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ORIGINAL ARTICLE

Study of osmotic dehydration of kiwi fruit using sucrose solution

Estudo da desidratação osmótica do kiwi usando soluções de sacarose

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Abstract

Osmotic dehydration of kiwi was evaluated using 45, 55 and 65 °Brix sucrose solutions. Free moisture, water activity and solutes gain decreased in fruit during the process. Water loss rates were higher in the beginning of drying. Water activity decrease was higher when the product was in 65 °Brix solution. The equilibrium moisture content estimated by the Peleg model decreased significantly with increasing concentration of the osmotic solution, and the diffusivity values of water loss were in the range from 1.5×10^{-9} to 1.9×10^{-9} m^2 s^{-1}. The osmotic pressures of the solutions were also predicted.

Keywords: Kiwi fruit; Osmosis; Dehydration; Diffusion coefficient; Water activity; Moisture content.

Resumo

Foi estudada a desidratação osmótica do kiwi, utilizando soluções osmóticas de sacarose a 45, 55 e 65 °Brix. Durante o tempo de desidratação, houve diminuição da umidade livre, da atividade da água e ganho de soluto pelo fruto. Observou-se um período inicial de secagem, em que as taxas de perda de água foram maiores. A diminuição da atividade da água foi maior quando o produto esteve imerso na solução a 65 °Brix. O teor de umidade de equilíbrio estimado pelo modelo de Peleg diminuiu significativamente com o aumento da concentração da solução osmótica e os valores de difusividade de água estiveram na faixa entre $1,5 \times 10^{-9}$ a $1,9 \times 10^{-9}$ m^2 s^{-1}. As pressões osmóticas das soluções também foram preditas.

Palavras-chave: Kiwi; Osmose; Desidratação; Coeficiente de difusão; Atividade de água; Teor de umidade.

1 Introduction

Candied fruits and vegetables are produced by osmotic dehydration (OD) when they are immersed in hypertonic sugar solution, which is used as a method of partial removal of water from foods (Sareban & Souraki, 2016; Abraão et al., 2013; Souraki et al., 2014b). OD has been proposed for intermediate moisture food production or as a preliminary stage for other operations, such as air drying or freezing (Lewicki & Lenart, 2015). Talens et al. (2002) mentioned that, when used as a pretreatment, the process improves quality in color and mechanical properties of the kiwi slices after freezing, reducing drip loss. In addition, OD is a suitable optional technology due to its simplicity, affordability, and use of low temperatures to protect nutritional and bioactive compounds in foods (Alfaro et al., 2018).

There are many types of OD: at atmospheric pressure, vacuum osmosis, vacuum pulse high pressure osmotic dehydration, and other methods that accelerate the overall drying rate, such as vacuum-ohmic heating, microwave vacuum, and ultrasound-assisted drying (Lagnika et al., 2018).

Due to difference between the osmotic pressure of the food and that of the solution, water is transported from the material into the solution. In addition, the osmotic solute diffuses from solution into the food. During OD the rate of water loss is directly proportional to: osmotic solution concentration; immersion time; temperature; weight ratio of the feed solution; agitation; and depends on food structure, solid size and geometry, and the area of mass exchange and system pressure (Herman Lara et al., 2013; Conceição Silva et al., 2012; Ruiz Lopez et al., 2010; Rastogi & Niranjan, 1998).

Lerici et al. (1985) mentioned that one of the main advantages of direct osmosis compared to other dehydration processes is to minimize fruit flavor alteration promoted by heat, and loss of color due to oxidative enzymatic browning, avoiding thus the use of sulfur dioxide. Another benefit is to require less energy when compared to hot air drying. As disadvantages of OD, one may cite the use of higher drying times, the extraction of natural acids by the osmotic solution and the increase in sugar concentration changing taste and product acceptance (Robbers et al., 1997).

From a nutritional standpoint, kiwi (*Actinidia deliciosa*) has low levels of saturated fats, cholesterol and sodium, and is a good source of dietary fiber, potassium and copper, with high levels of vitamin C and K (Beirão-da-Costa et al., 2006).

