Available online at http://journalijces.com

INTERNATIONAL JOURNAL OF CURRENT ENGINEERING SCIENCES

RESEARCH ARTICLE

ISSN: 2320- 9046

International Journal of Current Engineering Sciences- Vol. 5, Issue, 6, pp. 38-45, June, 2016

OBTAINING A MASS TRANSFER COEFFICIENT IN PLANT TISSUES USING THE APPROACH OF THE THERMODYNAMICS OF IRREVERSIBLE PROCESSES AND FICK'S LAW OF DIFFUSION

Sergio de Souza Castro[1*], Silvana Mattedi[2] and Modesto Antônio Chaves[3]

[1,2]PPEQ, Federal University of Bahia, R. Aristides Novis 2 Federação, Salvador, Bahia, Brazil
[1,3]DEA, State University of Southest of Bahia, Itapetinga, Bahia, Brazil

A R T I C L E I N F O

Article History:

Received 19th March, 2016
Received in revised form 14h April, 2016
Accepted 15th May, 2016
Published online 28th June, 2016

Key words:

Coefficient, Cupuassu, Osmotic Dehydration, Modeling, Mass Transfer.

A B S T R A C T

A model for the mass transfer coefficient of water for osmotically dehydrated fruits has been developed. The model aggregated transfer coefficient characteristics obtained by Fick's law and the phenomenological coefficient obtained by the thermodynamics of irreversible processes. The results showed that the mass transfer coefficient of water adapted to changes in sucrose concentrations and temperatures in the osmotic medium. The modeling showed that the simulation of osmotic dehydration must be conducted with both flows: simultaneous synergistic water loss and solid gain. The model was satisfactory for predicting the loss of water in the experimental conditions of the study and was well adjusted to the experimental data.

INTRODUCTION

Cupuassu (*Theobroma grandiflorum*) is a tropical fruit that has been commercially exploited, mainly because of its nutritional characteristics associated with pleasant taste and texture. Increased production and consumption of cupuassu, along with the fact that it's a highly perishable fruit, makes it urgent to develop alternative methods of processing and conservation.

Osmotic dehydration (O.D.) is a technique that consists of the partial removal of water from fresh fruits and vegetables with increased stability during storage, commonly applied prior to air drying (Silva *et al*., 2012). Particularly, osmotic dehydration is a technique that produces a dehydration-impregnation effect. It is very important in the processing and preservation of food, because it can improve the nutritional and sensory characteristics of the products (Oliver *et al*., 2012; Ozdemir *et al*., 2008).

O.D. consists of immersing the food in hypertonic solutions containing salts or sugars, which have an osmotic pressure. A chemical potential between plant cells and the osmotic solution is established, promoting the flow of water from the plant cells to the hypertonic solution. Furthermore, a simultaneous flow of solute is also established from the osmotic solution to the intracellular phase (Atares *et al*., 2011). In fact, when a cell tissue that is immersed in hypertonic solution it is exposed to a chemical potential gradient between the hypertonic solution and the intracellular liquid phase of the cells. This gradient causes water to leave the cells, producing physical and structural changes, (Marcotte and Maguer, 1992)such as weight loss, cell membrane rupture, etc.

Several factors influence the O.D., like the type and concentration of osmotic agents, the temperature, processing time, agitation and the ratio between the solution and the material to be dehydrated (Alves *et al*., 2005; Barat *et al*., 2001; Chenlo *et al*., 2007; El-Aouar *et al*., 2006). However, the compositions and the biological characteristics of the raw material, considered to be intrinsic factors, influence the simultaneous flow of mass transfer.

The cupuassu plant tissue is considered a multiphase, multicomponent system organized in microstructural elements that respond differently to various process conditions (Castro-Giráldez*et al*., 2011; Seguí *et al*., 2012). The three main microstructural elements are: The vacuole, the plasma membrane or plasmalemma and the

Corresponding author:* **Sergio de Souza Castro
PPEQ, Federal University of Bahia, R. Aristides Novis 2 Federação, Salvador, Bahia, Brazil and DEA, State University of Southest of Bahia, Itapetinga, Bahia, Brazil

cell wall. Between the plasma membrane and the cell wall there is the intracellular space (Toupin and Le Maguer, 1989). The volume of parenchymatous cells, like cupuassu cells, is mainly occupied by the central vacuole, which stores nutrients and water. Special attention must be given to the plasma membrane which provides an effective barrier to the entry of some high molecular weight components, such as sucrose. The transport of water through this membrane is done by a potential difference maintained between the cell and the medium and is called transmembrane transport. Plant cells also have a fairly rigid layer called a cell wall, which provides structural support and mechanical protection for the cell. The transport of solute and water through that structure occurs by diffusion, called apoplastic transport. A third transport, called symplastic transport, allows the exchange of material between cells through the plasmodesma (Castro-Giraldez *et al*., 2011; Toupin and Le Maguer, 1989). For this reason, knowing the response of each microstructure is one of the key factors to understand the O.D. process and describe it mathematically.

