

Factors affecting the mass transfer kinetics of osmotically dehydrated chayote (*Sechium edule* (Jacq.) Sw.)

Karina HUERTA-VERA¹, Adriana CONTRERAS-OLIVA^{2*},
Ma. de Lourdes ARÉVALO-GALARZA¹, Enrique FLORES-
ANDRADE³, Ma. Bernardita PÉREZ-GAGO⁴,
Diana P. USCANGA-SOSA²

¹Postgraduate College Montecillo Campus, Highway México-Texcoco, km. 36.5, P.C. 56230, Montecillo, Texcoco, Mexico; karina.huerta@colpos.mx; larevalo@colpos.mx

²Postgraduate College Córdoba Campus, Federal Highway Córdoba-Veracruz, km 348, Congregation Manuel León, P.C. 94946, Amatlán de los Reyes, Veracruz, Mexico; adricon@colpos.mx (*corresponding author); uscanga.diana@colpos.mx

³Veracruzana University, Faculty of Chemical Sciences, Ote. 6 1009, Rafael Alvarado, P.C. 94340, Orizaba, Veracruz, Mexico; enflores@uv.mx

⁴Valencian Institute of Agricultural Research, Center for Postharvest Technology, Highway CV-315, km 10.7, P.C. 46113, Moncada, Valencia, Spain; perez_mbe@gva.es

Abstract

The aim of this study was to apply osmotic dehydration (OD) to produce minimally processed chayote (*Sechium edule* (Jacq.) Swartz) slices. Thus, the effect of osmotic solution concentration, temperature, processing time, and vacuum pulse application on mass transfer during osmotic dehydration of the fruit was evaluated. The kinetics of water loss (WL), solids gain (SG), and water activity (a_w) were obtained using sucrose solutions with concentrations of 40, 50 and 60 °Bx at 25, 35 and 45 °C. Osmotic solution concentration, temperature, and processing time had a greater influence than vacuum pulse application on WL and SG . The temperature showed an Arrhenius-type dependence on effective diffusivity. The osmodehydrated chayote had lower a_w (up to 0.846), higher total soluble solids (TSS) content (up to 31.9 °Bx) and purer and more intense color (up to 18.75 in chroma) compared to fresh chayote. These findings suggest that OD allows for the production of minimally processed chayote that could be included in quick-cook products, such as salads or soup mixes.

Keywords: minimally processed foods; solid content; vacuum pulse; water activity; water loss

Introduction

Chayote (*Sechium edule* (Jacq.) Swartz) is native to Central America and belongs to the family Cucurbitaceae (Cadena-Iñiguez *et al.*, 2007). The fresh fruit contains 89 to 95% water and 2.0 to 3.6% potassium, calcium, phosphorus, magnesium, and total sugars. Additionally, it includes glutamic, aspartic, and

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leucine amino acids, vitamins C, K and A, and folic acid, among other components (Aguñiga-Sánchez *et al.*, 2015; Shafirany *et al.*, 2018). Additionally, chayote is a source of bioactive compounds (saponins, phenolic acids, flavonoids, triterpenes, and phytosterols) (Ordoñez *et al.*, 2006). However, although the demand for fresh fruit has increased in recent years, export to distant markets is limited because the embryo germinates prematurely while the fruit is still attached to the plant. This characteristic accelerates its deterioration and reduces quality and commercial value (Cadena-Iñiguez *et al.*, 2006). One way to extend the shelf life of chayote is by reducing its water content.

Air-drying is the most widely used technique to improve the stability of fruits and vegetables. However, this technique can lead to nutrient degradation and loss of sensory qualities. Various drying techniques have been employed to enhance the shelf life and quality of horticultural products. Convective drying, which uses hot air to remove moisture, is known for its efficiency in maintaining the nutritional quality of the product. For instance, studies have shown that convective drying methods can retain significant amounts of vitamins and minerals in various seeds, including pumpkin seeds (Mujaffar and Ramsumair, 2019). Similarly, solar drying, which utilizes solar energy to remove moisture, is recognized for its sustainability and cost-effectiveness. Research highlighted that solar drying effectively reduces moisture content while preserving the nutritional quality of brewer's spent grains (Capossio *et al.*, 2022).

Despite the benefits of convective and solar drying, these methods have limitations. Convective drying can sometimes lead to nutrient degradation due to high temperatures, while solar drying is dependent on weather conditions, which can affect consistency and control over the drying process. Air drying is another common method that involves exposing the product to air at ambient temperatures, often leading to longer drying times and potential microbial contamination if not managed properly (Guiné, 2018).

Osmotic dehydration (OD), on the other hand, is an energy-efficient method that operates at lower temperatures, reducing the risk of heat-induced degradation of sensitive nutrients (Derossi *et al.*, 2015). This technique consists of immersing a cell tissue in a hypertonic solution to promote water loss (*WL*) from the cells and achieve osmotic solids gain (*SG*) in the intercellular spaces and external cells cut from the plant tissue (Chiralt and Fito, 2003). OD allows for the production of partially dehydrated chayote with potential application as an ingredient or minimally processed product. Additionally, OD improves quality characteristics such as color, texture, and taste of the final product, and reduces energy requirements for subsequent thermal drying (Barragán-Iglesias *et al.*, 2018; Dermesonlouoglou and Giannakourou, 2018).

The process is carried out at atmospheric pressure or sub-atmospheric pressure for the first few minutes in a process called pulsed vacuum osmotic dehydration (PVOD). The pressure reduction promotes the removal of gas occluded in the pores of the product. When atmospheric pressure is restored, residual gas in the pores is compressed and the hypertonic solution flows into the pores through a hydrodynamic mechanism (HDM). This mechanism increases the area available for mass transfer due to the pressure difference (Fito, 1994; Corrêa *et al.*, 2014; De Jesus Junqueira *et al.*, 2018).

OD is influenced by variables associated with the process such as composition and concentration of the osmotic agent, temperature, immersion time, and presence or absence of agitation in the osmotic medium (Ito *et al.*, 2007; Torres *et al.*, 2007; Lombard *et al.*, 2008; Corrêa *et al.*, 2014); in addition, product characteristics such as species, variety, ripening stage, physicochemical properties and tissue structure also have an effect (Junqueira *et al.*, 2020).

OD is a diffusion process entropically regulated by the structure of plant cells and is related to the microstructural changes they undergo as a result of *WL* and *SG* (Flores-Andrade *et al.*, 2009). This process can be modeled based on Fick's second law, which holds that the external resistance to mass transfer is negligible compared to the internal resistance. Mass diffusivity is generally assumed to be constant throughout the process. However, if the product exhibits shrinkage during OD, the mass diffusivity may also vary. In this context, Azuara *et al.* (1992) propose a model based on Fick's second law, which contemplates unsteady one-dimensional diffusion through a thin plate/slice considering the effective diffusion variation during the

osmotic process. Counter current diffusion of water and solutes in the food during OD reduces the water activity (a_w) and increases the total soluble solids (TSS) of the final product (De Mello Jr *et al.*, 2019; Schincariol Paes *et al.*, 2019). Thus, the use of empirical models is a useful tool that could predict the a_w and TSS content of osmo-dehydrated chayote and provide information to design and optimize an OD method according to the sensory and physicochemical characteristics desired in the final product.

Information related to chayote dehydration processes is limited. Although the effect of OD pretreatment on air-drying of chayote was evaluated by Ruíz-López *et al.* (2010), there seems to be no information on the influence of process variables on the characteristics of osmotically dehydrated chayote. Knowing the impact of OD and process conditions on the physicochemical properties of chayote will allow obtaining osmotically dehydrated fruits that could be used as a quick-cook product or as an ingredient for salads and soup mixes. Therefore, the objectives of this study were (i) to evaluate the effect of osmotic solution concentration, temperature, processing time, and vacuum pulse application on the mass transfer, effective diffusivity, a_w , TSS, color, and volumetric shrinkage of chayote slices during OD and (ii) to evaluate the application of an empirical model in the prediction of a_w and TSS content during OD of chayote slices.

