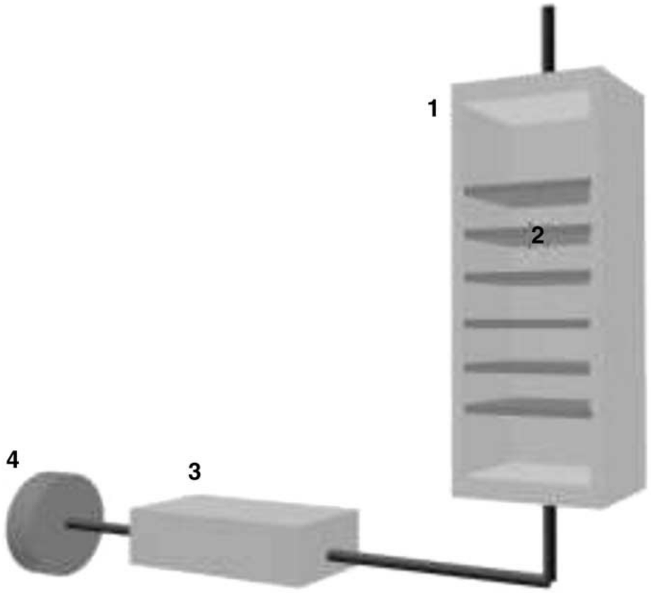

Fig. 2. Experimental setup for air-drying of papayas: (1) fixed bed dryer; (2) shelves with the papaya cubes; (3) heating box; (4) blower.

Each group sample was set in one dryer shelf and kept drying for 8.5 h. Every 30 min the papaya cubes were weighted in order to calculate its moisture content by mass balance. After the end of the air-drying process, all cubes of each group had their weight, moisture content and °Brix measured individually.

3. Mathematical model

Mathematical models for the osmotic dehydration and for the air-drying processes were developed in order to optimize the entire operation, searching for the minimum processing time. The model developed for the osmotic dehydration process has considered the mass transfer between the fruit and the osmotic solution (water and sucrose).

The mass balance for the fruit considers the mass transfer of water from the fruit to the osmotic solution and the mass transfer of sugar from the osmotic solution to the fruit:

$$\frac{\mathrm{d}M_{\mathrm{FR}}^{\mathrm{W}}}{\mathrm{d}t} = -K_{\mathrm{m}}^{\mathrm{W}} \cdot A_{\mathrm{FR}} \cdot \left(C_{\mathrm{FR}}^{\mathrm{W}} - C_{\mathrm{OS}}^{\mathrm{W}}\right) \cdot V_{\mathrm{FR}}, \tag{1}$$

$$\frac{\mathrm{d}M_{\mathrm{FR}}^{\mathrm{S}}}{\mathrm{d}t} = -K_{\mathrm{m}}^{\mathrm{S}} \cdot A_{\mathrm{FR}} \cdot \left(C_{\mathrm{FR}}^{\mathrm{S}} - C_{\mathrm{OS}}^{\mathrm{S}}\right) \cdot V_{\mathrm{FR}}. \tag{2}$$

During the osmotic dehydration process the fruit presents a considerable shrinkage, which has to be considered by the mathematical model in order to improve the physical representation of the process and to increase the confidence on the mass transfer coefficients that are obtained. In the model, the shrinkage effect was set to be proportional to the water mass change in the fruit, according to Eq. (3). The fruit area was assumed to decrease at a proportional rate following the area of a cube: $A_{\mathrm{FR}} = 6 \cdot a^2$, where a is the length, width and depth of the cube, and is calculated from the volume of the fruit ($V_{\mathrm{FR}} = a^3$). This proportionality showed to be a good approximation of the phenomena

$$\frac{\mathrm{d}V_{\mathrm{FR}}}{\mathrm{d}t} = \alpha \cdot \frac{\mathrm{d}M_{\mathrm{FR}}^{\mathrm{W}}}{\mathrm{d}t}. \tag{3}$$