Although kiwi fruit is widely consumed in Brazil, until now there is little data on its OD kinetics. The objectives of this paper were to study the influence of osmotic solution concentration on kiwi dehydration process and to evaluate water loss and solute gain as a function of time and use of different concentrations of osmotic solutions.

2 Material and methods

Kiwi was acquired in the Central Supply of Rio Grande do Sul (CEASA), in Porto Alegre, Brazil. The selection considered the absence of visual injuries and infections. The whole fruits were first washed and then treated with a mild heat by immersion in a water bath controlled at 45 °C for 25 minutes (Beirão- da- Costa et al., 2006), and stored under refrigeration (8 ± 2 °C) for 24 hours.

Fruits were peeled and carefully cut into uniform pieces (2.0 × 2.0 × 0.5 cm). Samples were placed in a metal grid inside a hermetically sealed container with magnetic stirring, containing the hypertonic solution in a fruit:syrup ratio of 1:4 for 300 minutes at 25 °C. Osmotic solutions were prepared with commercial sucrose diluted in distilled water at 45, 55 and 65 °Brix at 25 °C.

Changes in moisture content, water activity and soluble solids content were monitored at regular intervals during dehydration. For this, samples were removed from solution and placed on a paper towel to dry the excess of water and / or syrup which was covering the product surface.

Moisture content was determined by oven method, until constant weight (AOAC 925.45 method, Association of Official Analytical Chemist, 1990). Water activity was measured in a Novasina® hygrometer, A_W Sprint model (AOAC 978.18 method, 1990). Soluble solids were measured on a refractometer, model 113 Nova® device (AOAC 932.12 method, 1990) and the pH was measured in a Quimis pH meter (AOAC 943.02 method, 1990).

The moisture content estimation, at equilibrium conditions, was accomplished using Peleg's (1988) model, which describes the moisture sorption kinetics, in which the equilibrium condition asymptotically approaches on time (Khoyi & Hesari, 2007):

$$X_t - X_0 = -\frac{t}{k_1 + k_2 t} \quad (1)$$

where X_t e X_0 are the moisture content (dry basis) of the sample at dehydration time t and at outset respectively; k_1 e k_2 are model parameters.

The constant k_1 is related to the initial rate of water transfer through Equation 2.

$$\frac{dX}{dt} = \left|\frac{1}{k_1}\right| \quad (2)$$

The constant k_2 is related to water concentration at equilibrium conditions (X_∞), according to Equation 3.

$$X_\infty = X_0 - \frac{1}{k_2} \quad (3)$$

The Fick's Second Law was employed for water mass diffusivity determination. Calculations were made considering an infinite flat plate with thickness $2L$ and the following assumptions were used for the model development: uniform initial water concentration in kiwi; isothermal process; there is only the exit of water from kiwi to solution (other mass transfers in this direction do not occur); shrinkage is neglected; external resistance to mass transfer is negligible, resulting in the following initial and boundary conditions:

- uniform initial water concentration; $t = 0$; $-L < l < L$; $X = X_0$;
- symmetrical concentration; $t > 0$; $l = 0$; $dX/dt = 0$;
- condition of specified concentration. $t > 0$; $l = \pm L$; $X = X_\infty$.

According to Crank (1975), the dimensionless moisture content obtained by the solution of Fick's Second Law for diffusion in a plane sheet, assuming uniform initial distribution and a specified surface concentration as a function of time (t) is given by Equation 4.

$$\frac{M_t}{M_\infty} = 1 - \sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} exp\left\{-Fo(2n+1)^2 \pi^2 / 4\right\} \quad (4)$$

Where:

$$M_t = X_t - X_0$$

$$M_\infty = X_\infty - X_0$$

and Fo is the Fourier Number for diffusion, defined as:

$$Fo = \frac{D_e t}{L^2}$$

where D_e ($m^2\ s^{-1}$) is the effective mass diffusivity. Values of the Fourier number (Fo) were obtained by non-linear regression analysis from Equation 4, taking into account the first four terms of the series, and calculated by the Solver function of Excel program.