Several studies have described the process of modeling and mass transfer kinetics of O.D. based on thermodynamics, whose flow is a function, in particular of the chemical potential and the phenomenological coefficient (Castro-Giráldez *et al*., 2011; M. Ferrando and Spiess, 2001; Montserrat *et al*., 2003; Yang and Le Laguer, 1992) and in Fick's second law, where the flow occurs due to a concentration gradient and a binary mass transfer coefficient (Cardoso *et al*, 2007; Jalaee *et al*., 2011; Porciuncula *et al*., 2013; Singh *et al*., 2007). When using the Fick's second law, as reported by Castro-Geráldez *et al* (2011), the phenomenon is reduced to an apparent single coefficient that minimizes the complexity of the mass transfer system. On the other hand, the thermodynamic description transforms the phenomenological coefficient, in some cases, such as the value of an average coefficient, since it considers the water flow from the cytoplasm to the osmotic medium, where the cell is found.

Thus, this work aims to study the mass transfer coefficient of water during osmotic dehydration of cupuassu (*Theobroma grandiflorum*) due to the thermodynamic function of the irreversible processes and Fick's second law and develop a new model for predicting the mass transfer coefficient of water during osmotic dehydration.

MATERIAL AND METHOD

Samples of Cupuassu were obtained from the company Doce Mata, located in the city of Itabuna, southern Bahia, Brazil and stored at 5°C with a relative humidity of 80-90% before the experimental procedure. Immediately before use, samples were separated and the size was adjusted into small pieces of approximately 20 x 35 mm. The osmotic solutions were prepared by mixing commercial sucrose with the appropriate amount of distilled water.

Experimental procedure for osmotic dehydration

The cupuassu samples were placed in 150 ml beakers containing the sucrose solution in a solution/sample ratio of 10/1 (w/w) with sucrose concentrations of 30%, 40% and 50% at temperatures of 30 °C, 40°C and 50°C for a period of 10 hours for a full factorial design. Each treatment was performed in a thermostatic bath (TE-2005-TECNAL). The samples were agitated intermittently every 30 minutes with the magnetic stirrer (TE-0851-TECNAL) with the speed set at 200 rpm. To prevent evaporation of the osmotic solution, beckers were covered with plastic film during the tests. Intermittent stirring was performed in order to improve mass transfer and to prevent the formation of a film by crystallization of the solution around the samples, in addition to providing a uniform profile of concentration and temperature (Eren & Kaymak-Ertekin, 2007).

In each of the treatment times, samples were taken, according to the experimental design. To remove excess solution on the surface, the samples were place in a 200 ml Becker containing distilled water, where they were washed for 3 seconds and then the moisture was removed by gently wrapping them with paper towels for 4 seconds. The moisture content of the samples was determined in a vacuum oven according to the methodology proposed by the AOAC (AOAC, 2002). The soluble solid contents were determined with the sample at 20°C, using a digital refractometer (PAL-2, ATAGO) with an accuracy of 0.2%ºBrix. The assessment of the mass transfer between the solution and the sample during O.D. was made by calculating the water loss (*WL*), the solid gain (*SG*) and the flow of water (J_w). According to equations 1-4

$$WL(\%) = \frac{M_0 w_0 - M_t w_t}{M_0} \times 100 \quad (1)$$

$$SG(^oBrix) = \frac{M_t S_t - M_0 S_0}{M_0} \quad (2)$$

$$J_w = \frac{-\ M_w\ M_0}{t\ A\ Mr_w} \quad (3)$$

$$M_w = \frac{M_0 w_0 - M_t w_t}{M_0} \quad (4)$$

Being that w_0 and w_t are the initial and final concentration of water in the samples; S_0 and S_t the soluble solids in the beginning and end of the samples; M_0 and M_t are the initial and final masses for each sample (kg), Mr_w is the molecular mass of water (kg mol^{-1}), t is the variation in time and A is the surface area of the sample (m^2). The tests were randomized in order to minimize the effects of unexplained variability in responses observed due to external factors. All treatments were performed in duplicate and with one repetition, calculating the average value.

Theory

Fig. 1 shows the cellular microstructures and their relation to the water flow from the cytoplasm into the intracellular space ($J_{w,1}$) and from the intracellular space to the osmotic medium, passing through the cell wall ($J_{w,2}$). During the osmotic dehydration process, sucrose passes through the cell wall (Toupin and Le Maguer, 1989). By virtue of its molecular weight, according to Chenlo *et al*., (2007) sucrose can cross the cell wall, but it is not able to cross the plasma membrane and reach the cytoplasm, and therefore accumulates in the intracellular space. Because the plasma membrane is selective, a way to enable the entry of sucrose would be to destabilize the membrane by

creating an electrical potential. According to Sereno *et al*., (2001) this can be achieved by the presence of salt (Na+ ions) in the solution. Eren and Kaymak-Ertekin (2007) showed that adding NaCl to the solution optimizes the osmotic dehydration process. In this case, not only do the hygroscopicity characteristics of salt influence the water flow, but they also facilitate the entry of sugar into the cytoplasm.

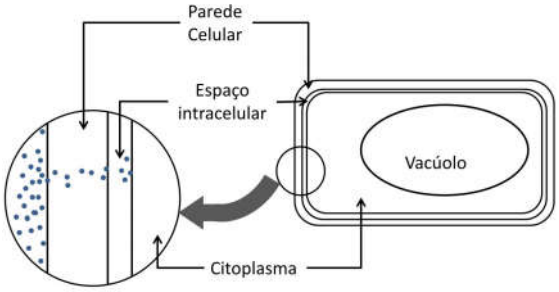

Figure 1 Water flow through the plasma Membrane and the cell wall

The accumulation of sucrose in the intracellular space accelerates the flow of water from the cytoplasm ($J_{w,\ 1}$). The $J_{w,1}$, has the plasma membrane, represented by the phenomenological coefficient, and the potential difference as its main limiting factors.