The mass balance for the osmotic solution considered the gain of water that is removed from the fruit and the loss of sugar to the fruit. As the material balances were based on mass balances, the amount of water leaving the fruit is equal to the amount of water entering the osmotic solution. The opposite occurs with the mass balance of sugar, where the amount of sugar entering the fruit is equal to the amount of water leaving the osmotic solution:

$$\frac{\mathrm{d}M_{\mathrm{OS}}^{\mathrm{W}}}{\mathrm{d}t} = -\frac{\mathrm{d}M_{\mathrm{FR}}^{\mathrm{W}}}{\mathrm{d}t}, \tag{4}$$

$$\frac{\mathrm{d}M_{\mathrm{OS}}^{\mathrm{S}}}{\mathrm{d}t} = -\frac{\mathrm{d}M_{\mathrm{FR}}^{\mathrm{S}}}{\mathrm{d}t}, \tag{5}$$

$$\frac{\mathrm{d}V_{\mathrm{OS}}}{\mathrm{d}t} = \frac{1}{\rho^{\mathrm{W}}} \cdot \frac{\mathrm{d}M_{\mathrm{FR}}^{\mathrm{W}}}{\mathrm{d}t}. \tag{6}$$

The model for the air-drying process follows the traditional equations for drying, considering the constant-rate period and the falling-rate period. The equation for the falling-rate period is a simplification of Fick's second law considering a long processing period (Perry & Green, 1999). The transition between the constant rate period and the falling rate period occurs at average moisture content of 4.0 ($g_{water}/g_{dry\ solids}$) and was estimated during air-drying of papayas without osmotic pre-treatment. During the experiments where the osmotic dehydration was used as pre-treatment, the moisture content of the fruit after dehydration was always lower than the transition point between the two periods and only Eq. (8) was used. Eq. (7) was used solely to calculate the air-drying process with osmotic dehydration pre-treatment:

$$\frac{dH}{dt} = -\frac{R \cdot A_{FR}}{M_S}, \tag{7}$$

$$\frac{dH}{dt} = -\frac{2\pi}{\delta^2} \cdot D \cdot (H - H_{eq}). \tag{8}$$

Experimental data were used to fit the effective mass transfer coefficients of the osmotic dehydration process and to fit the effective diffusion coefficient of the air-drying process. These parameters were adjusted using the developed model with a parameter estimating procedure that was built in Fortran, which was based on the minimization of the error sum of squares. The mathematical model equations were solved using numerical integration by the Runge–Kutta method. The F-test was used as a criterion to validate the model were the level of significance of the model was established comparing the listed F-values and the calculated F-values for each operating condition. Once the model has been validated it was used to optimize the total processing time to dry papayas by osmotic dehydration followed by air-drying. The optimization was done using the method of Levenberg–Marquardt and a computer program was built in Fortran using as objective function the minimization of the sum of the osmotic dehydration processing time plus the air-drying processing time.

4. Results and discussion

The mass transfer coefficients observed in the osmotic dehydration of papayas were estimated using the experimental data and the parameters of the models were adjusted using a parameter estimating procedure that was built in Fortran, using the Levenberg–Marquardt method to minimize the error sum of squares. The operating conditions of different runs of osmotic dehydration are shown in Table 2. The mass transfer coefficients for all operating conditions are presented in Table 3.

The validations of the model using the mass transfer coefficients are presented in Figs. 3 and 4. The model has represented very well (within 99% of confidence) the data points as can be seen in the figures.

As shown in Figs. 3 and 4, increasing the sucrose concentration of the osmotic solution leads to an increase in the water loss from the fruit to the osmotic solution with the increase in the osmotic pressure gradient and temperature. The influence of the osmotic solution on the effective mass transfer coefficient is stronger than the influence of the temperature in the process, especially at low temperatures, as shown in Fig. 5.

Table 2
Operating conditions used in osmotic dehydration of papayas

Operating condition	Temperature (°C)	Sugar concentration in the osmotic solution (°Brix)	Initial fruit mass (g)
A	50	50	316.7
B	70	50	307.4
C	50	70	312.4
D	70	70	305.8

Table 3
Effective mass transfer coefficients between the fruit and the osmotic solution

Operating condition	Effective mass transfer coefficient for water (1/h m^2)	Effective mass transfer coefficient for sucrose (1/h m^2)
A	69.14	20.12
B	207.45	25.89
C	304.56	24.86
D	359.88	37.46

The operating condition does not display a significant influence on the sucrose effective mass transfer coefficient between the solution and the fruit, which can be explained by the bigger size of the sucrose molecule, which suffers a higher resistance to enter the fruit.