Materials and Methods

Raw material

Chayote (*Sechium edule* var. *virens levis*) fruits from Huatusco, Veracruz, Mexico was harvested 33-35 days after anthesis. Fruits, washed with sodium hypochlorite solution (0.1%), were stored at 8 ± 1 °C for less than 15 days until study. The fruits had a moisture content of 91.25 ± 0.79 kg 100 kg⁻¹ (wet basis), an a_w of 0.981 ± 0.004 , and a TTS content of $5.07 \pm 0.43\%$. Color was measured with a colorimeter (KONICA MINOLTA®, mod. CR-400, Japan) and the values obtained were $L^*=74.04 \pm 0.43$, $a^*=-1.40 \pm 0.17$ and $b^*=10.49 \pm 0.47$.

Sample preparation and osmotic process

The chayote fruits were peeled and axially sectioned into slices 39 mm in diameter and 3.9 mm thick. Each slice was weighed and immersed in sucrose solutions (40, 50 and 60 °Bx) at 25, 35 and 45 °C, maintaining a 1:20 (w/w) fruit: solution ratio. These trials were conducted at atmospheric pressure or with vacuum (PVOD). For PVOD treatments, a vacuum oven (Heraeus, mod. D-6450, Hanau, Germany) was coupled to a vacuum pump (Labconco mod. No.117, US.). The vacuum pressure reached 115 mbar during the first 15 min. After that, atmospheric pressure was restored. Samples were removed from the solution after 10, 20, 30, 60, 120, 180, 240 and 300 min. The osmotic process was then stopped by immersing each sample in cold distilled water for 10 s. Excess surface water was gently removed with absorbent paper. The samples were weighed and the moisture content at the end of each immersion time was determined in a vacuum oven (Heraeus, mod. D-6450), at 60 °C for 24 h. Volume changes in the chayote slices due to osmotic dehydration were evaluated by the change in diameter, which was measured with a digital vernier caliper (Truper®, Mexico), and thickness, which was measured with a digital micrometer (Mitutoyo Digimatic Micrometer No. 293-721, Los Angeles, CA, US.). Other variables measured were a_w (Novasina LabMASTER water activity meter, mod. Standar, US), TSS (with ATAGO® equipment, PAL-1, Japan) and color parameters (KONICA MINOLTA®, mod. CR-400); for the color parameters, chroma and hue angle were calculated (McGuire, 1992).

Micrographs were used to analyze the changes in the parenchyma cells of the chayote mesocarp during OD. Chayote samples were lyophilized using Labconco equipment (Freezone 4.5) at a pressure of 1 Pa and a temperature of -86 °C for 72 h. Transversal cuts were performed to the samples, which were then placed on a slide to be covered by gold for 4 min in a JFC-1100 ionizer (JEOL LTD, Tokyo, Japan). The samples were examined using a JSM-35C® scanning electron microscope (JEOL LTD, Tokyo, Japan).

Mathematical models

The calculation of WL and SG during osmotic dehydration of the slices with respect to their initial mass (M_o) was carried out with equations (1) and (2):

$$WL = \frac{M_o X_o - M_t X_t}{M_o} \quad (1)$$

$$SG = \frac{M_o(X_o - 1) - M_t(X_t - 1)}{M_o} \quad (2)$$

Where M_o is the initial mass of the food at time 0, M_t is the mass of the food at time t , X_o is the initial moisture (wet basis) and X_t is the moisture content of the food (wet basis) at time t .

The kinetics of WL and SG in the slices during osmotic dehydration were modeled according to equations (3) and (4) (Huerta-Vera *et al.*, 2017):

$$WL = \frac{s_1 t WL_\infty}{1 + s_1 t} \quad (3)$$

$$SG = \frac{s_2 t SG_\infty}{1 + s_2 t} \quad (4)$$

The apparent diffusion coefficients of water and solids in the evaluated time periods were calculated from the WL and SG data, using equations (5) and (6) (Kvapil *et al.*, 2020):

$$D_w = \frac{\pi l^2}{4t} \left[\left(\frac{s_1 t}{1 + s_1 t} \right) \left(\frac{WL_\infty^{mod}}{WL_\infty^{exp}} \right) \right]^2 \quad (5)$$

$$D_s = \frac{\pi l^2}{4t} \left[\left(\frac{s_2 t}{1 + s_2 t} \right) \left(\frac{SG_\infty^{mod}}{SG_\infty^{exp}} \right) \right]^2 \quad (6)$$

Where WL is the estimated water fraction lost by food at time t , SG is the estimated solid fraction gained by food at time t , WL_∞ is the fraction of water lost by food at equilibrium, SG_∞ is the fraction of solids gained by the food at equilibrium, s_1 is the constant related to the rate of water loss (min^{-1}) and s_2 is the constant related to the rate of soluble solids entering the food (min^{-1}), l is the half-thickness of slab, and t is the time. The parameters s_1 and s_2 and the equilibrium values WL_∞ and SG_∞ of equations (3) and (4) were estimated by nonlinear regression using the Levenberg-Marquardt algorithm implemented in KaleidaGraph 4.5 software (Synergy, USA).

The calculated values of D_w or D_s were fitted to the Arrhenius-type equation to calculate the activation energy using equation (7):

$$D_w \text{ or } D_s = D_o \exp \left\{ \frac{-E_a}{R(T+273.15)} \right\} \quad (7)$$

D_o is the reference diffusion coefficient, E_a is the activation energy (kJ mol^{-1}), R is the universal gas constant ($8.314 \text{ kJ (mol K)}^{-1}$), and T is the temperature (K).

Quantification of a_w and total soluble solids (TSS)

To quantify a_w and TSS during time-dependent osmotic dehydration of slices, the experimental data were fitted with equations (8) and (9), with the empirical DR-Hill and Rational models respectively, implemented in Curve Expert Professional 2.6.5 software.

$$a_w = \alpha + \frac{\theta \tau^\eta}{\kappa^\eta + \tau^\eta} \quad (8)$$

$$^{\circ}\text{Bx TSS} = \frac{a + bt}{1 + ct + dt^2} \quad (9)$$

Where α , θ , κ , and η are parameters associated with the empirical DR-Hill Model, and a , b , c , and d are parameters associated with the empirical Rational Model, and t is the time (min).

Experimental design

All evaluations were performed in triplicate, and the results are presented as means \pm standard deviation of the replicates. For all experiments, a 3 x 3 x 2 factorial experimental design was implemented. The levels of the factors were: osmotic solution concentration (40, 50 and 60 °Bx), temperature (25, 35 and 45 °C) and vacuum pulse (0 and 115 mbar). All data were analyzed with KaleidaGraph 4.5 software (Synergy, USA) applying ANOVA, with a significance of 0.05. The significance of the differences between groups was evaluated using Tukey's test.

To determine the suitability and goodness of fit in the models, the following parameters were chosen: the coefficient of determination (R^2), chi-square (χ^2) and root mean square error ($RMSE$). The values of χ^2 , R^2 and $RMSE$ were evaluated with equations (10) - (12).

$$\chi^2_{\text{cal}} = \sum_{i=1}^N \frac{(O_i - E_i)^2}{(E_i)} \quad (10)$$

$$R^2 = 1 - \sum_{i=1}^N \frac{(O_i - E_i)^2}{(O_i - \bar{E}_i)^2} \quad (11)$$

$$RMSE = \frac{1}{N} \left[\sum_{i=1}^N (E_i - O_i)^2 \right]^{\frac{1}{2}} \quad (12)$$

Where N is the total number of data values used to fit the equation, O_i and E_i are the experimental and predicted model values, respectively, and \bar{E}_i is the average of all experimental data.

Results and Discussion

Mass transfer kinetics during osmotic dehydration

The kinetics of WL during osmotic dehydration of chayote slices in different osmotic treatment conditions are shown in Figure 1. At the beginning of the treatment, the mass transfer rate was higher and decreased over time, indicating that the system reached a state of pseudo-equilibrium due to the decrease in the chemical potentials of the water and solute between the chayote and the osmotic solution.