In order to evaluate the effect of the osmotic solution concentration on the values of moisture, water activity and concentration at the end of OD, a complete random design was employed. Treatments were compared by Tukey's means multiple comparison test by the SAS 9.3 program.

3 Results and discussion

Samples of fresh kiwi used in the experiments had the following physicochemical characteristics: moisture content of 87.73% ± 1.05%; water activity of 0.990 ± 0.001; 3.06 ± 0.25 of pH and 12.15 ± 0.75 °Brix; these values are close to those reported by Gerschenson et al. (2001): moisture of 84%, water activity of 0.99 and soluble solids between 11 and 14 °Brix.

Figure 1 shows that for the three hypertonic solutions used there was a reduction of moisture content over time of immersion, as a result of the water removal by the solution. The output rates of free water were higher as the solution concentration increased. This is explained by the fact that higher concentration differences between fruit and osmotic solution promote greater water losses (Robbers et al., 1997), as a consequence of the osmotic pressure gradient and the existing mass transport, with mass transfer rates dependent on concentration and temperature of osmotic solution (Rastogi & Niranjan, 1998). Figure 1 also shows that the highest rates of water loss occurred in the first 60 minutes, with a subsequent reduction. Similar behavior was observed by Mercali et al. (2010) during the OD of bananas in solutions containing sucrose and sodium chloride, and by Brochier et al. (2015), in which sorbitol and glycerol solutions were used to osmotically dehydrate yacon. Mavroudis et al. (2012) suggested that, during the mechanism of water diffusion, the movement of water occurs primarily through the apoplast, which is a set of compartments located externally to the plasma membrane, where water moves across the tonoplast and plasmalemma, to then diffuse throughout the cell wall, reaching the area corresponding to the tissue; then, the pores are filled with the osmotic solution.

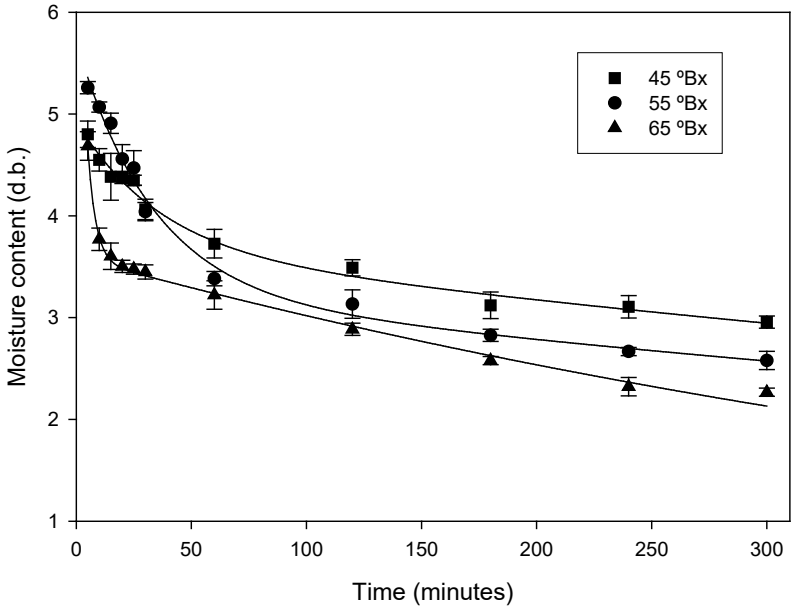

Figure 1. Variation of moisture content (dry basis) with immersion time during the osmotic dehydration of kiwi.

Figure 2 shows that water activity decrease was higher when the product was in a 65 °Brix solution. This is because, besides existing higher drying rates at this concentration, the increase in product sugar content led to a lower free water availability with consequent reduction of water activity. Talens et al. (2003) noted that osmotic solutions with low concentration resulted in slower mass transfer rates with kiwi, and the gain of sugars and water loss depend on the process conditions. It was also detected that the decrease in water activity was higher in the first 60 minutes, and in this period the largest amount of free water contained in fruit was withdrawn. Lerici et al. (1985) reported that water loss depends not only on water activity gradient between solution and fruit, but also on the solid gain; this phenomenon is possibly caused by the reduction

of diffusion coefficient of water in the interphase product / solution. The water activity reduction minimizes microorganisms growth; however, through this method, only partial dehydration of kiwi may be achieved (Simpson et al., 2015).