High temperatures (50–70 °C) were used to increase the effective mass transfer of water from the fruit to the osmotic solution. These temperatures have been previously tested and showed that papaya can be exposed to high temperatures without compromising product quality (Silva, 1998).

Experimental data was used to estimate the water effective diffusivity in the papaya during air-drying after going through the osmotic treatment. The operating conditions for the air-drying process were set at 60 °C and constant airflow (2.5 m/s). Five experiments (in triplicate) were carried out to study the influence of the osmotic treatment over the air-drying process. One experiment was carried out with the papayas without any osmotic pre-treatment and four experiments were carried out after the four osmotic treatment conditions described earlier (conditions A–D). The results have shown that the drying process and the effective diffusivity were not affected by the osmotic treatment. The water effective diffusivity found for the air-drying process was of 3.567×10^{-6} m^2/min. These parameters were determined using the Levenberg–Marquardt method to minimize the error sum of squares. Fig. 6 shows the experimental data and curve fitting for all operating conditions.

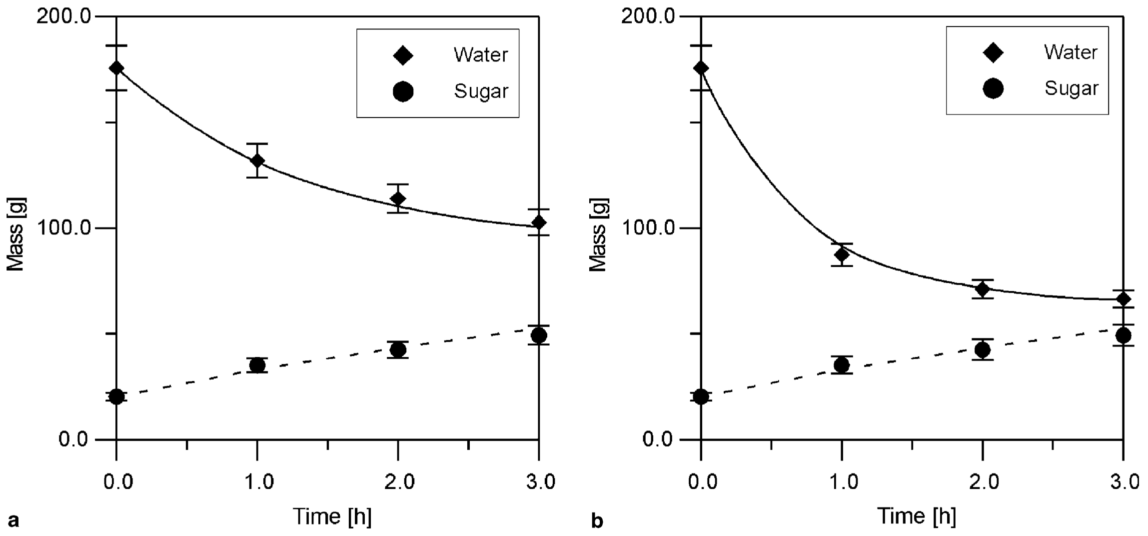

Fig. 3. Mass of water and sugar in the fruit under operation conditions A (a) and B (b) during the osmotic dehydration process. (a) Regression $R^2 = 0.998$; significant within 99% of confidence. (b) Regression $R^2 = 0.999$; significant within 99% of confidence.

