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Research article

Mathematical modelling of mass transfer phenomena for sucrose and lactitol molecules during osmotic dehydration of cherries

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HIGHLIGHTS

- Effective diffusion coefficients were calculated in cherry flesh and skin.
- The fastest molecular movement is during the first hours of starting the process.
- Diffusivity of water and lactitol molecules is differential.
- Cherry skin acts as a barrier to the diffusivity of substances.

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ABSTRACT

The diffusion phenomena of sucrose and lactitol in cherries using different proportions during osmotic dehydration was quantified by means of a mathematical model based on Fick's second law. The average effective diffusion coefficient for soluble solids in skin and flesh are 5.37 10^{-11} m^2/s and 1.24 10^{-10} m^2/s. Whereas, for water in skin and flesh are 9.27 10^{-09} m^2/s and 5.48 10^{-08} m^2/s. A significant difference for water diffusion coefficients ($p < 0.05$) was observed between the treatments. This could indicate that the diffusion between species and treatments is differential. Effective diffusion coefficients for water in skin and flesh are 2 orders of magnitude greater than effective diffusion coefficients for soluble solids. This is probably due to its lesser molecular weight. Furthermore, the effective diffusion coefficients for water and soluble solids in cherry skin are between 1 and 2 orders of magnitude lower than effective diffusion coefficients for both in cherry flesh, possibly due to the barrier effect exerted by the cherry skin.

1. Introduction

Osmotic dehydration is a technique that partially removes water from food tissues by immersion in a hypertonic solution [1, 2]. The food tissue and their quality are affected on a lesser scale compared with drying methods [3, 4]. Hence, 'osmotic dehydration', referred as 'Dewatering and Impregnation Soaking Process' (DISP) [5, 6, 7], involves immersing the food in hypertonic solutions, principally resulting in two simultaneous flows, one corresponding to the water outflow and the other to the solids income, considering the food as a reference [8, 9].

Mass transfer process has been modelled based on the Fickian diffusion theories [10, 11, 12], irreversible thermodynamics [13], multicomponent diffusion [14], and hydrodynamic flow [15]. Similarly, with regard to water loss and sucrose absorption, when varying concentration and temperature, changes were found [16, 17]. Simpson et al. [18] determined diffusion mechanisms exposing fruit to different electric fields.

On the other hand, as another methods used for osmotic dehydration can be mentioned microwave drying [3, 19], convective dehydrofreezing [20], ultrasound methods [17, 21], vacuum methods [22, 23], and vacuum pulsed osmotic dehydration (PVOD) [24], in which water loss kinetics, solids gain and stress at rupture, as well as the effective diffusivities using the hydrodynamic model were estimated, amongst others.

Zuritz & Maldonado [25]' developed a simple method, both mathematical (modelling) and experimental to determine sodium variable effective diffusion coefficients through olives skin. Further, Arauco variety green olives were debittered [26, 27] with lye in different

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concentrations of NaOH to undergo two tap water rinsing processes. Describing this phenomenon, effective diffusion coefficients were calculated using a composite hollow sphere model, to determine reducing sugars loss and NaCl molecular movement. With the aim of finding osmotic dehydration predictive models, studies on molecular transport in plant tissues were developed. Ability of each constituent to diffuse into the tissue is considered by transmembrane diffusion and mass transfer coefficients [28].

Barat et al. [29] based on Arrhenius model to obtain kinetic parameters that described apple slices osmotic dehydration phenomenon subjected to different concentrations of sugar - water and temperatures. In addition, water loss, sucrose gain, glucose and fructose concentration at different conditions, during osmotic dehydration of pineapple slices was analysed [30]. Whilst, changes in ionic movement for sodium and calcium in olives, through calculation of diffusion coefficients, was quantified [31].

On the other hand, from an economic perspective, cherries are amongst the most dynamic products in the world food trade. From 2000 to 2010, the volume traded worldwide has grown by more than 140 percent. Its cultivation generates high profitability in small areas and mobilizes local and regional economies. Although the northern hemisphere produces the highest percentage of cherries, there is a potential demand in the southern hemisphere to cover the off-season. In Argentina, the crop is distributed 46% in the province of Mendoza, 26% in South Patagonia and 21% in North Patagonia. The expanding market for processed cherries is growing for specific niches, such as maraschino cherries, and represents a significant economic opportunity. The main export destination for cherries are European countries, this being a commodity. Argentina is in the ranking of the nine main exporters of cherries in the world. Regarding exports from the southern hemisphere, Argentina competes with Chile and New Zealand [32, 33].

