



# Structural properties and solute transfer relationships during sucrose and stevia osmotic dehydration of apple

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## Abstract

The objective of this research was determined the structural changes in plant tissue during osmotic dehydration (OD) of apple in stevia and sucrose aqueous solutions. Macro and microstructural properties at different thicknesses of the sample were determined. For the study of structural properties, samples were cut in five slices at different thicknesses (0.5, 2, 4, 7, 10 mm in z direction) from the surface to the sample center. Anhydrous real density, volume and microscopy images in sample slices were determined and its relationship with the transfer of water and solutes inside the tissue were analyzed. Anhydrous real density in food considering the solids density in the sample was determined. Volume change as a function of moisture migration in the sample was evaluated. Apple samples were immersed into sucrose (30 and 50° Brix) and stevia (3 and 6%) osmotic solutions at 30 °C and 50 °C. The results showed an increase in the anhydrous real density in the area of greater loss of moisture and greater accumulation of solutes within the food. The volume increased in the thicknesses of the center of the sample where the moisture concentration was highest. The greatest alterations of the plant cell structure in the surface of the sample were observed.

**Keywords** Structural changes · Osmotic dehydration · Solute transfer · Properties

## List of symbols

$m$	Total mass of the sample (g)
$m_{ds}$	Mass of the dry solids and water mass contained in the sample (g)
$P_1$	Pressure before volume of gas (kg/cm <sup>2</sup> )
$P_2$	Pressure after volume of gas (kg/cm <sup>2</sup> )
$V_{ds}, V_w$	Volume of the dry solids and water in the sample (m <sup>3</sup> )
$V_p$	Volume of the sample (m <sup>3</sup> )
$V_c$	Volume of the container cell of the sample (m <sup>3</sup> )
$V_A$	Volume of gas added (m <sup>3</sup> )
$X_w$	Mass fraction of water ( $\frac{g_{water}}{g_{water} + g_{dry\ solid}}$ )
$X_{wb}$	Moisture content wet basis ( $\frac{g_{water}}{g_{dry\ solid} + g_{water}}$ )
$X_{ds}$	Mass fraction of the dry solid ( $\frac{g_{dry\ solid}}{g_{water} + g_{dry\ solid}}$ )

## Greek letters

$\rho$	Density (kg/m <sup>3</sup> )
$\rho_w$	Water density (kg/m <sup>3</sup> )
$\rho_{ds}$	Anhydrous real density (kg/m <sup>3</sup> )

## Introduction

Osmotic dehydration (OD) is essentially a mass transfer process that involves the migration of water from the food into the external osmotic solution and the transport of the solutes in plant tissue simultaneously. Studies show that OD induces major microstructural changes in food materials [1–5]. According to Islam and Flink [6] and Lenart and Flink [7], the transport properties of the food materials depend on tissue properties, especially the intercellular spaces. Hence knowledge of the microstructure is essential for understanding the water and solute transfer in a food material.

Many authors have been determined the properties and structural changes in food osmodehydrated from a global analysis of the sample, at the same time the effect of osmotic dehydration on cellular structure and the mass transfer only as a function of the dehydration time or of the process operating conditions have been determined [1–3, 8–10]. Salvatori and Alzamora [11] through microscopic observations stated

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that at the beginning of the osmotic process, cell walls of apple tissues deformed remaining bounded to plasmalemma during the cell shrinkage caused by water loss, while at the end of the OD a recovery of cell structure was observed. The recovery has been attributed to the bulk flux of osmotic solution into the fruit tissue due to the relaxation of the mechanical energy accumulated in the deformed shrunken cellular structure. Nieto and others [1] pointed that the loss of moisture and the increase of the real density had a significant effect on the collapse of plant tissue. Samples treated for OD showed a general collapse of tissues and a reduction in intercellular spaces. Tortoe and Orchard [12] stated that the analysis of fresh and osmotically dehydrated tissues, showed different levels of cellular alteration in samples treated by osmotic dehydration. They observed microstructural features such as shape and size changes in cell and intercellular spaces and cell wall deformation-relaxation from 3 h after starting osmotic treatment. Finished the process the dehydrated tissues illustrate larger intercellular spaces, due to solubilisation of the pectin in the middle lamella that results in the decline of the intercellular adhesion which lead to easy separation of cells.

Water and solute migration and changes in the cell structure are the two major factors for understanding and control of the mechanisms occurring in osmotic dehydration of food. According to Gekas [13], the structural alterations are related of water outlet from to cells and the solute penetration inside of the plant tissue. Hence, the study of the properties under a global approach, it only gives us information about the structural changes present in the samples in general during the osmotic dehydration time; nevertheless, does not provide a satisfactory explanation regarding the effect that the outlet of water from the food and the accumulation of the solutes of the osmotic solution on the surface of the plant tissue (impregnation) have on the structural changes of the dehydrated tissue. The accumulation of solutes on the surface of the plant tissue that has been verified by several authors [14–18]. But, the effect of the unequal distribution of the solutes in the osmodehydrated plant tissue on the structural changes observed in the different thickness of the food have not been documented. Accordingly, the cellular microstructure of apple may behave differently in response to osmotic dehydration depending on the depth of cut analyzed. For this reason, the development of methods that allow a the specific analysis of structural properties at different thickness of the sample, to increase the scientific knowledge about the relationship between structural features and solutes transfer during OD process, allowing a better comprehension of mass transfer mechanisms.