The cell wall is considered a rigid microstructure and therefore, it can be considered that the water flow will not occur due to a selective structure, but by simple diffusion of solvent molecules across a rigid structure. In this case, Fick's second law can be applied. Therefore, the water flow through the cell should be computed in two ways: the transmembrane transport and apoplastic transport (Toupin and Le Maguer, 1989).

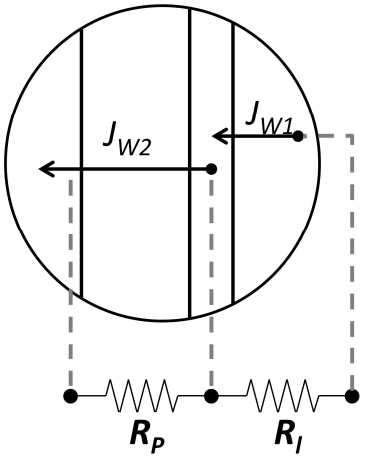

Figure 2 Resistance of the cell wall and phenomenological resistance that limits the flow of water in the plant cell

Making an analogy of the mass transfer process using an electric circuit, Fig. 2, the potential difference can be defined as being the solvent concentration difference between the cell and the medium. In this case, the flow, which originates from a potential difference, is limited by two main factors, or resistors, in the plant cells. According to Fig. 2, these two limiting factors in the water flow can be reduced to a single equivalent factor. This equivalent factor will be responsible for limiting the cytoplasm water outlet to the medium where the cell is located.

Modelling

Transmembrane Transport

Castro-Giráldez *et al*. (2011) showed that the forces that promote mass transfer can be analyzed by irreversible thermodynamics. The equilibrium thermodynamics of a system can thus be analyzed in terms of Gibbs free energy. Thus, according to Seguí *et al*. (2012) the forces that promote mass transfer during osmotic dehydration of isolated cells can be defined as an extended chemical potential of water (μ_W^{ext}) (Eq. 5).

$$\mu_W^{ext} = \mathrm{R}\,T ln a_w + \overline{V_w}\ \ P \qquad (5)$$

Where R is the universal constant of ideal gases (J $mol^{-1}K^{-1}$), T is the temperature (ºC), a_w is water activity, $\bar{V}_w$ is the partial molar volume of water ($m^3\ mol^{-1}$) and P is the change in pressure (kg $m^{-1}s^{-2}$).

During the O.D. process, Seguí *et al*. (2012) experimentally demonstrated the existence of at least two phases in the complete plasmolysis of cells: one phase during which there is substantial deformation phenomena, and another where they are not noticeable. In the latter case, it means that the second term on the right side of the equation can be neglected, Eq. 6 and 7, and the phenomenological coefficient ($mol^2J^{-1}\ m^{-2}s^{-1}$) can be obtained (L_W).

$$J_w = \text{-}L_W\ \mu_W^{ext} \qquad (6)$$

Where J_w is water flow (mol $m^{-2}s^{-1}$)

Or

$$J_{w,1} = \text{-}L_W \mathrm{R}T ln\left(\frac{a_w^{out}}{a_w^{in}}\right) \qquad (7)$$

Where a_w^{out} and a_w^{in} are the water activities outside the cell and inside the cell, respectively.

The phenomenological resistance (R_l) is given by Eq. 8

$$R_l = \frac{1}{L_w\ \ T\bar{V}_w} \qquad (8)$$

Where R_l is given bys m^{-1}.

According to Norrish (1966) water activity can be determined by Eq. 9.

$$a_w = x_w \cdot e^{(k\ (x_s)^2)} \qquad (9)$$

Where $x_w$the molar fraction of water k is is a dimensionless constant, characteristic for each kind of solute, and x_s molar fraction of sucrose. According to Labuza(1984) for sucrose this value is equal to -6.47. Substituting Eq. 9 by 7 and after the application of the mathematical properties of the water flow logarithm to the transmembrane transport to the intracellular space can be defined as:

$$J_w = L_w \mathrm{R}T(lnx_w^{in}\quad lnx_w^{out}) + L_w \mathrm{R}Tk(x_s^{out}\quad x_s^{in}) \qquad (10)$$

Due to its molecular weight and the selectivity of the plasma membrane, sucrose cannot penetrate into the cytoplasm. In this case, the sucrose concentration in the cytoplasm is equal to zero and Eq. 6 is reduced to Eq. 11.

$$J_w = L_w \mathrm{R}T(lnx_w^{in}\quad lnx_w^{out}) + L_w \mathrm{R}Tk(x_s^{out}) \qquad (11)$$

By substituting Eq. 6 by Eq. 5 and comparing it with Eq. 11, we can be observe that the term for the osmotic pressure is equal to the second term on the right hand side of Eq. 11. Therefore,

$$\bar{V}_w \;\; P = \mathrm{R}Tk(x_s^{out}) \tag{12}$$

In fact, when comparing Eq. 12 with Clyperon's equation, we can conclude that it refers to pressure. Therefore, the osmotic pressure inside the cell is the result of the amount of sucrose in the intracellular space. Thus, the osmotic pressure in the intercellular space (eq.8) will be one of the factors that influences the water flow from inside the cell to the medium and thus, to osmotic dehydration.