Nowadays, there is a growing demand for low calorie foods. Due to the increase in obesity, diabetes, and associated diseases, it has been estimated that overweight and the number of diabetic patients will increase worldwide (FAO, 2017) [34]. As a result, polyols blends have been used to modify viscosity and especially to sweeten foods [35]. In addition, the polyalcohols that are gaining popularity in the treatment of patients with irritability bowel syndrome (IBS) [36].

In particular, lactitol is a bulk sweetener with prebiotic characteristics, because it is fermented by the intestinal microbiota and resistant to digestion [37]. So Lactitol (4-O-a-D-galactopyranosyl-D-glucitol) >98% is hydrolysed by microbial enzymes in the large intestine to galactose and glucitol [38]. This provides 2–2.4 kcal/g and its sweetness compared to sucrose is 30–40%, therefore it is chosen for foods such as hard and soft candies, ice cream, chocolate, and some baked goods [36].

Based on what was presented above, the objective of this work is to apply a mathematical model of mass transfer phenomenon in an osmotically dehydrated cherries matrix, submerged in a hypertonic sucrose solution and partially replaced by lactitol.

2. Materials and methods

The cherries were pitted with a manual pitter, sized and desulfited by an immersion in a water bath for 24 h, prior to the candying process. In order to dehydrate osmotically the fruit, a method of multiple impregnations called “Slow Method”, or “French” was used [39]. Which consisted of placing the fruits in a hypertonic solution of a relatively low initial concentration and gradually increased until reaching the desired final concentration, letting them settle in a period of 24 h between each concentration.

Eighteen kilograms of cherries were used. The sweetener solution was added to these in enough quantity to cover them completely (proportion of 1: 1.2 solid - liquid). Three treatments were performed, T0: sucrose 100%, T1: sucrose 75% – lactitol 25%, T2: sucrose 50% – lactitol 50%. The experiment was maintained under constant stirring with a paddle stirrer, and permanently at 60 °C by means of a heating plate.

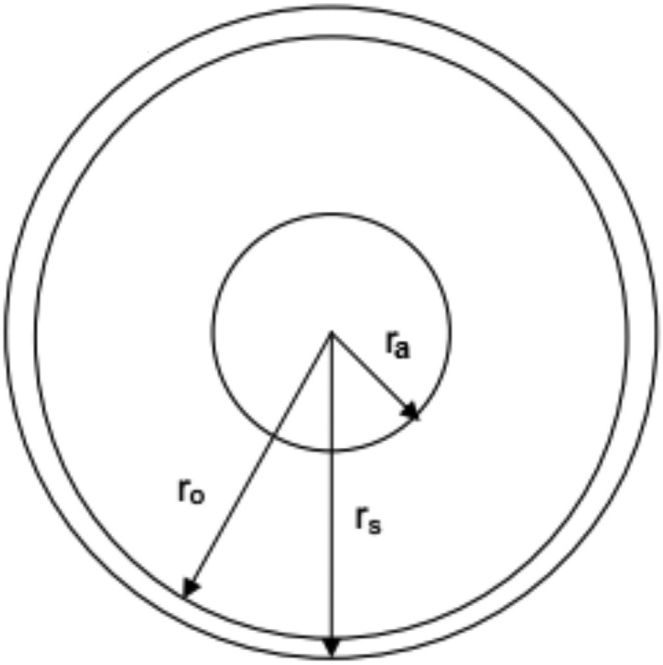

Figure 1. Cherry cross-section diagram showing radial dimensions.

The process started with an initial concentration of 25 °Brix in the sweetener solution, to avoid formation of wrinkles in the fruit. The prepared syrup was daily boiled and then the temperature lowered until it reached 60 °C. The cherries were placed in syrup and left in it, for 24 h until the next impregnation. This process was repeated successively to achieve a concentration of soluble solids in a nominal amount of 10 °Brix in every new impregnation. Five impregnations in total were performed: 25, 35, 45, 55 and 65° Brix.