On the other hand, changes in plant cell structure have been mostly associated with the water loss suffered by the tissue during the OD process [19–21]. It is true that the water loss in the food is responsible for many of the

alterations of the plant structure such as: loss of cell turgor pressure, splitting and degradation of the middle lamella, alterations in cell wall resistance, deformation and/or cell wall failure, lysis of membranes (plasmalemma and tonoplast), cellular collapse, plasmolysis and tissue shrinkage [3, 4, 9, 22]. However, solute transport in plant tissue also induces significant changes in cell microstructure. The effect of solute migration on the macro and microstructural properties of osmodehydrated foods has been poorly documented. Particularly the high adsorption of solutes on the surface of the food when osmotic solutions of sucrose or natural sweeteners such as stevia are used cause significant changes in the real density and volume in this area of the food, resulting in significant alterations of the structure plant cell that can be seen through microscopy images. Hence, the aim of this research was determined the structural changes in plant tissue during osmotic dehydration (OD) of apple in stevia and sucrose aqueous solutions at different thicknesses of the sample and analyzed its relationship with the transfer of solutes in the food.

## Materials and methods

### Sample preparation

Fresh apples (*Granny Smith*) cultivar (85% w/w moisture content, wet basis and 13.2° Brix of soluble solids content) were purchased in a local market. Apples were peeled and cut parallel to the main axis to obtain cylinders 3 × 3 cm (diameter-length). The same apple lot was used in each experiment in order to minimize biological variability and changes in cellular structure. Longitudinal area of the samples was covered with a metallic adhesive tape. Water and solutes transfer inside the sample unidirectional were considered.

### Osmotic dehydration process

The OD process was evaluated used sucrose (30 and 50° Brix) and stevia (3 and 6% w/w) osmotic solutions at 30 and 50 °C. A factorial 2<sup>2</sup> experimental design was applied with three replicates. ANOVA was used to determine statistically significant differences ( $\alpha = 0.01$ ).

Aqueous solutions of commercial sucrose and stevia plant leaf extracts were used as osmotic agents. The osmotic treatment was applied for a time of 10 h (600 min). The ratio weight osmotic solution:fruit was of 20:1 w/w with a constant agitation of 130 cycles/minutes using a cylindrical magnetic stirrer (6 cm length × 1 cm diameter).

## Macro and microstructural properties in plant tissue

Apple cylinders were cut in slices to thicknesses of 0.5, 2, 4, 7 and 10 mm from the surface to the center of the sample. Anhydrous real density, volume and microscopy images in each slice of the sample were determined and its relationship with moisture loss and sucrose concentration in plant tissue were analyzed.

The volume of the samples was measured by gas displacement using a stereopycnometer (SPY—5DC Quantachrome, USA) and nitrogen as working gas at a pressure of 1.1951 kg/cm<sup>2</sup>. For the calculation Eq. 1 was used.

$$V_p = V_c + \frac{V_A}{1 - \frac{p_1}{p_2}} \quad (1)$$

The anhydrous real density of the apple sample was determined considering the concept of real density for mixtures in a solid material taking  $n=2$  (Eq. 2).

$$\frac{1}{\rho} = \sum_{i=1}^n \frac{X_i}{\rho_i} \quad (2)$$

Under this approach, anhydrous real density is considered as the ratio  $\rho_{ds} = m_{ds}/V_{ds}$  with  $V_{ds} = V_p - V_w$  and  $\rho_w = m_w/V_w$ . Dry solids mass of the samples is related with moisture content of the wet solid (Eq. 3).

$$\rho_{ds} = \frac{m_{ds}}{V_{ds}} = \frac{m(1 - X_{wb})}{\frac{m(\rho_w - \rho \cdot X_{wb})}{\rho_w \cdot \rho}} \quad (3)$$

If we consider that  $X_w + X_{ds} = 1$  with  $X_w = X_{db}$  then  $X_{ds} = 1 - X_{wb}$  Eqs. 4 and 5 are obtained.

$$\frac{1}{\rho} = \frac{X_{ds}}{\rho_{ds}} + \frac{X_w}{\rho_w} \quad (4)$$

$$\rho_{ds} = \frac{X_{ds}}{\left(\frac{1}{\rho} - \frac{X_w}{\rho_w}\right)} \quad (5)$$

The plant cell microstructure through microscopy images of the sample of fresh and dehydrated in sucrose and stevia osmotic solutions were observed using an environmental scanning electron microscope (FEI Quanta 3D FEG). Before the test, the samples were frozen cryogenically with liquid nitrogen and cut using a microtome. Microscopy images at different depths of the sample (1, 2, 3, 5, 7, 10 mm) in cross section and an amplitude of 100× were obtained.

## Mass transfer in sample

Moisture content and solute concentration in the sample were determined in order to analyze its relationship with the macro and microstructural properties. Moisture content were determined gravimetrically, with the dried mass obtained in a vacuum dryer at 70 °C until constant weight [23].