Apoplastic transport

Abbasi Souraki *et al*. (2012) modeled the mass transfer of water and solute in green bean samples using Fick's law. According to Seguí *et al*.(2012), this modeling reduces the transfer process to a single coefficient and does not reflect the truth about the process. Toupin and Le Maguer (1989) showed that mass transfer through the cell wall has no selectivity, and therefore, in this microstructure, Fick's second law for simple diffusion of solute and solvent may account for the mass transfer process (eq. 13).

$$J_{w,2} = -CD_{AB}\frac{dx_w}{dh} = -CD_{AB}\frac{(x_w^{out}-x_w^{in})}{1000\times H} \tag{13}$$

Where C is the molar concentration (mol m^{-3}), D_{AB} is the binary coefficient of the mass transfer ($\mathrm{m}^2\mathrm{s}^{-1}$), and H is the thickness (m) of the cell wall.

In this case, the resistance to the mass transfer process in the wall (R_w) is given by Eq. 14:

$$R_p = \frac{1000\times H}{D_{AB}} \tag{14}$$

Thus, the mass transfer of water will be determined by two resistances: the resistance of the wall ($\mathrm{s\,m}^{-1}$) or diffusive resistance (R_p) and plasma membrane resistance or phenomenological resistance (R_l). An overall mass transfer coefficient for water can be obtained by means of the total flow ($J_{w,t}$), eq. 15,

$$J_{w,t(t-0)} = UA.\;\; x_{ml} \tag{15}$$

Where UA is the overall mass transfer coefficient ($\mathrm{m}^2\mathrm{s}^{-1}$), given by Eq. 16

$$UA = \frac{1}{(R_p+R_l)} \tag{16}$$

and xm_L is the logarithmic mean of the molar fraction obtained by Eq. 17

$$x_{ml} = \frac{x_t - x_0}{ln\left(\frac{x_w^{out}}{x_w^{in}}\right)_t - ln\left(\frac{x_w^{out}}{x_w^{in}}\right)_0} \tag{17}$$

Where

$$x_t = x_{w,t}^{in} - x_{w,t}^{out} \tag{18}$$

$$x_0 = x_{w,0}^{in} - x_{w,0}^{out} \tag{19}$$

The new resistances in the wall and plasma membrane are defined proportionally by equations 20 and 21.

$$R_p = \frac{D_{AB}+L_w\mathrm{R}T1000H}{L_w\mathrm{R}TD_{AB}} \times \left(\frac{x_w^{out}-x_w^{in}}{lnx_w^{in}-x_w^{out}}\right) \tag{20}$$

$$R_l = \frac{D_{AB}+L_w\mathrm{R}T1000H}{L_w\mathrm{R}TD_{AB}} \times \left(\frac{lnx_w^{in}-lnx_w^{out}}{lnx_w^{in}-x_w^{out}}\right) \tag{21}$$

The new mass transfer coefficient of water can be determined by the new model of the mass transfer coefficient ($\mathrm{m}^2\mathrm{s}^{-1}$), called the Castro-Mattedi-Chaves (CMC) model, Eq. 22,

$$D_{CMC} = \frac{L_w\mathrm{R}TD_{AB}}{D_{AB}+L_w\mathrm{R}T1000H} \tag{22}$$

The mass transfer coefficients L_w and D_{AB} were simultaneously determined using eq. 16, 20 and 21.

RESULTS AND DISCUSSION

Figs. 3, 4 and 5 show the water flow behavior in sucrose solutions at 30%, 40% and 50% at temperatures of 30°C, 40°C and 50°C. In these figures, it is possible to see that the higher the concentration of sucrose in the solution, the less flow there will be. Some factors may contribute to this. For example, in Fig. 3, the increased concentration, at a constant temperature of 30°C causes an increase in solute gradient between the a sample and the medium, thus promoting an increase in osmotic pressure. This increase in osmotic pressure will allow a quick outflow of water to occur, mainly in the initial moments of the osmotic treatment (Kowalska *et al*., 2008). After this time, smaller amounts of water flow from the sample to the medium, providing a decreasing flow. Thus, when considering the loss of water at 30°C, it can be noted that as the concentration of solute in the solution increases, the loss of water increases and its flow is reduced over time. Furthermore, with increasing sucrose concentration gradient between the solution and the sample, there is an increased flow of sucrose from the osmotic medium to the sample. This flow will increase the sucrose accumulation in the intracellular space, which will provide a variable resistance to the passage of the water.