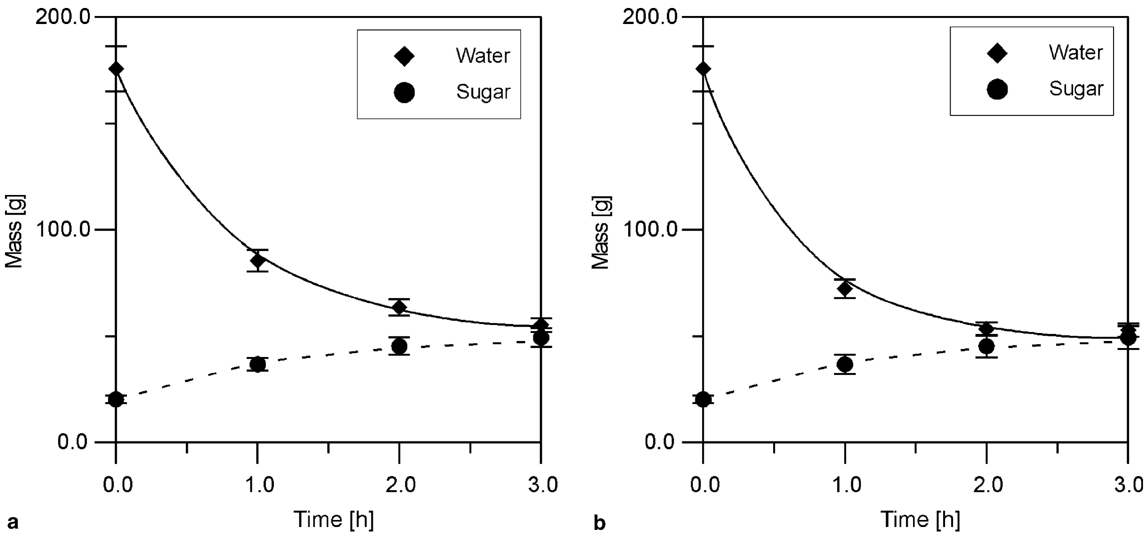

Fig. 4. Mass of water and sugar in the fruit under operation conditions C (a) and D (b) during the osmotic dehydration process. (a) Regression $R^2 = 0.991$; significant within 99% of confidence. (b) Regression $R^2 = 0.990$; significant within 99% of confidence.

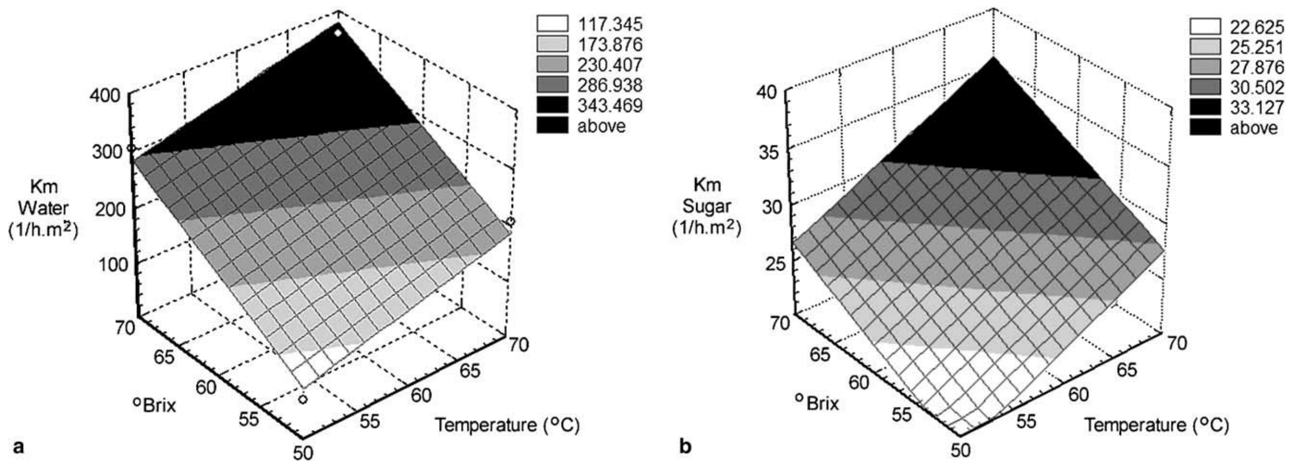

Fig. 5. Effective mass transfer of water (a) and sugar (b) as function of the osmotic treatment temperature (°C) and osmotic solution soluble content (°Brix).