Stevia concentration was evaluated through the analytes with greater sweetening power in stevia: stevioside and rebaudioside A. Standards (<95%) were purchased from Merck (Germany). For the quantification a HPLC (Perkin Elmer Flexar) with a UV-Vis Flexer detector at a wavelength of 210 nm and a C18 column (Thermo Scientific 250 mm×4.6 mm) were used. The separation in isocratic form was made using as mobile phase acetonitrile (ACN):water (65:35 v/v) at a flow rate of 1 mL/min.

Sucrose concentration was analyzed using a chromatograph (Dionex Ultimate 3000, Thermo Scientific) with an Amino NH<sub>2</sub> column (ApHera Superco 150 mm×2.0 mm) and a refraction index detector (Refracto Max 521). As a mobile phase ACN:water (75:25 v/v) was used at a flow rate of 0.3 mL/min. The quantification of stevioside, rebaudioside A and sucrose concentration was based on the measurement of the sample peaks area interpolating in the calibration curve.

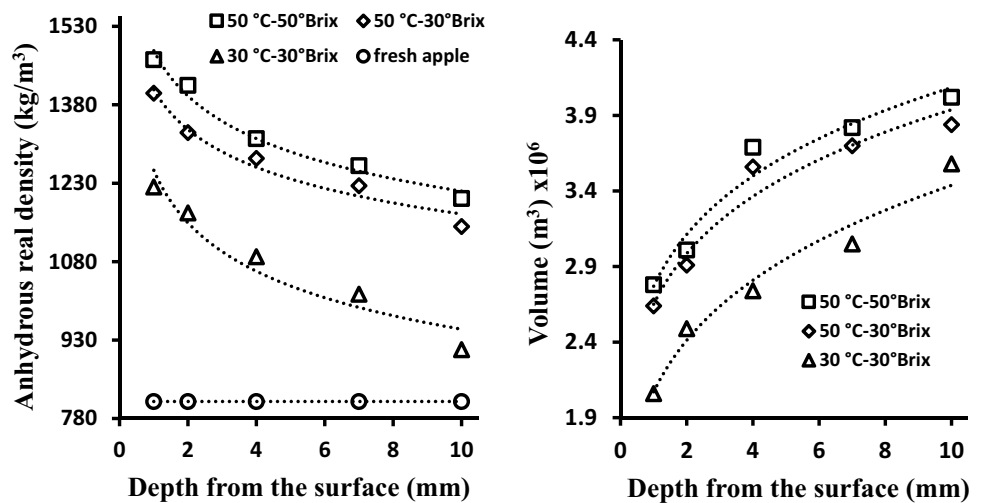
## Results and discussions

### Macro and microstructural properties of samples during osmotic treatment

Water and solute transfer inside plant tissue during the OD process, caused changes in the structural properties of the food. Volume and real density as a function of the water content have been studied. The increase of real density when moisture content decreases in the food has been verified by other authors [20, 24, 25].

In this paper, the change in volume in different thickness of the sample has been related with the moisture content. Anhydrous real density and microstructural changes in apple slices were related with solute concentration in plant tissue. Volume and anhydrous real density at different depths of dehydrated sample were showed in Fig. 1. The volume is less in the thicknesses of the surface (0.5, 2, 4 mm) and increases considerably in the product center (7–10 mm). The volume is closely related to water amount contained in plant cell structure. The volume profiles for the different thicknesses evaluated (Fig. 1) show that the volume is greater in the center of the sample where the moisture content is higher (Fig. 5). The relationship between volume and water content during the OD of plant tissue has been verified by other authors [1, 19, 26]. Nieto

**Fig. 1** Anhydrous real density and volume of samples treated in sucrose osmotic solution



et al. [1] found a linear relation between water loss and the decrease of volume in apple samples whereas Mavroudis et al. [19] observed a linear decrease on volume of apple with the decrease of water in the fruit. Mayor et al. [26] observed a directly proportional relationship between decrease of volume and water loss during OD of pumpkin in NaCl-sucrose osmotic solution.

Unlike the result found by others authors where only the volume variation was determined as a function of the osmotic dehydration time of the apple, considering the volume of the global sample in each analyzed time interval, in this research, the volume of the sample osmodehydrated at 5 thickness (0.5, 2, 4, 7, 10 mm) from the surface to apple samples center was studied. This analysis allowed to determine more accurately the variation of volume in different thicknesses of the sample and relate the values obtained with the migration of moisture within the plant tissue during the osmotic process. However, a similarity found with these works is that during the osmotic treatment the authors reported a decrease in the sample volume at the end of the osmotic treatment where the moisture content decreased significantly. A similar trend in our volume curves as a function of the thickness of the sample was observed, since the volume values were lower in the thickness of the sample surface where the humidity concentration also decreased.

Volume depreciation on sample surface at 0.5, 2, 4 mm of thicknesses occurs due to significant moisture loss suffered in this area of the plant tissue and the increase in the solute concentration on the surface. Water flow due to internal pressure in extra and intracellular spaces and saturation of tissue superficial area by solutes accumulation, cause deformation-relaxation phenomena in the matrix of cell wall and in membrane outer layer, resulting in a decrease in the volume of sample surface. Additionally, water flow on the surface causes the collapse and rupture of cell structure, which will be analyzed later by microscopy images.