The staining was carried out between third and fourth impregnation with erythrosine and amaranth to 0.0238% and 0.019% respectively and addition of 2% citric acid, until obtaining a pH of 3.5 with the purpose to produce the dye precipitation inside the cell tissue. Then the pH was brought to 3.8 with 10% $NaHCO_3$ solution. Finally, with the last impregnation, once the flesh reached 55 °Brix, the cherries were packed in 360 cm3 glass jars, covered and placed in a boiling water bath for 20 min.

During the process, the following parameters were measured in triplicate: soluble solids with refractometer Atago, in solution and flesh, and moisture in a dried oven at 100 ± 5 °C for 24 h.

The sampling frequency after every impregnation was:

Every one hour, three cherries were extracted from different parts of the container, to measure the concentration of soluble solids in flesh by squeezing them manually and measuring the flesh juice for 6 h.

In order to measure the concentration of soluble solids in the syrup, three liquid samples were taken from different part of the container, during the first 6 h.

2.1. Mathematical modelling

During osmotic dehydration process, effective diffusion coefficients for both solutes, in skin and flesh, were calculated. A hollow sphere diffusion model was fitted to experimental values.

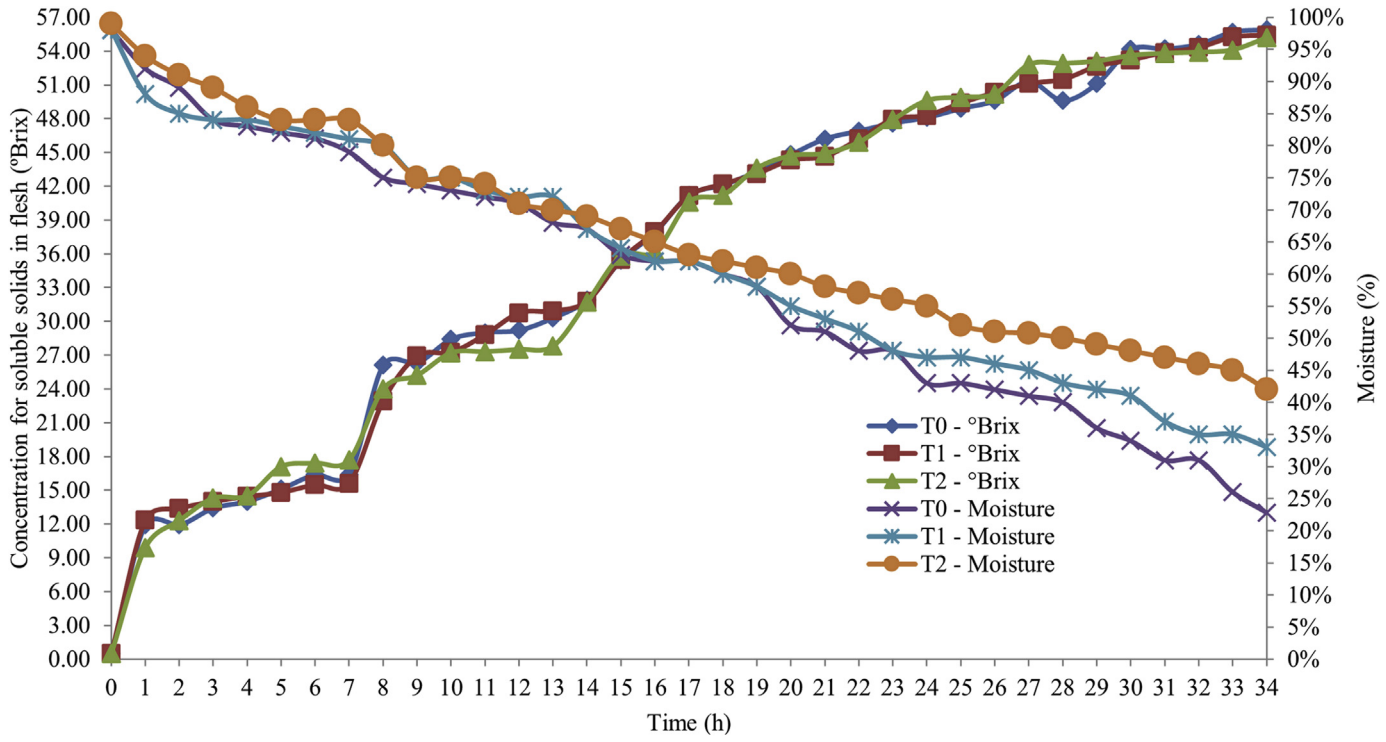

Figure 2. Evolution of °Brix of soluble solids in cherry flesh and Moisture in relation to time.

2.2. Theory

In first instance, an equation was found that governs the molecular diffusion phenomenon through a solid porous matrix. A diffusion equation was developed for a sphere with a hollow spherical centre and variable boundary condition. Constant initial condition $C = C_i$.

However, for the development of the experiment, it is necessary to use the following assumptions (Figure 1).

(1) The cherry is considered a hollow sphere.
(2) The accumulation of solute in the thick cherry skin (r_s - r_0) is negligible compared to the flow through the porous surface and the flow itself, so that a steady state process is assumed through the skin or quasi - stationary.
(3) In this case, there is no generation of substances by reaction, so the term Ri is neglected.