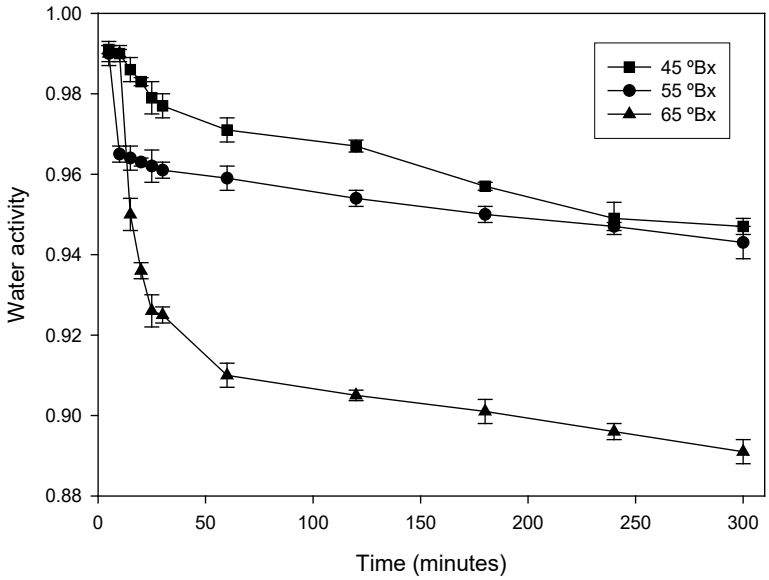

Figure 2. Variation of water activity with immersion time during the osmotic dehydration of kiwi.

Figure 3 shows the increase of soluble solids concentration in fruit over time, with higher gain when the solution had higher osmotic concentration. This behavior is due to the fact that the water diffusion is accompanied by the simultaneous counter diffusion of the osmotic solution solute to the food (Abraão et al., 2013; Rastogi & Niranjan, 1998). The highest rates of solute gain occurred during the first 45 minutes for the three solutions, and for the solution of 65 °Brix equilibrium was reached after 250 minutes. In general, the solute uptake behavior has an exponential trend. In this regard, Mercali et al. (2012) found that the gain of solutes rose exponentially with time in a study of banana osmo-dehydration. In another research, Talens et al. (2003) studied the kiwi osmotic dehydration using 45 and 65 ºBrix sucrose solutions under atmospheric pressure and vacuum pulses, until the fruit reaches 30 ºBrix. The authors found that the mass fraction in the liquid phase was 0.294 ± 0.011 for all treatments.

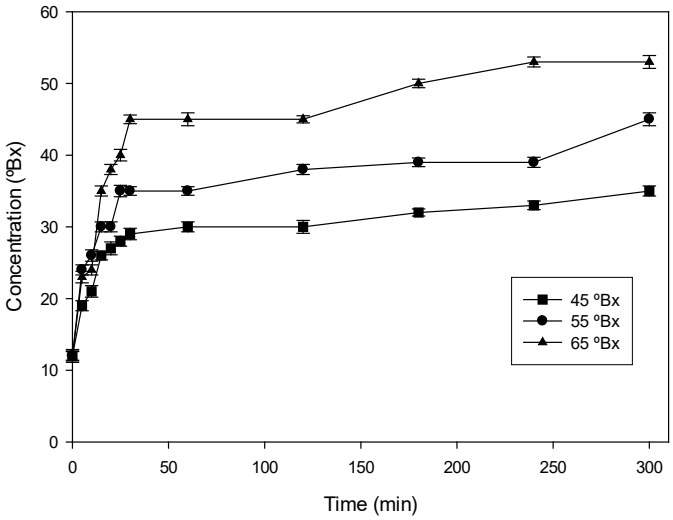

Figure 3. Variation of soluble solids with immersion time during the osmotic dehydration of kiwi.