WL was positively affected by the temperature and osmotic solution concentration (Figure 1). This indicates that increasing either of these parameters accelerates the WL of chayote during OD and PVOD. WL was favored with higher solution concentrations because the large amount of solute increases the osmotic pressure. Lombard *et al.* (2008) and Corrêa *et al.* (2014) studied the OD and PVOD of guava slices and pineapple cylinders in sucrose solutions (35 to 65 °Bx) and observed that increasing the concentration in the sucrose solution promoted WL .

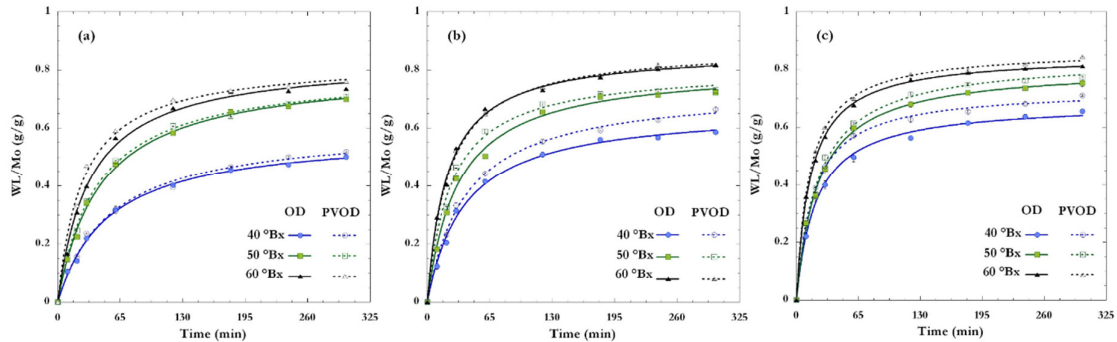


Figure 1. Water loss during osmotic dehydration of chayote slices in sucrose solutions (a) process at 25 °C; (b) process at 35 °C; (c) process at 45 °C. OD: without modifying the atmospheric pressure, PVOD: osmotic dehydration with a 115-mbar vacuum pulse for 15 min

Higher temperatures increased the chayote *WL* rate in the first minutes of the process. It is possible that the reduction in the viscosity of the osmotic medium and the modification of the viscoelastic properties of the product are due to the swelling and plasticization of the cell membranes; this results in greater mass transfer. Ito *et al.* (2007) reported the positive effect of increasing temperature (20 to 40 °C) on the kinetics of osmotically dehydrated mango slices in sucrose solutions (45 to 60 °Bx) and PVOD. The results of Ruiz-López *et al.* (2011) and Abraão *et al.* (2013) in terms of the *WL* of carambola slices and pumpkin cylinders, osmotically treated in sucrose solution (40 to 60 °Bx), also increased with temperature (40 to 75 °C).

The vacuum pulse applied at the beginning of the osmotic process also caused an increase in *WL* in chayote (Figure 1). Lower than standard pressure causes the release of gas trapped in the intercellular spaces of the tissues, while when atmospheric pressure is restored, the empty intercellular spaces are filled with osmotic solution. This increases the available mass transfer surface area. The results were similar to those observed by Batista de Medeiros *et al.* (2019) in osmotically treated mango rectangles in sucrose solution (50 °Bx) at 30 °C and a vacuum pulse of 200 to 300 mbar.

There was also agreement with the observations documented by De Jesus Junqueira *et al.* (2017) in eggplant in a ternary solution at 30 °C and a vacuum pulse of 145 mbar. These authors reported that the increased *WL* in the samples occurred as a result of the hydrodynamic mechanism and the deformation phenomenon induced by the pressure drop caused, at the same time, by the vacuum pressure. The influence of the vacuum pulse on the equilibrium *WL* (WL_{∞}) of the chayote was more effective with lower osmotic solution concentrations (40 °Bx), probably due to the lower viscosity.

Higher concentrations of the osmotic solution increased the *SG* of chayote, due to the increase in the osmotic gradient (Figure 2). Increasing the temperature of the osmotic medium also caused an increase in the *SG* of the chayote. This influence of temperature in osmotic treatments was demonstrated in other studies and has been related to increased cell membrane permeability, reduced osmotic solution viscosity, and external resistance to mass or solute transfer (Ito *et al.*, 2007; Ruiz-López *et al.*, 2011, Dermesonlouoglou and Giannakourou, 2018).

The effect of PVOD on chayote *SG* did not generate differences in samples treated with 50 and 60 °Bx sucrose solutions at 45 °C with respect to OD (Figure 2). Shi *et al.* (1995) studied the OD and PVOD of apricot, strawberry and pineapple cubes with sucrose solution (65 °Bx) and observed that vacuum pulse application did not increase *SG* compared to OD. Gomes Corrêa *et al.* (2016) observed a similar effect of vacuum pulse application on solids incorporation in the OD of tomatoes with different ternary osmotic solutions. Similar behavior was observed by Barat *et al.* (2001) with a high osmotic solution concentration and/or high temperature during the PVOD process; these conditions decreased *SG* due to the collapse of the cell structure, which, in turn, promoted partial expulsion of the osmotic solution and internal gas release. All

of this led to a reduction in the internal pore volume available for solute impregnation. In addition, Fito (1994) reported that the use of a vacuum pulse is effective in increasing *WL*, but has no influence on the *SG* of osmotically dehydrated fruits. These results exhibit that osmotic solution concentration, temperature and processing time had a greater influence ($p \leq 0.05$) than vacuum pulse on the kinetics of osmotically dehydrated chayote slices.

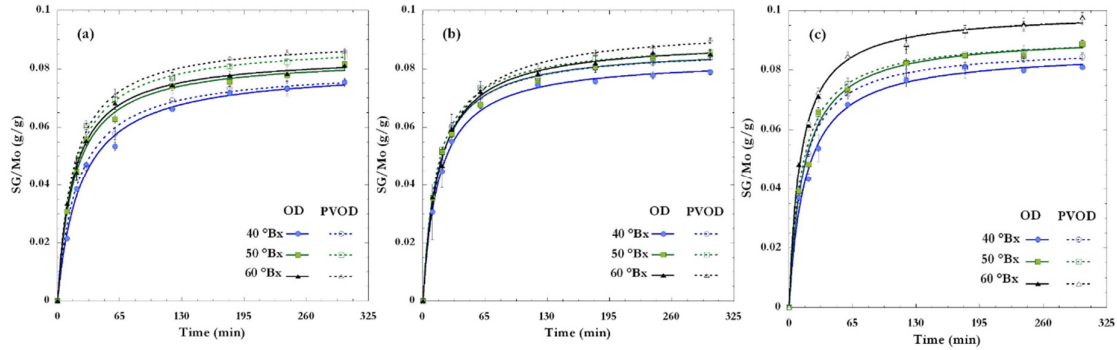


Figure 2. Solids gain during osmotic dehydration of chayote slices in sucrose solutions (a) process at 25 °C; (b) process at 35 °C; (c) process at 45 °C. OD: without modifying the atmospheric pressure, PVOD: osmotic dehydration with a 115-mbar vacuum pulse for 15 min

Vieira *et al.* (2012) osmodehydrated guavas in sucrose solutions (40 to 60 °Bx) with a temperature between 20 and 40 °C, and Viana *et al.* (2014) osmodehydrated fodder palm cladodes in sodium chloride solutions (5 to 15 °Bx) with a temperature between 30 and 50 °C; these authors observed that the influence of vacuum pulse application was lower than that of concentration and temperature. The authors attributed the results to differences in the microstructure of each product, particularly the porosity of the plant tissue, which determines the effect level of the vacuum pulse.

The results obtained in the present study are congruent with the values of the kinetic parameters obtained with Azuara's model (Table 1). The high values of R^2 and the low values of both χ^2 and $RMSE$ in Azuara's model suggest the suitability of the model to describe mass transfer kinetics during osmotic dehydration of chayote slices.