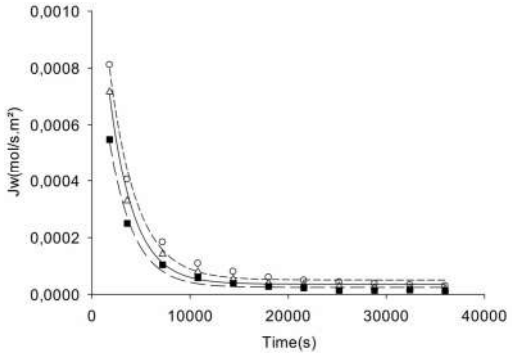

Figure 3 Kinetics of water flux during the osmotic treatment at temperature of 30°C and sucrose concentration: Experimental (○) 30% (Δ) 40% and (■) 50%; Simulation (---) 30% (—) and 40% (-) 50%

It can be seen that by keeping the temperature constant and varying only the concentration, noticeable differences can be noted between the flows in Figs. 3, 4 and 5. Fig. 4 shows a similar behaviour, with a small difference for the flow in the concentration of 40% sucrose when compared with Fig. 3. But Fig. 5 shows that at a temperature of 50°C, the flow of water to the 40% sucrose concentration is near the flow of water in a 50% sucrose concentration. In this case, the temperature is a fact that influences the water flow, but only at the temperatures and

concentrations at or above 50°C and 40%, respectively, as seen in the comparison of water flows in the figures at the same temperature. This is due to the increased solubility of the sucrose in the cell wall and the permeability of the cell's plasma membrane.

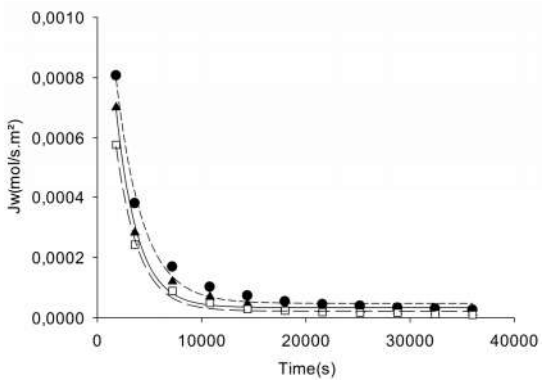

Figure 4 Kinetics of water flux during the osmotic treatment at temperature of 40 ° C and sucrose concentration: Experimental (●) 30% (▲) and 40% (□) 50%; Simulation (---) 30% (─) and 40% (-) 50%

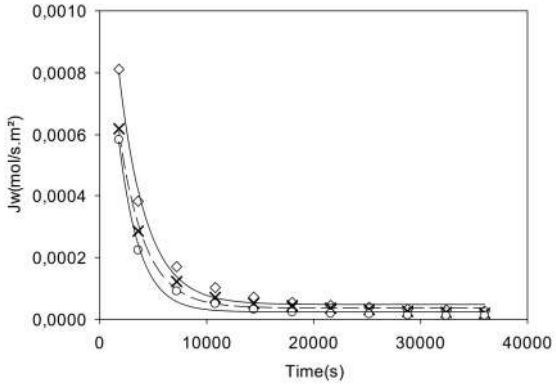

Figure 5 Kinetics of water flux during the osmotic treatment at temperature of 50°C and sucrose concentration: Experimental ( ) 30% (x) 40% and (○) 50%; simulation (─) 30% (---) 40% and (─) 50%.

The increased flow with increasing temperature is only noticeable when comparing the temperatures 30°C and 40°C, according to the comparison between Figs. 3 and 4. When comparing the flow at temperatures of 40 and 50°C, Figs. 4 and 5, there are no major differences. This leads us to believe that there is an optimal point of maximum flow at around 40°C. Changing the concentration to 40% and varying the temperature, the flow behavior and water loss are similar to those observed in the concentration of 30%. However, one difference is noted: an optimal loss of water now seems to be located between the temperatures 30 and 40°C, showing that the increase in temperature to around 40°C satisfies, initially, the production of osmotically dehydrated fruit between the 30 and 40% sucrose concentration.

At the 50% concentration, the differences between the flows and the loss are minimal, which can be seen in Fig. 5. Therefore, it can be seen that the temperature variation will influence solutions with low concentration of solute less than or equal to 40%. According to Eren and Kaymak-Ertekin (2007), high concentrations make the solution more viscous, which makes the mass transfer of water between the sample and the medium difficult. In this sense, the saturation of the solute in the intracellular space takes place faster, which means that there is an increase in resistance to the passage of water, reducing the water flow from the sample to the medium.

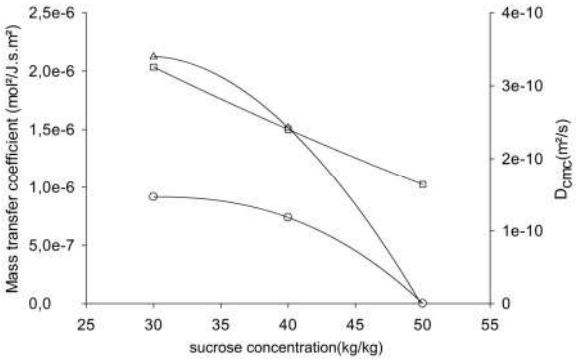

Figure 6 Variation in the mass transfer coefficient at 30°C with varying concentrations of sucrose: L_w (○), D_{AB} (□) and D_{CMC} (Δ).