4.1. Process optimization

The drying process of papayas involves first the osmotic dehydration process followed by air-drying. Total processing time can be optimized in order to reduce the drying process to a minimum, which can reduce costs and increase the overall productivity. The osmotic dehydration is used while the water loss rate of the fruit is higher than the rate that would be obtained by the air-drying process. When the water loss rate in the osmotic dehydration gets lower than the one that would be obtained in the air-drying process, then the fruit is transferred from the osmotic dehydration to the air-drying equipment, where the fruit stays till drying is completed.

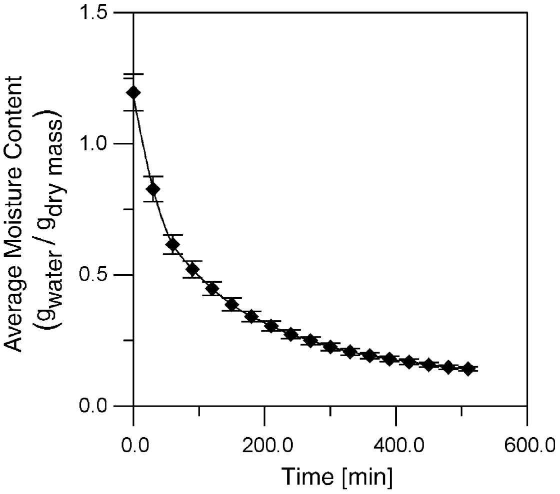

Fig. 6. Average moisture content in the fruit during the air-drying process. Regression $R^2 = 0.995$; significant within 99% of confidence.

Table 4
Total processing time and solute concentration of the final dried product

Air-drying	
Total processing time (min)	1130.0
Solute concentration (°Brix)	66.5
Osmotic dehydration (50 °C, 50 °Brix) followed by air-drying	
Total processing time (min)	733
Time in osmotic dehydration (min)	200
Time in air-drying (min)	533
Solute concentration (°Brix)	72.8
Osmotic dehydration (50 °C, 70 °Brix) followed by air-drying	
Total processing time (min)	490
Time in osmotic dehydration (min)	133
Time in air-drying (min)	357
Solute concentration (°Brix)	73.0
Osmotic dehydration (70 °C, 50 °Brix) followed by air-drying	
Total processing time (min)	621
Time in osmotic dehydration (min)	151
Time in air-drying (min)	470
Solute concentration (°Brix)	72.2
Osmotic dehydration (70 °C, 70 °Brix) followed by air-drying	
Total processing time (min)	450
Time in osmotic dehydration (min)	125
Time in air-drying (min)	325
Solute concentration (°Brix)	73.9

The results show that the use of osmotic dehydration followed by air-drying is an advantage when high concentrations of sucrose solution (70 °Brix) are used in the osmotic dehydration process. Table 4 presents the total processing times and the fruit solute concentration (°Brix) for the final product for solely the air-drying process operating at 65 °C and for the osmotic dehydration process followed by air-drying operating at 65 °C for all operating condition used in the osmotic dehydration experiments. All simulations stopped at the same final fruit moisture content (0.25 $g_{water}/g_{dry\ solids}$).

Table 4 shows that using an osmotic solution with high sucrose concentrations (70 °C and 70 °Brix) speeds up the process, reducing the drying period in 11.3 h if compared to solely using the air-drying process to dry papayas. Even when using low sucrose concentrations (50 °C and 50 °Brix) the total process is reduced in 6.6 h showing that the osmotic dehydration is extremely useful to reduce the drying processing time of papayas.

5. Conclusions

The model that has been developed for the process of osmotic dehydration considers the mass diffusion between the fruit and the osmotic solution (water and sucrose) and the loss of water by evaporation. The shrinkage effect was also considered and it is very important to account correctly the concentrations of water and sugars inside the fruit.

The estimated parameters allowed to simulate the drying process and to optimize the system in order to reduce the total processing time. The results show the advantage of using high sucrose concentrations for the osmotic solution, and the use of the osmotic treatment to reduce the total processing time of fruit drying.

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