Table 1. Kinetic parameters of Azuara's model for water loss (*WL*) and solids gain (*SG*) during osmotic dehydration of chayote slices under different osmotic treatment conditions

Process	° Bx	Temp. (°C)	s_1 (min ⁻¹)	WL_{∞}	R^2	χ^2 ($\times 10^3$)	RMSE ($\times 10^3$)	s_2 (min ⁻¹)	SG_{∞}	R^2	χ^2 ($\times 10^3$)	RMSE ($\times 10^3$)
OD	40	25	0.0189 ± 0.0009	0.5852 ± 0.0066	0.9954	4.32	3.19	0.0412 ± 0.0010	0.0804 ± 0.0004	0.9880	0.76	0.71
		35	0.0257 ± 0.0007	0.6703 ± 0.0074	0.9929	6.33	4.85	0.0592 ± 0.0021	0.0838 ± 0.0001	0.9777	0.14	0.37
		45	0.0482 ± 0.0007	0.6848 ± 0.0043	0.9886	3.16	4.79	0.0618 ± 0.0015	0.0856 ± 0.0007	0.9954	1.03	0.85
	50	25	0.0225 ± 0.0001	0.8064 ± 0.0034	0.9959	4.38	4.41	0.0574 ± 0.0012	0.0840 ± 0.0005	0.9909	0.26	0.52
		35	0.0314 ± 0.0004	0.8136 ± 0.0006	0.9910	5.81	6.38	0.0678 ± 0.0019	0.0868 ± 0.0008	0.9966	0.22	0.49
		45	0.0438 ± 0.0006	0.8092 ± 0.0085	0.9940	2.51	3.64	0.0690 ± 0.0006	0.0916 ± 0.0001	0.9893	0.84	0.85
	60	25	0.0301 ± 0.0002	0.8401 ± 0.0011	0.9925	7.33	6.16	0.0639 ± 0.0017	0.0844 ± 0.0008	0.9907	0.25	0.44
		35	0.0486 ± 0.0005	0.8700 ± 0.0004	0.9946	2.90	4.72	0.0609 ± 0.0010	0.0896 ± 0.0002	0.9919	0.31	0.50
		45	0.0684 ± 0.0009	0.8506 ± 0.0037	0.9983	0.66	2.16	0.0863 ± 0.0013	0.0994 ± 0.0003	0.9919	0.26	0.53

PVOD	40	25	0.0182 ± 0.0002	0.6070 ± 0.0019	0.9904	3.54	4.66	0.0474 ± 0.0023	0.0806 ± 0.0009	0.9857	0.33	0.57
		35	0.0247 ± 0.0006	0.7423 ± 0.0059	0.9943	2.02	3.88	0.0672 ± 0.0009	0.0871 ± 0.0005	0.9964	0.16	0.43
		45	0.0568 ± 0.0010	0.7324 ± 0.0023	0.9904	1.03	3.74	0.0743 ± 0.0005	0.0877 ± 0.0009	0.9980	0.08	0.34
	50	25	0.0244 ± 0.0004	0.8035 ± 0.0035	0.9960	1.92	3.72	0.0599 ± 0.0008	0.0881 ± 0.0006	0.9867	0.50	0.73
		35	0.0407 ± 0.0003	0.8081 ± 0.0029	0.9832	5.77	6.98	0.0690 ± 0.0014	0.0895 ± 0.0019	0.9979	0.07	0.34
		45	0.0433 ± 0.0005	0.8417 ± 0.0003	0.9904	2.98	5.14	0.0788 ± 0.0008	0.0915 ± 0.0006	0.9973	0.04	0.25
	60	25	0.0387 ± 0.0003	0.8330 ± 0.0028	0.9879	4.74	6.23	0.0607 ± 0.0011	0.0908 ± 0.0002	0.9852	0.21	0.54
		35	0.0455 ± 0.0004	0.8814 ± 0.0019	0.9957	1.13	3.47	0.0547 ± 0.0014	0.0942 ± 0.0007	0.9949	0.12	0.43
		45	0.0730 ± 0.0013	0.8679 ± 0.0036	0.9951	0.50	2.86	0.0881 ± 0.0005	0.0994 ± 0.0006	0.9832	0.10	0.42

Mean values ± standard deviation (n=3). OD, without modifying the atmospheric pressure. PVOD, osmotic dehydration with a 115-mbar vacuum pulse for 15 min

Effective diffusivity

The water (D_w) and solids (D_s) diffusion coefficients for the OD of chayote slices over time were calculated with equations (5) and (6) (Table 2). The average values of the effective diffusion coefficient ranged from 2.36×10^{-10} to $5.25 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$ and 3.79×10^{-10} to $5.73 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$ for water and solids, respectively.

Table 2. Diffusion coefficients of water (D_w) and solids (D_s) during osmotic dehydration of chayote slices under different osmotic treatment conditions

Process	° Bx	Temperature (°C)	$D_w \times 10^{-10} (\text{m}^2 \text{ s}^{-1})$	R ²	$D_s \times 10^{-10} (\text{m}^2 \text{ s}^{-1})$	R ²
OD	40	25	2.36 ± 0.05	0.9954	3.79 ± 0.13	0.9880
		35	2.97 ± 0.04	0.9929	4.89 ± 0.02	0.9777
		45	4.08 ± 0.04	0.9886	4.99 ± 0.02	0.9954
	50	25	2.69 ± 0.04	0.9959	4.51 ± 0.05	0.9909
		35	3.39 ± 0.03	0.9910	4.97 ± 0.05	0.9966
		45	4.03 ± 0.18	0.9940	5.12 ± 0.04	0.9893
	60	25	3.38 ± 0.02	0.9925	3.38 ± 0.02	0.9907
		35	4.26 ± 0.02	0.9946	4.95 ± 0.14	0.9919
		45	5.25 ± 0.03	0.9983	4.93 ± 0.05	0.9919
PVOD	40	25	2.38 ± 0.03	0.9904	5.73 ± 0.02	0.9857
		35	2.76 ± 0.04	0.9943	4.62 ± 0.05	0.9964
		45	4.13 ± 0.05	0.9904	4.81 ± 0.05	0.9980
	50	25	2.82 ± 0.02	0.9960	4.36 ± 0.23	0.9867
		35	3.88 ± 0.07	0.9832	4.73 ± 0.10	0.9979
		45	3.90 ± 0.02	0.9904	4.89 ± 0.10	0.9973
	60	25	3.68 ± 0.05	0.9879	4.45 ± 0.03	0.9852
		35	3.97 ± 0.02	0.9957	4.16 ± 0.02	0.9949
		45	4.69 ± 0.01	0.9951	5.05 ± 0.22	0.9832

Mean values ± standard deviation (n=3). OD, without modifying the atmospheric pressure. PVOD, osmotic dehydration with a 115-mbar vacuum pulse for 10 min

The values of the effective diffusion coefficients had the same order of magnitude and were similar to those obtained in the osmotic treatment of papaya (Rodrigues *et al.*, 2003), guava (Corrêa *et al.*, 2010), apple (Souraki *et al.*, 2014), tomato (Gomes Corrêa *et al.*, 2016), carrot, eggplant and beetroot (Junqueira *et al.*, 2020).

According to Flores-Andrade *et al.* (2009), the diffusion process during OD is regulated by an entropic mechanism related to changes in microstructural and transport properties in the food matrix and induced by mass fluxes (*WL* and *SG*).

The diffusion coefficients reflect the ease and/or difficulty with which water and sucrose molecules move through the chayote plant matrix. Average D_w values slightly lower than those of D_s (Table 2) could be due to the diffusion of water from the cells to the osmotic solution via the symplast (plasmodesmata) and through the aquaporins (protein channels) in the lipid bilayer (Chiralt and Fito, 2003; Castro-Giráldez *et al.*; 2011).

In contrast, sucrose diffusion is limited to extracellular spaces (apoplastic transport) and most of it remains on the surface of the plant tissue (Shi and Maguer, 2003). This allows the formation of compact sucrose layers on the tissue and represents an additional external resistance to water diffusion.