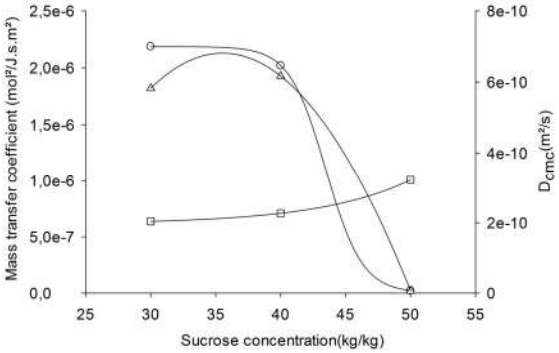

Figure 7 Variation in the mass transfer coefficient at 50°C with varying concentrations of sucrose: L_w (○), D_{AB} (□) and D_{CMC} (Δ).

Fig. 6 and 7 show the behavior of the mass transfer coefficients determined by Eqs. 16, 20, 21 and 22. Fig. 6 shows the variation of the phenomenological coefficient (L_w) as a function of sucrose concentration. As the sucrose concentration increases, the value of the L_w tends to decrease. This happens because the sucrose concentration gradient between the medium and the osmotic solution decreases with over time, which will cause an increase in the water mass transfer resistance from the sucrose concentration in the intracellular space. As such, there will be a reduction in the water flux from the cell cytoplasm to the osmotic medium. However, at lower sucrose concentrations, below 40%, the variation of the phenomenological coefficient behavior is around 10% when compared with high sucrose concentrations (above 50%), whose behavioral variation is around 90%. According to Seguí *et al*. (2012), the plasma membrane tends to adapt to new conditions of equilibrium by changing its permeability due to pressure. This adaptation will be represented by the modification in the value for L_w. For moderate temperatures (around 40°C), the values of L_w do not show major changes. However, for higher temperatures (equal to 50°C), the values of the mass transfer coefficients showed the behavior shown in Fig. 7. It can be seen at 50ºC, with concentration variations that all coefficients decreased. The value of D_{CMC} presents behavior similar to the values of D_{AB} up to a 40% sucrose concentration. However, for sucrose concentrations above 40%, the value of D_{CMC} tends to approach the values of L_w. This characteristic of this new coefficient shows that the mass transfer process at all times and in varying

concentrations, is not governed by only one coefficient but by the characteristics presented by the two coefficients. The values of D_{AB} are more sensitive, but not exclusively, to the variation of the concentration of the solute, as imposed by Fick's law. But the L_w, related to the plastic membrane, is more sensitive to temperature variations, but also not exclusively. Thus, the values of D_{CMC} more easily adapt to the variation in concentration and temperature by being able to incorporate the two features of these mass transfer coefficients.

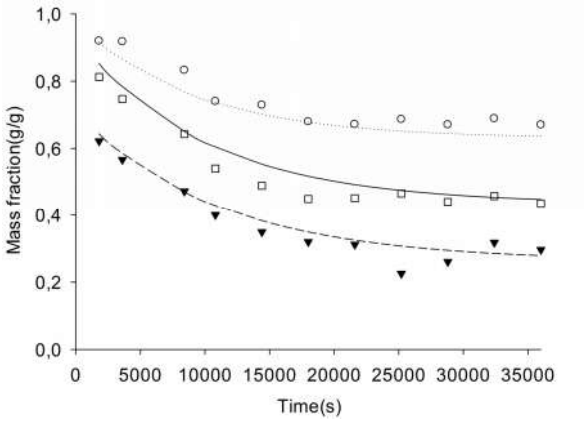

Figure 8 Variation of the mass fraction of water in cupuassu samples at a temperature of 30°C in the concentrations of Sucrose: Experimental, 30% (○), 40% (□) and 50% (▼); Simulated 30% ( ), 40% (-) and 50% (-)

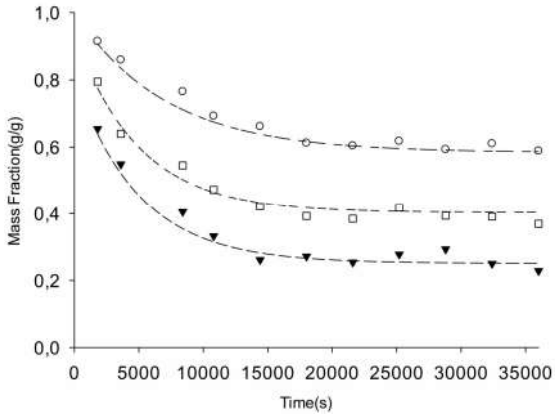

Figure 9 Variation of the mass fraction of water in the cupuassu samples at 40ºC in the sucrose concentrations of: Experimental, 30% (○), 40% (□) and 50% (▼); Simulated 30% (- -), 40% (———) and 50% (——)

Figs. 8, 9 and 10 show the experimental values of the variation of the mass fraction of water in cupuassu samples and the values that were obtained with the new mass transfer coefficient. Fig. 8 shows the simulation of the loss process, with D_{CMC} of 5.82E-10 m²/s for a concentration of 30%, D_{CMC} = 6.17E-10 m²/s for a concentration of 40 and D_{CMC} = 5.82E-12 m²/s for a concentration of 50% in samples of cupuassu at 30ºC. The RMSE values obtained were 0.044, 0.036 and 0.036, for concentrations of 30%, 40% and 50%, respectively, indicating that the model shows good accuracy for the estimated water loss. The values found for the means the bias error (MBE) for each of the sucrose concentrations, namely 30%, 40% and 50%, was 0.036, -0.03 and 0.021, respectively, showing that although at the 40% concentration the MBE value was negative, indicating an underestimation, this value is not as small as -10, considered the threshold value for model underestimation.