Anhydrous real density value of fresh apple is consistent with that reported in the literature by Fernandez et al. [25] of  $802 \pm 10 \text{ kg/m}^3$  for the *Granny Smith* cultivar. Anhydrous real density within the dehydrated sample that represents the density of solids in the food was calculated using the equations for mixtures of compounds in a solid material (Eqs. 2–5). As can be seen in Fig. 1, the anhydrous real density is higher at the samples surface thickness and decreases in the center thicknesses. Anhydrous real density increases in the area inside plant tissue where the solute concentration is higher. The increase of anhydrous real density on samples surface at 0.5 and 2 mm of depth (Fig. 1) coincides with the area of greatest concentration of sucrose (accumulation) in the samples (Fig. 6) and is where the greatest structural changes are appreciated according to the microscopy images shown below.

Nieto et al. [1] studied the behavior of the real density as a function of the dehydration time for sucrose treated apples. These authors found that the real density did not vary significantly with time but only increased in the last drying stages. The result observed in the real density profiles gave evidence of the non-ideal behavior of apple tissues during osmotic treatment in sucrose solutions. The trend in real density profiles found by these authors, couldn't be compared with our results, because they studied the real density of the sample as a function of process time and in this investigation the real density as a function of the thickness of the sample was determined. Nevertheless, these authors observed that real density increased at the end of the osmotic treatment where the moisture content in the samples is low, which coincides with the results reported in this work since, as shown in Fig. 1, the real density of the samples is higher in the thicknesses of the surface of the food (0.5, 2 mm) where the moisture content in the tissue is lower (Fig. 5).

Multiple evidences reveal the study of the plant tissue structure osmodehydrated through microscopy images [1,

12, 27, 28]. Dehydrated apple structure in sucrose and stevia osmotic solution were analyzed by scanning electron microscopy (SEM) (Figs. 2, 3 and 4). The micrographs permitted the observation of the microstructural features at different depths of plant tissue. Differences between fresh and osmotically dehydrated tissues were observed.

The tissue of a fresh apple is composed of numerous cells and intercellular spaces. The microphotographs obtained from the fresh apple tissue are shown in Fig. 2. The figure shows anisotropic tissues with cells and intercellular spaces distributed in heterogeneous form and arranged in a grid

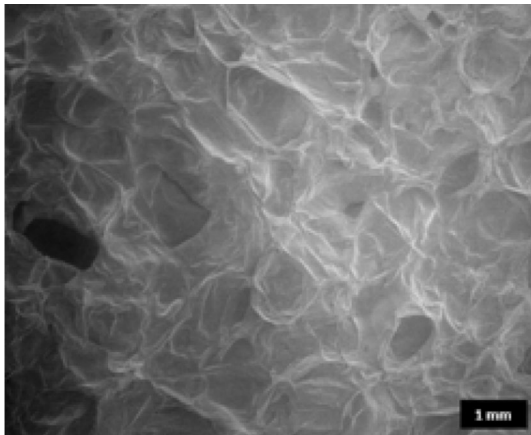


Fig. 2 Microscopy of fresh apple tissue

pattern. Small spaces were observed in the contact zones between three neighboring cells. Irregular, rounded and in some cases elongated forms are seen in the cells.

Figures 3 and 4 show scanning electron microscope micrographs of the samples treated in sucrose and stevia osmotic solutions. The removal of water and incorporation of solutes affected the cellular structure of the sample causing notable changes in the microstructure.

As shown in Fig. 3, the greatest damage to the cell structure of the samples dehydrated in stevia osmotic solution was observed in the thicknesses of 1 and 2 mm close to the surface of the sample. Large intercellular spaces were present in these thicknesses.

On the samples treated in stevia solution at a depth between 0.5–2 mm the greatest moisture loss and an increase in solute concentration was found (Fig. 8). Moisture loss from the cells will cause the cells to shrink and induce enlargement of the intercellular spaces. Subsequently, the plasma membrane detaches from the cell wall resulting in plasmolysis of the plant cell. During plasmolysis, a modification of the permeability properties of the plasma membrane has been observed. Additionally, the removal of water causes folds, and cracks of the cell wall with plasmolysed appearance as a result of osmotic stress [29]. In tissue center at depths of 5–10 mm the cells remained intact and it observed very similar to the microscopic features of fresh apple.