D_w increased with increasing sucrose concentration and osmotic solution temperature in OD and PVOD (Table 2). Assis *et al.* (2016) studied the OD of apple in sucrose and sorbitol solutions (25 to 65 °Bx) at 25, 40, and 60 °C, and Sharma and Dash (2019) osmodehydrated black jamun (*Syzygium cumini*) in sucrose solution (60 °Bx) in a range of 30 to 50 °C; they noted that the effect of temperature on D_w may be due to the increase in membrane permeability and the fact that the temperature decreases the viscosity of the osmotic solution; this enhances capillary flow through the pores.

In the present study, PVOD did not increase effective water diffusion compared to OD. This result coincided with that documented by Escriche *et al.* (2000) in kiwifruit. These authors reported that with mass transfer during osmotic dehydration of kiwifruit with sucrose solution (65 °Bx) and concentrated grape juice (63 °Bx), D_w did not differ between OD and PVOD. This is attributable to the structural characteristics of the fruits studied, since the vacuum effect depends on the porosity of the fruit.

With respect to D_s , increasing the concentration and temperature of the sucrose solution also increased the D_s in OD and PVOD (Table 2). However, for the osmotic treatment with solutions at 40 and 50 °Bx, the differences were not significant when increasing the temperature from 35 to 45 °C. Furthermore, there was no significant difference at 60 °Bx at temperatures from 25 to 35 °C, however, at 45 °C the D_s values were higher. Lazarides and Mavroudis (1996) studied the OD of potato with corn syrup solution and observed that at 45 °C the tissue was damaged, resulting in a drastic increase in solute uptake. According to Chiralt and Fito (2003), *WL* causes alteration of the cell membrane and when this occurs with a critical water content, solutes diffuse freely throughout the tissue, in addition to open intercellular spaces. However, temperature limits are set by the thermal tolerance and stability of the cell membrane of the tissue under study (Lazarides, 2001).

Osmotic dehydration is an entropically regulated process; in this case, by increasing the osmotic solution temperature from 25 to 45 °C, the water and sucrose molecules increase the speed and amplitude of their vibration; this facilitates their displacement through the plant matrix, including that of the chayote. The dependence of the effective diffusivity values of water and sucrose on temperature was described by an Arrhenius-type equation (Equation (7)). The natural logarithm of the average values of the diffusivities of water ($\ln D_w$) and solids ($\ln D_s$) were plotted against the inverse absolute temperature (T^{-1}) to calculate the activation energy (E_a) (Figures not shown). E_a is the minimum amount of energy required by a system in order to initiate a given process. The E_a values required to initiate water removal and solids uptake in chayote during osmotic dehydration under OD and PVOD conditions are presented in Table 3. The E_a for water and sucrose diffusion ranged from 9.49 to 21.54 kJ mol⁻¹ and from 3.61 to 10.17 kJ mol⁻¹, respectively. High E_a values for D_w indicate that a large amount of energy is needed for water to flow from the cells and cross the semipermeable membranes to the osmotic solution, while lower E_a values for D_s indicate that it requires little energy to diffuse into the extracellular spaces and adhere to the surface of the chayote slices. The energy required coincided with the average D_w values and were slightly lower than the D_s ones (Table 2).

The E_a for the diffusivity of water and solids during OD and PVOD decreased with an increasing sucrose solution concentration (Table 3). Increasing the solute concentration increases the vibration and collision frequency of the molecules, so the energy required for water and sucrose molecules to diffuse decreases. Falade *et al.* (2007) studied osmotic dehydration of watermelon using sucrose solutions, finding that the higher the osmotic solution concentration, the less energy required for moisture removal and solute uptake.

The E_a values for PVOD were equal to or lower than for OD (Table 3). Barat *et al.* (2001) showed that, in apple, the E_a value was almost the same for OD and PVOD and suggested that this may be due to the fact that the mass transfer mechanisms involved in the composition changes of the liquid phase of the food were the same after vacuum application.

Table 3. Activation energy required for diffusion of water and solids during osmotic dehydration of chayote slices in sucrose solutions

Process	Concentration (°Bx)	Activation energy (KJ (mol k) ⁻¹)	
		Water diffusivity	Solids diffusivity
OD	40	21.54 ± 1.14 ^a	10.17 ± 1.02 ^a
	50	17.18 ± 0.48 ^b	5.02 ± 0.58 ^c
	60	17.26 ± 0.16 ^b	5.09 ± 0.39 ^c
PVOD	40	21.54 ± 0.72 ^a	7.41 ± 0.99 ^b
	50	12.83 ± 0.59 ^c	3.61 ± 0.28 ^c
	60	9.49 ± 0.14 ^d	3.96 ± 0.19 ^c

Mean values ± standard deviation (n=3). OD, without modifying the atmospheric pressure. PVOD, osmotic dehydration with a 115-mbar vacuum pulse for 15 min. Means with the same letter are not significantly different in Tukey's test ($P \leq 0.05$)

Escriche *et al.* (2000) and Panades *et al.* (2008) observed that the higher E_a value in kiwifruit and guava corresponded to OD and that this may be due to the fact that the effect of temperature is greater when the process is controlled by pseudo-diffusion mechanisms; in addition, it is less influential where the HDM acts, in the PVOD. However, according to Chakraborty and Samanta (2016), processes with lower E_a values could also indicate much lower energy consumption compared to processes with high E_a values.

Water activity

Water removal and solids uptake in chayote during the osmotic treatments coincided with the decrease in a_w according to the empirical DR-Hill Model (Equation (8)). The average values of R^2 , χ^2 and RMSE obtained by fitting the model parameters for the a_w data during the processing time for OD were 0.986-0.999, 1.59×10^{-5} - 4.98×10^{-5} , and 2.65×10^{-4} - 13.4×10^{-4} , respectively. The corresponding R^2 , χ^2 and RMSE values for PVOD were 0.982-0.999, 1.39×10^{-5} - 9.09×10^{-5} , and 3.18×10^{-4} - 12.7×10^{-4} , respectively (Table 4).

These high R^2 values and low χ^2 and RMSE ones (Table 4) suggested the suitability of the DR-Hill equation for estimating the a_w of chayote slices during osmotic dehydration at given solution concentrations and temperatures during immersion time under OD and PVOD conditions.

The initial a_w value of the fresh-cut chayote was 0.981 ± 0.004 , while the a_w of the osmotically dehydrated chayote slices ranged from 0.849 ± 0.001 to 0.901 ± 0.001 and 0.846 ± 0.001 to 0.898 ± 0.001 for the OD and PVOD treatments, respectively.

The vacuum pulse applied at the beginning of the osmotic process did not significantly modify a_w with respect to OD. However, the decrease in a_w accelerated with increasing concentration and temperature of the sucrose solution. This confirmed the interactive effects of these two variables on the mass transfer of chayote. Similar trends were observed by De Mello Jr *et al.* (2019) in the osmotic treatment of green fig in sucrose solution (40 to 60 °Bx) and by Dermesonlouoglou and Giannakourou (2018) in the osmotic treatment of apricot in non-conventional solutions (glycerol, erythritol, calcium chloride) at 25-45 °C. These authors

reported that the decrease in a_w in the samples occurred as a consequence of the increase in the concentration and temperature of the osmotic solution that promoted *WL* and *SG* in the cellular matrix of the product, which leads to a more stable product. Moraga *et al.* (2011) studied the stability of osmodehydrated grapefruit during refrigerated storage and reported that osmotic treatments extend shelf life and decrease the relative rate of food spoilage reactions.