Fig. 9 shows that there is a change in water loss with the increase in temperature to 40°C in concentrations of 30%, 40% and 50% for the cupuassu samples during osmotic dehydration. The values obtained for the root mean square error (RMSE) were 0.028, 0.025 and 0.021, for concentrations of 30%, 40% and 50%, respectively. The RMSE values do not show large variations, indicating that at 40ºC, the model can accurately predict the water loss for the cupuassu samples during osmotic dehydration. The MBE values found for the simulation were -0.022, 0.026 and -0.021 for concentrations of 30%, 40% and 50%, respectively. Comparing these values with the graphs, it can be observed that the underestimation of the model at concentrations of 30% and 50% are also not so significant, also indicating the good predictive capability of the behavior of water during osmotic dehydration at 40ºC.

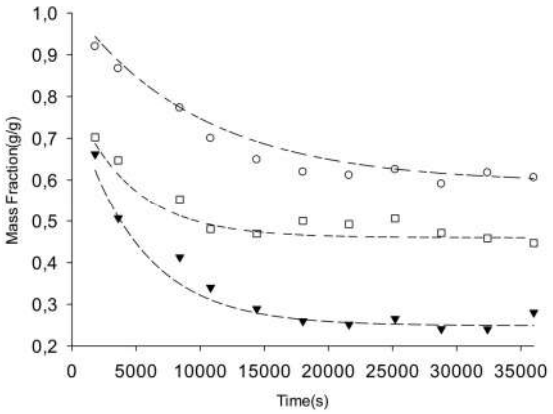

Figure 10 Variation of the mass fraction of water in the cupuassu samples at 40ºC in the sucrose concentrations of: Experimental, 30% (○), 40% (□) and 50% (▼); Simulated 30% (- -), 40% (———) and 50% (——)

Fig. 10 shows the change in water loss due to time at 50ºC with concentrations of 30%, 40% and 50% for cupuassu samples during the osmotic dehydration process. It is possible to note that for this temperature, the loss behavior is completely different at 30°C and 40°C.

The values obtained for the RMSE were 0.027, 0.028 and 0.031, for concentrations of 30%, 40% and 50%, respectively. The RMSE values do not show large variations, indicating that also at 50°C, the model is satisfactory for predicting the water loss of cupuassu samples during osmotic dehydration. The MBE values found for the simulation were 0.021, -0.018 and -0.015 for concentrations of 30%, 40% and 50%, respectively.

At the temperature of 50°C, the plastic membrane becomes more permeable to the passage of water. Therefore, greater water loss should be expected. Also, due to reduction in viscosity of the sucrose solution, more solute diffuses across the cell wall, thus contributing to greater water loss. However, over time the intracellular space will be saturated by the presence of sucrose, which causes, as previously discussed, there to be increasing resistance to the passage of water. Therefore, it is not possible to dissociate the loss of water from sucrose gain during the osmotic dehydration process. This fact explains why some authors, such as Mercali *et al*.(2011),Monnerat *et al*. (2010) and Lenart (1996) have concluded that at the beginning the process, greater loss of water is expected in

the first minutes or at the initial moments, because during this time, the resistance due to the presence of sucrose has not yet reached its maximum value.

Therefore, as previously demonstrated in Eq. 6, the simulation of the dehydration process should be done in the presence of sucrose in order to maintain the dependence of these flows.

CONCLUSION

The model proposed for mass transfer coefficient of water during the dehydration process of fruits was found to be satisfactory. The model can add not only the characteristics of the cell wall, but also the plasma membrane, which was demonstrated by their approximation to the diffusivity coefficient (D_{AB}) related to the diffusion of solute through the cell wall, whose increase is due to high concentrations and low (30°C) and moderate (40°C) temperatures. For high temperatures, the model will be more influenced in the phenomenological coefficient (L_w), which is associated with the plasma membrane, where moderate (40°C) and high (above 50°C) temperatures will cause changes in its permeability.

Reference

Abbasi Souraki, B, Ghaffari, A & Bayat, Y. (2012). Mathematical modeling of moisture and solute diffusion in the cylindrical green bean during osmotic dehydration in salt solution. *Food and Bioproducts Processing*, *90*(1), 64–71.

Alves, D. G., Barbosa, J. L, Antonio, G. C & Murr, F. E. X. (2005). Osmotic dehydration of acerola fruit (Malpighia punicifolia L.). *Journal of Food Engineering*, *68*(1), 99–103.

Atares, L, Sousa Gallagher, M. J & Oliveira, F. A. R. (2011). Process conditions effect on the quality of banana osmotically dehydrated. *Journal of Food Engineering*, *103*(4), 401–408.

Barat, J. M, Fito, P & Chiralt, A. (2001). Modeling of simultaneous mass transfer and structural changes in fruit tissues. *Journal of Food Engineering*, *49*(2-3), 77–85.

Cardoso Andrade, S. A., de Barros Neto, B, Cavalcanti Nóbrega, A, Moreira Azoubel, P & Barbosa Guerra, N. (2007). Evaluation of water and sucrose diffusion coefficients during osmotic dehydration of jenipapo (Genipa americana L.). *Journal of Food Engineering*, *78*(2), 551–555.