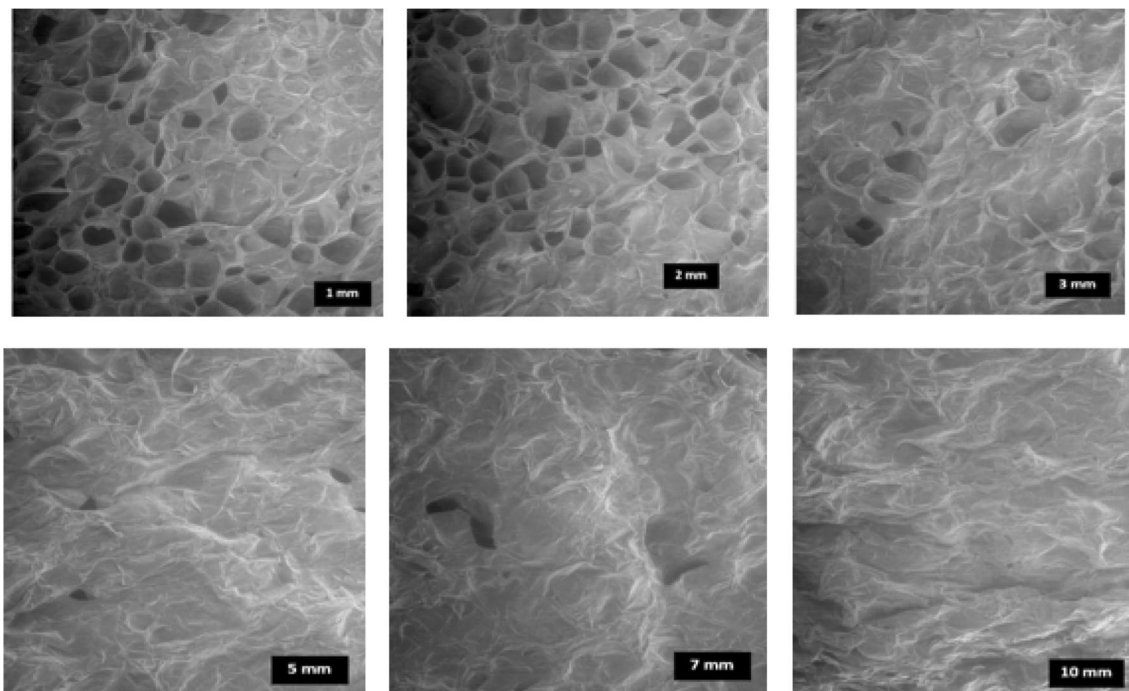


Fig. 3 Microscopy of the apple treated in stevia osmotic solution (50 °C, 3%) at thickness of 1, 2, 3, 5, 7, 10 mm (100 ×)