Table 4. Estimated parameters of the DR-Hill Model for water activity (a_w) during osmotic dehydration of chayote slices under different osmotic treatment conditions

Process	°Bx	Temp. (°C)	a	θ	η	κ	R^2	$\chi^2 (\times 10^{-5})$	RMSE ($\times 10^{-4}$)
OD	40	25	0.9876 ± 0.0015	-0.0899 ± 0.0036	1.6715 ± 0.1755	60.219 ± 1.2193	0.9956	2.72	6.37
		35	0.9852 ± 0.0053	-0.1132 ± 0.0129	1.2460 ± 0.2075	78.632 ± 3.3170	0.9983	1.59	4.83
		45	0.9826 ± 0.0007	-0.1098 ± 0.0060	1.2641 ± 0.1057	60.098 ± 5.8492	0.9971	2.28	5.71
	50	25	0.9856 ± 0.0015	-0.0942 ± 0.0026	1.5707 ± 0.0664	62.536 ± 0.3644	0.9975	3.29	6.95
		35	0.9877 ± 0.0049	-0.1623 ± 0.01483	0.8887 ± 0.0909	120.41 ± 13.609	0.9977	2.14	5.62
		45	0.9943 ± 0.0069	-0.2719 ± 0.0169	0.6226 ± 0.0449	306.80 ± 37.819	0.9994	4.98	2.65
	60	25	0.9822 ± 0.0021	-0.0944 ± 0.0032	1.6891 ± 0.1087	58.962 ± 2.0695	0.9951	2.80	6.40
		35	0.9704 ± 0.0018	-0.1187 ± 0.0009	1.1849 ± 0.0174	70.054 ± 2.9766	0.9966	3.78	7.35
		45	1.0318 ± 0.0085	-0.2047 ± 0.0077	0.7055 ± 0.0164	17.206 ± 2.0334	0.9869	2.84	13.4
PVOD	40	25	1.0194 ± 0.0253	-0.1404 ± 0.0357	1.0190 ± 0.2857	45.630 ± 12.118	0.9990	2.04	6.24
		35	0.9721 ± 0.0015	-0.0960 ± 0.0030	1.5032 ± 0.0747	85.125 ± 4.2112	0.9988	7.22	3.68
		45	0.9626 ± 0.0008	-0.0856 ± 0.0029	1.6897 ± 0.0910	71.120 ± 0.9671	0.9975	1.66	5.57
	50	25	1.0054 ± 0.0174	-0.1310 ± 0.0284	1.0897 ± 0.3114	54.186 ± 9.4700	0.9989	2.14	6.35
		35	0.9707 ± 0.0023	-0.1232 ± 0.0051	1.2152 ± 0.0553	99.591 ± 0.8611	0.9989	5.37	3.18
		45	1.0478 ± 0.0074	-0.6580 ± 0.0497	0.3147 ± 0.0201	5510.9 ± 1966.4	0.9994	7.76	11.8
	60	25	0.9855 ± 0.0097	-0.1036 ± 0.0110	1.4624 ± 0.1853	57.670 ± 8.4003	0.9974	1.39	5.07
		35	1.0311 ± 0.0150	-0.2201 ± 0.0228	0.5952 ± 0.0624	46.307 ± 7.4465	0.9962	2.79	7.24
		45	2.5223 ± 0.1695	-1.6986 ± 0.1666	0.5307 ± 0.0387	0.1101 ± 0.0205	0.9823	9.09	12.7

Mean values ± standard deviation (n=3). OD, without modifying the atmospheric pressure. PVOD, osmotic dehydration with a 115-mbar vacuum pulse for 15 min

Total soluble solids

The migration of sugars from the osmotic solution to the extracellular spaces via plasmodesmata and the adhesion of solutes at the interface increased *TSS* in the chayote slices.

The empirical Rational Model (Equation (9)) was fitted to the experimental *TSS* content data obtained during osmotic dehydration of the slices (Table 5). The correlation coefficient R^2 , χ^2 and *RMSE* for OD were 0.990-0.997, 1.03×10^{-2} - 72.4×10^{-2} , and 0.03-0.41, whereas for PVOD they were 0.988-0.998, 0.77×10^{-2} - 6.01×10^{-2} , and 0.05-0.18. This indicates that the Rational Model equation is suitable and accurate for predicting the *TSS* content of chayote during osmodehydration treatments under the conditions studied.

Table 5. Estimated Rational Model parameters for total soluble solids content (*TSS*) during osmotic dehydration of chayote slices under different osmotic treatment conditions

Process	°Bx	Temperature (°C)	a	b	c	d	R ²	χ ² (×10 ⁻²)	RMSE
OD	40	25	2.4035 ± 0.0808	0.2422 ± 0.0172	0.0225 ± 0.0020	-6.9 e-06 ± 1.6 e-06	0.9973	1.03	0.03
		35	3.9809 ± 0.2859	0.3645 ± 0.0328	0.0263 ± 0.0022	-6.6 e-06 ± 2.4 e-05	0.9964	72.4	0.41
		45	5.2024 ± 0.3084	0.3589 ± 0.0309	0.0185 ± 0.0021	-1.4 e-05 ± 3.0 e-06	0.9935	9.93	0.16
	50	25	3.9015 ± 0.6959	0.6538 ± 0.1572	0.0578 ± 0.0146	-6.2 e-05 ± 1.4 e-05	0.9904	5.21	0.10
		35	3.7778 ± 0.5820	0.7069 ± 0.0764	0.0517 ± 0.0051	-7.4 e-05 ± 4.7 e-06	0.9979	2.34	0.06
		45	6.3483 ± 0.4529	0.3660 ± 0.0511	0.0165 ± 0.0022	-1.6 e-05 ± 5.7 e-07	0.9975	1.52	0.05
	60	25	5.3709 ± 0.6754	0.6273 ± 0.1784	0.0420 ± 0.0147	-3.9 e-05 ± 1.7 e-05	0.9931	5.34	0.10
		35	5.1711 ± 0.1712	0.4817 ± 0.0130	0.0244 ± 0.0013	-3.1 e-05 ± 2.0 e-06	0.9970	6.96	0.14
		45	5.8717 ± 0.2477	0.5639 ± 0.0445	0.0191 ± 0.0016	-1.0 e-05 ± 5.7 e-07	0.9974	5.13	0.11
PVOD	40	25	-4.3466 ± 2.0390	1.4558 ± 0.1671	0.1421 ± 0.0139	-0.0001 ± 1.0 e-05	0.9896	1.66	0.05
		35	6.5850 ± 0.1248	0.1578 ± 0.0118	0.0086 ± 0.0010	-5.6 e-06 ± 5.7 e-07	0.9886	6.01	0.11
		45	7.5970 ± 0.4441	0.1465 ± 0.0146	0.0039 ± 0.0003	5.5 e-07 ± 2.1 e-07	0.9986	2.28	0.09
	50	25	3.8152 ± 0.3330	0.4023 ± 0.0357	0.0262 ± 0.0026	-1.4 e-05 ± 2.1 e-06	0.9945	1.38	0.05
		35	4.0637 ± 0.9815	0.7933 ± 0.1260	0.0535 ± 0.0090	-7.8 e-05 ± 1.3 e-05	0.9938	4.89	0.12
		45	6.9191 ± 0.4168	0.3301 ± 0.0228	0.0128 ± 0.0009	-1.1 e-05 ± 1.5 e-06	0.9955	3.68	0.13
	60	25	4.2745 ± 0.6074	0.6323 ± 0.0856	0.0383 ± 0.0066	-3.7 e-05 ± 9.7 e-06	0.9923	0.77	0.05
		35	8.4549 ± 0.2052	0.1398 ± 0.0164	0.0023 ± 0.0009	1.6 e-07 ± 3.1 e-07	0.9983	7.49	0.18
		45	3.3688 ± 0.1979	0.8022 ± 0.0312	0.0272 ± 0.0014	1.6 e-05 ± 2.0 e-06	0.9984	2.46	0.09

Mean values ± standard deviation (n=3). OD, without modifying the atmospheric pressure. PVOD, osmotic dehydration with a 115-mbar vacuum pulse for 15 min

The *TSS* value of the fresh-cut chayote was 5.07 ± 0.43 °Bx, while at the end of the osmotic treatments the *TSS* values for OD were in the range of 10.7 ± 0.10 - 29.96 ± 0.41 °Bx and for PVOD they were in the range of 12.93 ± 0.40 - 31.90 ± 0.17 °Bx. The *TSS* of chayote increased substantially with osmotic treatment time. Chaguri *et al.* (2016), who osmodehydrated green banana in sorbitol and glycerol solutions (40-60 °Bx) at between 25 and 45 °C, and Schincariol Paes *et al.* (2019), who osmotically dehydrated cambuci (*Campomanesia phaea* (O. Berg) Landrum) in ternary solutions (40-60 °Bx) at 25 °C, reported that the *TSS* of the samples increased with the osmotic treatment time derived from solute diffusion and adhesion on the food surface.