Analyzing the three graphics, it is observed that the solute concentration exerted a strong effect on dehydration process, especially at 65 °Brix. El-Aouar et al. (2006) also observed that the osmotic solution concentration was the most important factor in weight loss and loss of water, followed by immersion time in papaya dehydration with sucrose.

Singh et al. (2007) observed an increase in water loss and a solute gain in carrot cubes over time; however, water loss and solutes gain into the fruit were greater in the initial stage of osmosis than in the following periods. These authors suggested that, in this stage, rapid water loss and entry of solids around the surface may have resulted from the structural changes, allowing compaction of these layers on the surface and increasing the resistance to mass transfer of solutes and water. Next, over time and with the water removal from sample to solution, and with the ingress of solute into the sample, the transport potential of water and solute decreased.

Turgor loss was detected during kiwi osmotic dehydration, affecting the tissue mechanical behavior, due to changes in cell wall resistance, in volume fractions of air and liquid, and modifications in size and shape of the samples (Chiralt et al., 2001).

Castro-Giráldez et al. (2011) stated that the kiwi behaves as a viscoelastic solid, noting that, at the beginning of the osmotic treatment, expansion and contraction of the tissue were observed. They also found that the mass flow of water and sucrose decreased with the treatment time. A possible cause for this behavior may be the fact that, as the water concentration decreases and the solute concentration increases, the free volume of diffusion decreases.

Table 1 presents the average values of moisture, water activity and soluble solids after dehydration (300 minutes). It was observed that there were significant differences between solutions ($p < 0.05$) regarding the final concentration of soluble solids reached by samples. Samples showed different water activity in solutions of 45 and 65 °Brix. As for the final moisture achieved, there were significant differences; the higher the solution concentration, the smaller the moisture.

Table 1. Soluble solids, water activity and moisture content of the osmodehydrated kiwi.

Solution concentration (°Brix)	Soluble solids (°Brix)	Water activity	Moisture (dry basis)
45	35.1 ± 1.5[a]	0.95 ± 0.02[a]	2.95 ± 0.06[a]
55	44.9 ± 1.7[b]	0.94 ± 0.02[a,b]	2.58 ± 0.09[b]
65	53.2 ± 1.4[c]	0.89 ± 0.03[b]	2.27 ± 0.04[c]

Means with different letters differ significantly ($p < 0.05$).

The osmotic pressures of solutions could be predicted from the equation 5 (El-Aouar et al., 2006):

$$\pi = -4.6063 \times 10^{5} T \ln(a_w) \quad (5)$$

where π is the osmotic pressure (Pa), T is the absolute temperature (K) and a_w is the water activity.

The values that correspond to solutions of 45, 55 e 65ºBrix, were 5.78×10^6, 8.55×10^6 e 12.79×10^6 Pa, respectively.

When the fruit is immersed into an osmotic solution, there is a critical concentration, below which tissue takes up water; but above it, dewatering of tissue occurs (Goula et al., 2017). In this condition, osmotic pressures of the osmotic solution and inside the cells are equals (Bellary & Rastogi, 2012).

According to the classification of Maltini et al. (2003), food dehydration by osmosis can result in high moisture foods (0.99 to 0.95 a_w), reduced moisture content (0.95 to 0.85 a_w) or intermediate moisture (from about 0.85 to 0.65 a_w). In our case, the dehydrated products obtained resulted in foods with reduced water

activity. Thus, it was found that there was a high incorporation of fruit solutes, which is undesirable, since it is recommendable that dehydration must be conducted under conditions that allow the smallest possible incorporation of solutes.