Castro-Giraldez, M, Tylewicz, U, Fito, P. J, Dalla Rosa, M & Fito, P. (2011). Analysis of chemical and structural changes in kiwifruit (Actinidia deliciosa cv Hayward) through the osmotic dehydration. *Journal of Food Engineering*, *105*(4), 599–608.

Castro-Giráldez, M, Fito, P. J & Fito, P. (2011). Nonlinear thermodynamic approach to analyze long time osmotic dehydration of parenchymatic apple tissue. *Journal of Food Engineering*, *102*(1), 34–

Chenlo, F, Moreira, R, Fernández-Herrero, C & Vázquez, G. (2007). Osmotic dehydration of chestnut with sucrose: Mass transfer processes and global kinetics modelling. *Journal of Food Engineering*,

El-Aouar, Â. A, Azoubel, P. M, Barbosa, J. L & Murr, F. E. X. (2006). Influence of the osmotic agent on the osmotic dehydration of papaya (Carica papaya L.). *Journal of Food Engineering*, *75*(2), 267–274.

Eren, I & Kaymak-Ertekin, F. (2007). Optimization of osmotic dehydration of potato using response surface methodology. *Journal of Food Engineering*, *79*(1), 344–352.

Ferrando, M & Spiess, W. E. L. (2001). Cellular response of plant tissue during the osmotic treatment with sucrose, maltose, and trehalose solutions. *Journal of Food Engineering*, *49*(2-3), 115–127.

Ferrando, M & Spiess, W. E. L. (2003). Effect of osmotic stress on microstructure and mass transfer in onion and strawberry tissue. *Journal of the Science of Food and Agriculture*, *83*(9), 951–959.

Jalaee, F, Fazeli, A, Fatemian, H & Tavakolipour, H. (2011). Mass transfer coefficient and the characteristics of coated apples in osmotic dehydrating. *Food and Bioproducts Processing*, *89*(4), 367–374.

Kowalska, H, Lenart, A & Leszczyk, D. (2008). The effect of blanching and freezing on osmotic dehydration of pumpkin. *Journal of Food Engineering*, *86*(1), 30–38.

Labuza, T. P. (1984). Application of chemical kinetics to deterioration of foods. *Journal of Chemical Education*, *61*(4), 348.

Lenart, A. (1996). OSMO-convective drying of fruits and vegetables: technology and application. *Drying Technology*, *14* (2), 391–413.

Marcotte, M & Maguer, M. Le. (1992). Mass transfer in cellular tissues. Part II: Computer simulations vs experimental data. *Journal of Food Engineering*, *17*(3), 177–199.

Mercali, G. D, Ferreira Marczak, L. D, Tessaro, I. C & Zapata Noreña, C. P. (2011). Evaluation of water, sucrose and NaCl effective diffusivities during osmotic dehydration of banana (Musa sapientum, shum.). *LWT - Food Science and Technology*, *44*(1), 82–91.

Monnerat, S. M, Pizzi, T. R. M, Mauro, M. A & Menegalli, F. C. (2010). Osmotic dehydration of apples in sugar/salt solutions: Concentration profiles and effective diffusion coefficients. *Journal of Food Engineering*, *100*(4), 604–612.

Oliver, L, Betoret, N, Fito, P & Meinders, M. B. J. (2012). How to deal with visco-elastic properties of cellular tissues during osmotic dehydration. *Journal of Food Engineering*, *110*(2), 278–288.

Ozdemir, M, Ozen, B. F, Dock, L. L & Floros, J. D. (2008). Optimization of osmotic dehydration of diced green peppers by response surface methodology. *LWT - Food Science and Technology*, *41*(10), 2044–2050.

Porciuncula, B. D. A, Zotarelli, M. F, Carciofi, B. A. M & Laurindo, J. B. (2013). Determining the effective diffusion coefficient of water in banana (Prata variety) during osmotic dehydration and its use in predictive models. *Journal of Food Engineering*, *119*(3), 490–496.

Seguí, L, Fito, P. J & Fito, P. (2012). Understanding osmotic dehydration of tissue structured foods by means of a cellular approach. *Journal of Food Engineering*, *110*(2), 240–247.

Sereno, A. M, Moreira, R & Martinez, E. (2001). Mass

transfer coefficients during osmotic dehydration of apple in single and combined aqueous solutions of sugar and salt. *Journal of Food Engineering*, *47*(1), 43–49.

Singh, B, Kumar, A & Gupta, A. K. (2007). Study of mass transfer kinetics and effective diffusivity during osmotic dehydration of carrot cubes. *Journal of Food Engineering*, *79*(2), 471–480.

Toupin, C. J & Le Maguer, M. (1989). Osmotically-induced mass transfer in plant storage tissues: A mathematical model. Part II. *Journal of Food Engineering*, *10*(2), 97–121.

Yang, D. C & Le Laguer, M. (1992). Osmotic dehydration of strawberries in a batch recirculation system. *Journal of Food Quality. [Trumbull, Conn. : Food & Nutrition Press] Dec 1992. v. 15 (6) P. 387-397*, *15*, 387–397.

****