Increasing the temperature and concentration of the osmotic solution improved *TSS* uptake in chayote with OD and PVOD. These results agree with those of Barragán-Iglesias *et al.* (2018), who studied the osmotic pretreatment of papaya in calcium hydroxide and sucrose solutions and indicated that increasing the temperature and concentration of the osmotic solution promotes mass transfer and consequently *TSS* gain in plant tissue.

Color

The decrease in a_w and incorporation of soluble solids in chayote slices during osmotic treatments also modified the surface properties of the plant matrix to reflect visible light. The chayote mesocarp contains chlorophylls (Cadena-Iníguez *et al.*, 2011) and carotenoids (Loizzo *et al.*, 2016) that confer the creamy yellow to pale green color of the fresh flesh (Figure 3a). Fresh fruit values were lightness 74.04 ± 0.43 , chroma 10.50 ± 0.45 , and hue 82.29 ± 1.21 .

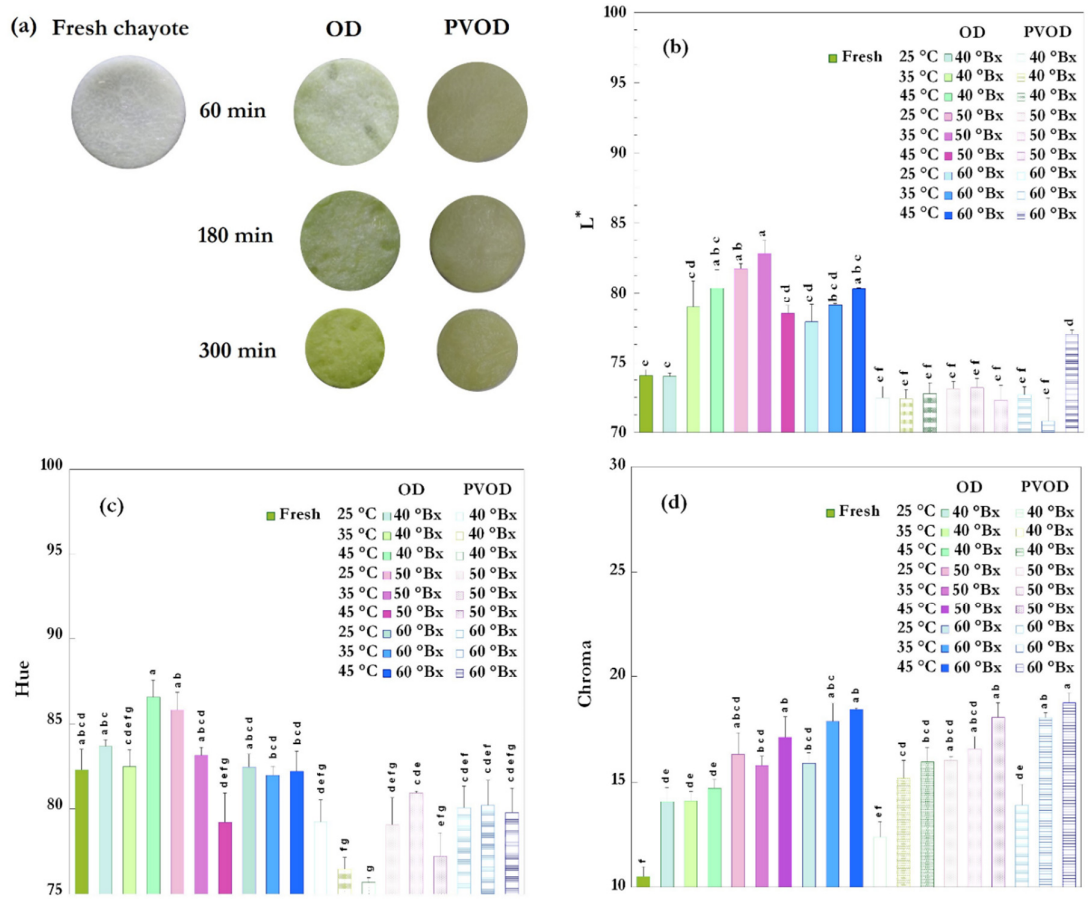


Figure 3. Color properties of fresh and osmodehydrated chayote for 300 min. (a) color changes in chayote slices during osmotic dehydration with sucrose solution at 50 °Bx and 35 °C, (b) lightness (L^*); (c) hue angle (Hue); (d) chroma. OD: without modifying the atmospheric pressure, PVOD: osmotic dehydration with a 115-mbar vacuum pulse for 15 min

The osmodehydrated product preserved the lightness (L^*) in the PVOD samples compared to the fresh samples (Figures 3a and b). The change is associated with transparency due to the total or partial replacement of the gas present in the pores by the osmotic solution through a hydrodynamic mechanism. The effect of vacuum pulse application was also observed in other osmodehydrated fruit and vegetable tissues, such as pear (Moreno *et al.*, 2011), strawberry (Moreno *et al.*, 2012), eggplant (De Jesus Junqueira *et al.*, 2017), beetroot and carrot (De Jesus Junqueira *et al.*, 2018).

However, an increase in L^* of up to 11.85 % was observed in the OD-treated samples (Figure 3a and b). According to Vieira *et al.* (2012), this is attributable to sugar impregnation on the fruit surface.

Also, minor differences in hue values were observed between osmotically treated and fresh samples (Figure 3c). Overall, color expressed as hue ranged from 79.22 ± 1.70 to 86.57 ± 0.99 and 75.69 ± 0.27 to 80.94 ± 0.11 for OD and PVOD, respectively. These values correspond to cream yellow (Hue ≤ 90).

Green and yellow color changes in chayote can be evaluated by chroma. A significant increase in chroma values was observed in the osmodehydrated samples compared to the fresh ones (Figure 3d). Rodrigues *et al.* (2003) also observed similar behavior for osmotically treated papaya.

The higher chroma value represents purer and more intense color as observed in Figure 3a, this change plays a key role in the overall quality of osmotically dehydrated chayote slices. The increase in greenness and yellowness is clear and appears to be a result of *WL*, sucrose absorption, and concentration and/or retention of pigments (chlorophylls and carotenoids) in the plant matrix.

Volume changes during osmotic dehydration

The parenchymal cells of the fresh chayote mesocarp are connected to each other by the median lamella. These cells are turgid, with a high level of mechanical energy stored in the wall/membrane system, and with heterogeneous intercellular spaces of up to $150 \mu\text{m}$, as observed in Figure 4c.