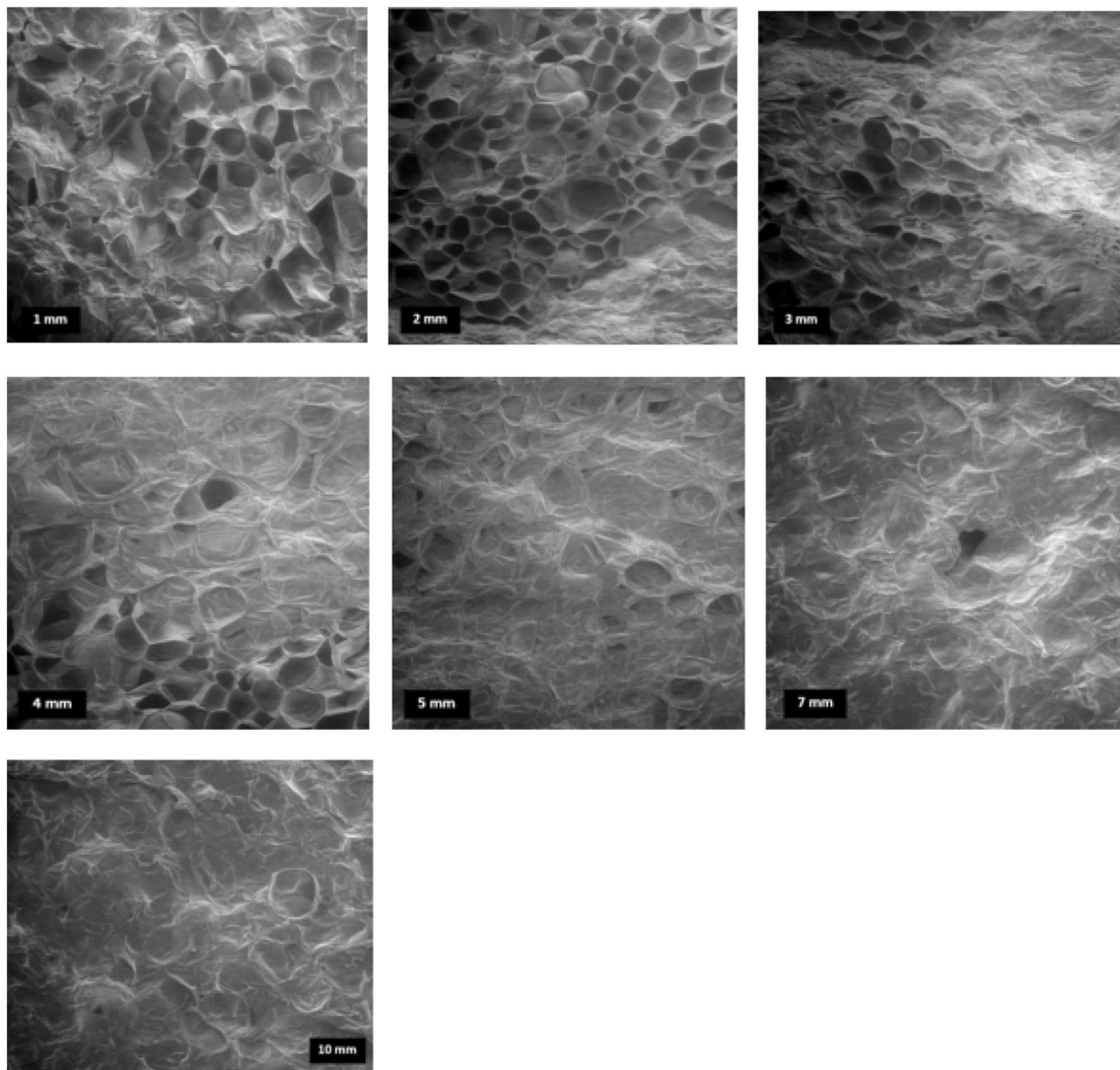
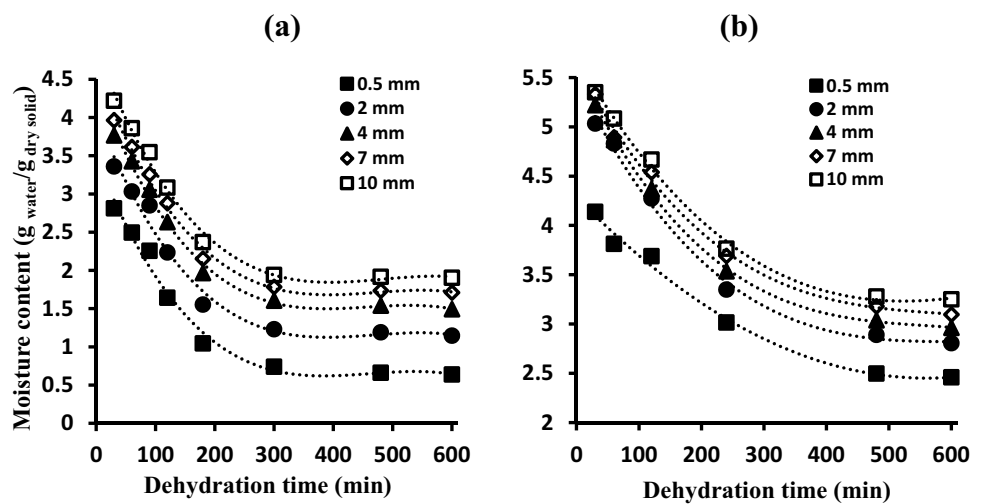
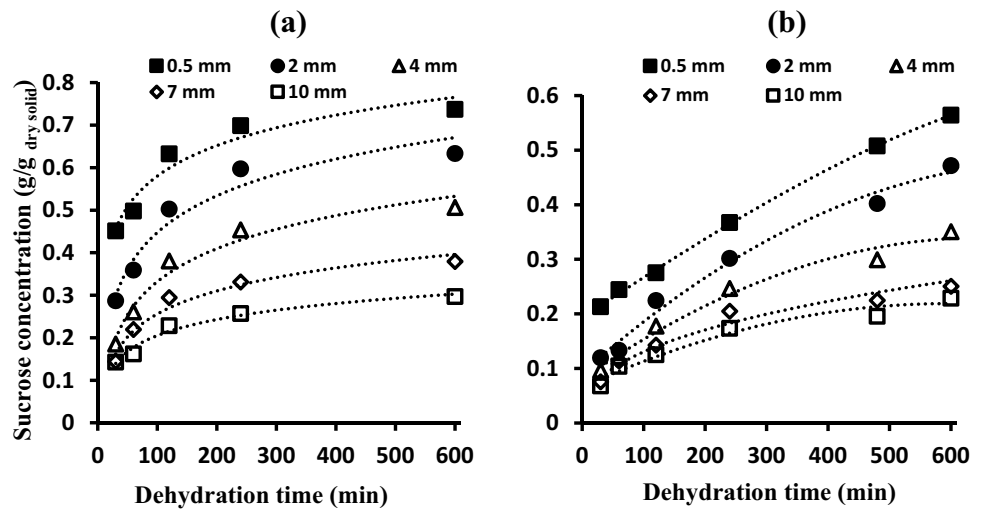


Fig. 4 Microscopy of the apple treated in sucrose osmotic solution (50 °C-30° Brix) at thickness of 1, 2, 3, 4, 5, 7, 10 mm (100 ×)

Fig. 5 Kinetics of moisture content in samples a 50 °C, 50°Brix and b 50 °C, 30°Brix



**Fig. 6** Kinetics of sucrose concentration in samples **a** 50 °C, 50°Brix and **b** 50 °C, 30°Brix



The influence of the distribution of solutes within the food on the plant macro and microstructure has been poorly documented in the literature, in particular, from the perspective of the accumulation of solutes on the surface of the food [18]. In Fig. 3 notable structural changes in the thicknesses of 1 and 2 mm were observed. At depths between 0.5–2 mm in the sample the highest concentration of the stevia osmotic solution was found (Fig. 8). These results indicated that the increase in the concentration of solutes on the tissue surface had a significant effect on changes in the plant microstructure during the OD process.