Table 2 presents the values of equilibrium moisture content and water mass diffusivity. It is observed that the equilibrium moisture content decreased significantly ($p < 0.05$) with the increase of the osmotic solution concentration, and it was close to the values obtained experimentally at the end of drying (Table 1). As for the effective mass diffusivity, it was in the range from 1.5×10^{-9} to 1.9×10^{-9} m^2 s^{-1} and it was significantly higher ($p < 0.05$) when the osmotic solution of 65 °Brix was used. Santagapita et al. (2016), reported values of water diffusivity of 1.23×10^{-9} to 1.51×10^{-9} m^2 s^{-1}, for osmotic dehydration of kiwi fruits using sucrose solution (61.5%), continuously stirred with a propeller to become negligible the external resistance to mass transfer. Silva et al. (2014), using various diffusion models with surface resistance of heat exchange in pineapple dehydration with sucrose solutions of 40 and 70 °Brix at 30 °C, reported values of water diffusivity from 3.31×10^{-9} to 4.35×10^{-9} m^2 s^{-1}, respectively, being larger with increasing concentration of the osmotic solution. Rastogi & Raghavarao (2004) reported average effective diffusivity value of $0.66 \pm 0.02 \times 10^{-9}$ m^2 s^{-1} for osmotic dehydration of potato sucrose solution at 50 °Brix at 25 °C. Khoyi & Hesari (2007) reported diffusivity values from 1.066×10^{-9} to 4.061×10^{-9} m^2 s^{-1} for water loss during apricot OD using sucrose solutions of 50%, 60% and 70% at temperatures from 30 to 70 °C, stating that higher temperatures and concentrations accelerate the mass transfer. However, these values were higher than those reported by Porciuncula et al. (2013) for banana when using osmotic solution of 65 °Brix at 60 °C, for the model with diffusion coefficient dependent on moisture; the obtained values ranged from 2.12×10^{-10} to 3.98×10^{-10} m^2 s^{-1}. Souraki et al. (2014a), studying the osmotic dehydration of apple in the form of infinite plate and considering shrinkage during drying in sucrose solutions at concentrations between 30% and 50% at temperatures between 30 °C and 50 °C, obtained values of effective diffusivity in the range from 1.36×10^{-10} m^2 s^{-1} to 2.00×10^{-10} m^2 s^{-1} and from 0.87×10^{-10} m^2 s^{-1} to 1.27×10^{-10} m^2 s^{-1} without and with shrinkage, respectively. In pumpkin dehydration with sucrose solutions at temperatures of 40, 50 and 60 °C, Abraão et al. (2013) observed a significant increase in the effective diffusivity of water when the concentration of sucrose solution increased from 40 °Brix to 50 and 60 ºBrix, while from 50 to 60 ºBrix there was no significant change, with values in the range from 10^{-9} to 10^{-10} m^2 s^{-1} for the different temperatures and concentrations studied. During osmotic dehydration of sapodilla (*Achras zapota* L.) at 40 ºBrix of sucrose and 28 °C, Coimbra et al. (2017) reported a value of 0.39×10^{-10} m^2 s^{-1}.

Table 2. Equilibrium moisture (dry basis) and water mass diffusivity (m^2 s^{-1}) of the osmodehydrated kiwi.

Solution concentration	X_∞	R^2	$D_e \times 10^9$	R^2
45 °Bx	2.89 ± 0.08^a	0.998	1.77 ± 0.05^b	0.975
55 °Bx	2.38 ± 0.05^b	0.999	1.65 ± 0.07^b	0.954
65 °Bx	2.20 ± 0.04^c	0.997	1.86 ± 0.01^a	0.967

Means with different letters differ significantly ($p < 0.05$).

Some authors state that the differences between the values of diffusion coefficient found in literature may be due to the method and the model of estimation used, and the variation in composition and physical structure of the food (Abraão et al., 2013) in addition to the shrinkage, plasmolysis and denaturation of the fruit cell wall due to high temperatures (Porciuncula et al., 2013); solutes incorporation and loss of solids to the solution are not provided in the models of heat exchange by diffusion used. About Peleg´s model, Simpson et al. (2017) mention that is one of the most used equations able to predict water migration during food drying.

4 Conclusions

Upon osmotic dehydration of kiwi, it was possible to reduce the amount of free water in the fruit, with the consequent decrease of the water activity and increase of solids content in the product. The rate of water loss was greater during the first hour of drying. The use of an osmotic solution with 65 °Brix resulted in a significant increase in water diffusivity, being the most indicated to this process.

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