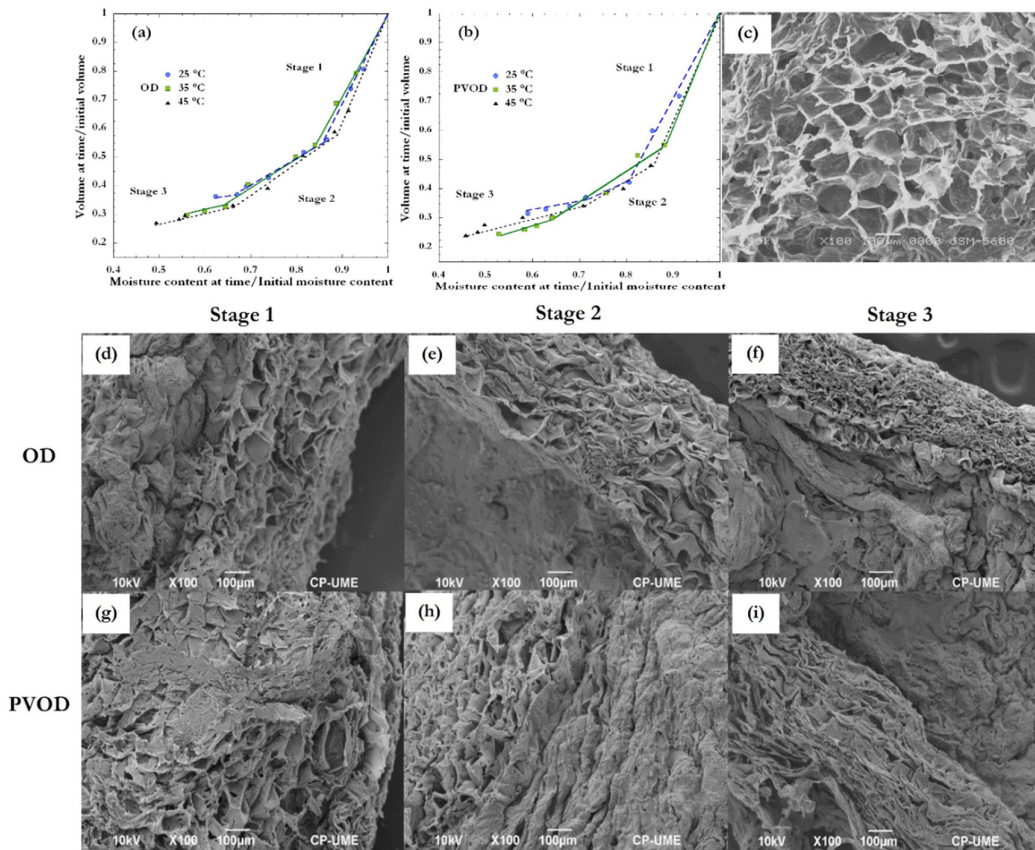


Figure 4. Changes in volume and moisture content and SEM micrograph of chayote slices during osmotic dehydration; (a) and (b) changes in volume and moisture content for OD and PVOD, respectively; (c) SEM micrograph chayote without osmotic treatment; SEM micrograph of the surface and inner part of osmodehydrated chayote by OD at $35 \text{ }^\circ\text{C}$ in $50 \text{ }^\circ\text{Bx}$ sucrose solution, (d) for 60 min, (e) for 180 min, and (f) for 300 min; and SEM micrograph of the surface and inner part of osmodehydrated chayote by PVOD at $35 \text{ }^\circ\text{C}$ in $50 \text{ }^\circ\text{Bx}$ sucrose solution; (g) for 60 min, (h) for 180 min, and (i) for 300 min. OD: without modifying the atmospheric pressure, PVOD: osmotic dehydration with a 115 mbar vacuum pulse for 15 min

When a plant tissue such as chayote is dehydrated in an osmotic solution, mass transfer phenomena such as *WL* and *SG* modify the physicochemical properties and structure of the tissue. These changes include water mobility and distribution, volume contraction, color modification and mechanical properties, among others. In this regard, Azuara *et al.* (2002), Flores-Andrade *et al.* (2009) and Seguí *et al.* (2012) note that during OD the cells undergo three phases of dehydration as a function of the loss of cell volume. Thus, the change in the chayote mesocarp's parenchyma cells during OD can be represented from the beginning of the treatment until complete plasmolysis by plotting the volumetric shrinkage of the chayote slices *vs* the moisture content (Figure 4a and b).

In stage 1, the difference in chemical potential between the cells and the osmotic solution results in a flow of cellular water out of the protoplast. The protoplast and cell wall that are linked by binding sites shrink and deform together until the stretching forces of the membrane reach their limit and it detaches from the cell wall at the ends; however, they maintain contact in other regions (incipient plasmolysis). These changes cause a reduction in the volume of the chayote slices, while the decrease in moisture content is due to *WL* and the formation of compact layers of sucrose on the surface of the parenchymal cells of the chayote mesocarp (Figure 4d and g).

Stage 2 is characterized by contraction of the protoplasm and vacuole due to *WL* across the plasma membrane, which increases the driving forces of stretching between the membrane and cell wall, until the membrane is completely detached and elastically contracted (plasmolysis). As a consequence, there is an increase in porosity as new intracellular spaces are created that will be occupied by the osmotic solution, directly compensating for the loss of volume and decreasing the water content (Figure 4e and h). Because of this, the volumetric shrinkage in stage 2 is less than that in stage 1.

In stage 3 (Figure 4f and i), the cell structure begins to collapse, but the cell wall continues to be attached to the protoplast by elastic structures called hechtian strands. Both cellular components continue to act as physical barriers to mass transfer. At this stage, there is a slight volumetric contraction in the chayote slices, but solute uptake causes a further decrease in moisture content.

Regarding the use of a vacuum pulse at the beginning of the osmotic process (PVOD), the displacement of the stages at lower water contents are shown in the Figure 4b. This can be explained by the entry of a hydrodynamic flow of osmotic solution into the intracellular space due to an HDM.

Conclusions

For the process conditions studied, the osmotic solution concentration, temperature, and processing time had a greater influence than vacuum pulse application (PVOD) on the mass transfer kinetics of osmotically dehydrated chayote slices in sucrose solutions. The influence of temperature on effective diffusivity presented Arrhenius-type dependence, and E_a showed similar energy requirements for OD and PVOD, and low energy requirements for high concentrations of osmotic solution. Osmodehydrated chayote slices presented lower a_w (up to 0.846), higher *TSS* content (up to 31.9 °Bx), and purer and more intense color. The volumetric shrinkage of the samples allowed representing three phases of dehydration that the parenchymal cells of the mesocarp undergo during OD.

The high R^2 values and low χ^2 and *RMSE* ones represented the suitability of the empirical DR-Hill and Rational models to predict the a_w and *TSS* content of osmodehydrated chayote slices under the conditions studied. These results could be useful in the design and optimization of an OD method for chayote based on the sensory and physicochemical characteristics desired in the final product.

These findings suggest that OD allows obtaining minimally processed chayote slices that could be included in quick-cook products, such as salads or soup mixes.

Nomenclature and Abbreviations

a	Parameters associated with the empirical Rational Model in Eqs. (9)
a_w	Water activity
b	Parameters associated with the empirical Rational Model in Eqs. (9)
c	Parameters associated with the empirical Rational Model in Eqs. (9)
d	Parameters associated with the empirical Rational Model in Eqs. (9)
D_0	Reference diffusion coefficient
D_s	Apparent diffusion coefficients of solids ($m^2 s^{-1}$)
D_w	Apparent diffusion coefficients of water ($m^2 s^{-1}$)
E_a	Activation energy ($kJ mol^{-1}$)
E_i	Predicted values
HDM	Hydrodynamic mechanism
l	Half-thickness of slice (m)
M_t	Mass of the food at time t (g)
M_0	Initial mass of the food at time 0 (g)
N	Total number of data values used to fit the equation
OD	Osmotic dehydration
\bar{O}	Average of all experimental values
O_i	Experimental values
PVOD	Pulsed vacuum osmotic dehydration
R	Universal gas constant ($8.314 kJ (mol K)^{-1}$)
RMSE	Root mean square error
R^2	Coefficients of determination
SEM	Scanning electron microscopy
SG	Solids gain (g solids gain g^{-1} initial weight)
SG_∞	Fraction of solid gain by the food at equilibrium (g solids gain g^{-1} initial weight)
s_1	Constant related to the water-loss rate (min^{-1})
s_2	Constant related to the rate of soluble solid entry into the food (min^{-1})
T	Temperature (K)
TSS	Total soluble solids
t	Time (min)
WL	Water loss (g water g^{-1} initial weight)
WL_∞	Fraction of water loss by the food at equilibrium (g water g^{-1} initial weight)
χ_{cal}^2	Chi-square
X_0	Initial moisture content (wet basis)
X_t	Moisture content in the food (wet basis) at time t
α	Parameters associated with the empirical DR-Hill Model in Eqs. (8)
η	Parameters associated with the empirical DR-Hill Model in Eqs. (8)
θ	Parameters associated with the empirical DR-Hill Model in Eqs. (8)
k	Parameters associated with the empirical DR-Hill Model in Eqs. (8)

Authors' Contributions

Conceptualization: ACO; Methodology: ACO and KHV; Investigation: KHV and ACO; Validation: ACO; Formal analysis: KHV and EFA; Writing – Original Draft: KHV; Writing – Review & Editing: ACO, MLAG, EFA, MBPG and DPUS; Supervision: ACO; Funding Acquisition: ACO. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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