The solutes accumulation on sample surface caused thickening and edge twisting of cell walls, as well as detachment of cellular fibrils, producing an increase anhydrous real density on this area of plant tissue. Some authors have analyzed the changes in the microstructure of the tissue for different kinds of osmotic agents and stages of OD process [1, 12, 27, 28]. However, no studies were found where changes in plant macro and microstructure based on the distribution of the solutes inside plant tissue.

Microscopy images of dehydrated samples in sucrose solution are presented in Fig. 4. As shown in figure, the greatest damage to the plant cell structure of the samples at depths of 1, 2 and 3 mm were observed. In this case similar to the samples treated in stevia solution, the surface of the vegetable tissue of the apple dehydrated in sucrose shows large intercellular spaces with cell shrinkage, folds and cracks in the cell wall [12].

In the thicknesses between 0.5 and 3 mm the lowest moisture content and the highest concentration of sucrose in the samples were obtained (Figs. 5 and 6). The effect of moisture loss from plant tissue during osmotic dehydration on the changes that the plant microstructure undergoes has been studied by other authors [19–21]. Salvatori and Alzamora [11] observed that at the beginning of the glucose osmotic process, cell walls of apple tissues deformed remaining

bounded to plasmalemma during the cell shrinkage caused by water loss in the samples. In turn, Nieto et al. [1] reported that in the samples treated in sucrose showed a general collapse of tissues and folding of cells walls with an important reduction in intercellular spaces was also observed as a consequence of the loss of moisture in the samples. Tortoe and Orchard [12] observed the cells of fresh materials exhibited a noticeable cell wall, whereas osmotically dehydrated cells depicted broken and distorted cell walls. The decrease of water content in tissue surface caused plasmolysis in the cell structure, resulting in deformation, contraction, and collapse of most cells; similarly, the intercellular spaces also become contracted and deformed in the area collapsed. The collapse in the tissue surface could also be due to the impregnation of solutes on this area, which would explain the increased of the anhydrous real density values in the food surface during osmosis. In the sample center at thicknesses of 5–10 mm the cell structure remained similar to the microscopic features of fresh apple.

Figures 3 and 4 clearly showing a different degree of cellular alteration and collapse in the samples treated in stevia solution compared with the osmodehydrated samples in sucrose. The cellular collapse and the changes observed in the cellular microstructure of the samples treated in sucrose osmotic solution reached a depth of 3 mm from the surface while the samples dehydrated in stevia osmotic solution the area of microstructural alterations was of 2 mm approximately (Figs. 3 and 4). These results are consistent with the fact that the sucrose solution caused a greater loss of moisture and increase of the solutes concentration in the sample (Figs. 5 and 6) compared with the sample dehydrated in stevia osmotic solution (Fig. 8). Moisture loss from the cells cause the cells to shrink, induce enlargement of the intercellular spaces and the detachment of the membrane plasma from the cell wall resulting in plasmolysis of the plant cell [8, 12]. The increase of sucrose concentration on

sample drives cell structure plasmolysis, causing that the modification of the cellular structure appears to a greater depth in the fruit.

In both, the samples dehydrated in osmotic stevia solution and those treated in sucrose solution, the collapse and alterations of the cell microstructure were observed in the thicknesses of the surface of the plant tissue, which shows that the accumulation of solutes in this food area directly influences the changes that the plant cell microstructure undergoes during the osmotic dehydration process.

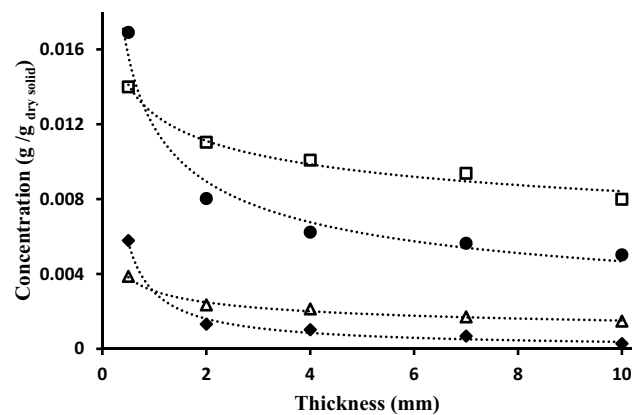
### Moisture and solute transfer in the sample

Moisture and solute transfer in plant tissue during OD process could cause changes in plant cell structure. The study of the distribution of water and solutes in food and its relation with structural properties is essential for identifying the mechanisms involved in mass transfer in OD. The kinetic behavior of the moisture content in different thicknesses of the sample is presented in Fig. 5. Moisture content in the center thicknesses of the sample (7–10 mm) was higher than in the surface (0.5–3 mm) ( $P < 0.01$ ). This trend was found for both concentrations of the 30 and 50°Brix osmotic solution, as well as for all time periods analyzed. Other authors as Ramallo and Mascheroni [16] and Mourão et al. [30], found a similar trend in studies of tissue water distribution during the OD of foods.

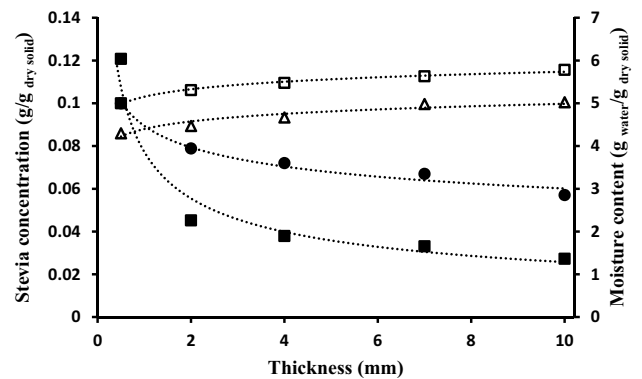
On the other hand, sucrose concentration on sample surface (0.5–3 mm) was significantly higher compared to food center (7–10 mm) for all times analyzed ( $\alpha < 0.01$ ). The concentration of the osmotic solution significantly ( $\alpha < 0.01$ ) influenced the sucrose transport in the plant tissue. The increase in the concentration of the osmotic medium at 50° Brix caused an increase in the retention of sucrose on the food surface up to 40% higher than that achieved with the concentration at 30° Brix.

Stevioside and rebaudioside A concentration profiles in plant tissue (Fig. 7) showed a similar trend to that observed in sucrose concentration profiles. The concentration of stevia compounds in the samples increased significantly on the surface of the food (0.5, 2 mm) and was lower in center thicknesses (5–10 mm). The concentration of the osmotic solution had a significant effect on the concentration of the solute in the area near to the interface to 0.5 mm. However, unlike sucrose profiles, in the others analyzed thicknesses (2, 4, 7, 10 mm) the concentration of the stevia compounds in the sample decreased with the increase in the concentration of the solution.

Moisture content and osmotic solution concentration in the samples treated in stevia solution was showed in Fig. 8. Moisture profiles of samples treated in stevia solution were a similar trend to those observed in samples osmodehydrated in sucrose solution. The concentration of stevia solution



**Fig. 7** Stevioside and rebaudioside A concentration in samples treated by osmotic dehydration in stevia solution: (open triangle) stevioside concentration at 50 °C, 3%; (open square) rebaudioside A concentration at 50 °C, 3%; (filled diamond) stevioside concentration at 50 °C, 6%; (filled circle) rebaudioside A concentration at 50 °C, 6%



**Fig. 8** Stevia osmotic solution concentration and moisture content in samples dehydrated: (filled square) stevia osmotic solution concentration at 50 °C, 6%; (filled circle) stevia osmotic solution concentration at 50 °C, 3%; (open triangle) moisture content dry basis at 50 °C, 6%; (open square) moisture content dry basis at 50 °C, 3%

showed a similar behavior of stevioside and rebaudioside A. The differences related to the effect of the concentration of the osmotic solution on the retention profiles of solutes found in the samples dehydrated in stevia and sucrose osmotic solutions could be related to the molecular mass of both molecules: sucrose and stevioside. The stevioside molecule has a molecular mass of 804.80 g/mol while the molecular mass of sucrose is 342.29 g/mol.

The increase in the concentration of the stevia solution to 6% caused the accumulation of the stevioside molecules on the surface of the plant tissue (0.5 mm) near to the interface due to the high value of the molecular mass of the stevioside molecule. The accumulation of stevioside molecules from the stevia osmotic solution on the surface acts as a barrier that limits the outflow of water and the migration of



solutes into the food [18]. Solute accumulation in tissue surface during osmotic dehydration of food has been found by other authors [15–18, 24], as well as, the effect of the high concentration of some osmotic agents on the decrease in the concentration of solutes inside the food. However, a clear explanation of the phenomenon has not been provided.

The results found in this paper, show that the study of the macro and microstructural properties of the plant tissue, analyzing the sample in a global way does not allow an adequate description of the phenomena involved in the food OD process. The morphological complexity of the fruits and the multicomponent properties of the osmotic solutions cause an unequal distribution of water and solutes within the plant tissue during the OD of fruits, so a global approach will limit the identification of the mechanisms involved in mass transfer within the food. Additionally, the results presented reveal that the migration of solutes within the plant tissue changes with depth of the sample, which means that only the specific determination of the physical and structural properties at different depths of the sample will allow a clear description of the phenomena that promote the transport of solutes within the food. On the other hand, the relationship between the accumulation of solutes of the osmotic solution on the surface of the food and the changes in the macro and microstructural properties in this area of the tissue were demonstrated, which is very important for the identification of the mechanisms involved in solute transfer, which is currently the main unsolved problem behind mass transfer.

## Conclusions

The results found in this research, showed that there is a direct relationship between changes in macro and microstructural properties and the concentration of solutes within plant tissue. The real anhydrous density increased in the area of highest solute concentration, while the volume in this area decreased. The major alterations in the microstructure of the plant cell were caused by the accumulation of solutes and the increase of the moisture loss in the thicknesses of the surface of the plant tissue (0.5–3 mm) of the osmodehydrated samples in osmotic solutions of stevia and sucrose. The results indicated that the specific analysis of the properties in food allowed a better understanding of the mechanisms involved in mass transfer during the OD of fruits, providing a better description of the phenomenon of osmotic dehydration, compared to the determination of properties under a global approach.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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