(4) Molecular diffusion is the only transport mechanism for water within the solid and soluble solids within the fruit, so there is no convective transport $v_r = v_\theta = v_\Phi = 0$.
(5) The flesh of cherries is considered homogeneous, and its properties isotropic.
(6) The diffusion process presents radial symmetry and diffusion is unidirectional.
(7) Due to the great agitation of the liquid surrounding the internal and external surfaces (high mass Biot number), the concentration in these instantly acquires the concentration of the liquid.
(8) The thickness of the epidermis is much smaller than the radii of the inner and outer faces, so the difference in surface areas can be neglected and the thickness assumed as (r_s - r_0).

2.3. Calculation

Under the previous assumptions, the one-dimensional diffusion equation using constant effective coefficients in flesh (D_F) and skin (D_S), and further assuming negligible convective transport, is expressed as:

$$\frac{\partial C_i}{\partial t} = D_{ij}\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial C_i}{\partial r}\right)\right] \quad (1)$$

Thus, the dimensionless equation can be expressed as follows [40, 41]:

$$\frac{\partial \mathcal{C}}{\partial \Theta} = \frac{2}{R}\frac{\partial \mathcal{C}}{\partial R} + \frac{\partial^2 \mathcal{C}}{\partial R^2} \quad (2)$$

Eq. (1.1) is subject to the following initial and boundary conditions:

$$\text{I. C.: at } \Theta = 0 \qquad \mathcal{C} = \mathcal{C}_i \qquad \text{at a} \leq R \leq 1 \quad (3)$$

$$\text{B. C.1: at } \Theta > 0 \qquad \mathcal{C} = \frac{\mathcal{C}_s - \mathcal{C}_s}{\mathcal{C}_i - \mathcal{C}_s} = 0 \qquad \text{at R} = \text{a} \quad (4)$$

$$\text{B. C.2: at } \Theta > 0 \qquad \frac{\partial \mathcal{C}}{\partial R} = -\left[\frac{\frac{D_S}{r_s - r_0}}{\frac{D_L}{r_0}}\right](\mathcal{C} - \mathcal{C}_s) \qquad \text{at R} = 1 \quad (5)$$

where:

$\Theta = \frac{\mathcal{D}_{ij}\, t}{r_o^2}$; $R = \frac{r}{r_0}$; $a = \frac{r_a}{r_0}$; $\mathcal{C} = \frac{C_{(t)} - C_S}{C_i - C_S}$

Following the resolution methodology and applying the initial and boundary conditions, the following expression can be obtained:

$$\sin(\lambda_n)\left[(a{\lambda_n}^2 + 1)\cos(\lambda_n a) + (a\lambda_n - \lambda_n)\sin(\lambda_n a)\right] + \cos(\lambda_n)\left[(a\lambda_n - \lambda_n)\right.$$
$$\left.\cos(\lambda_n a) - (a{\lambda_n}^2 + 1)\sin(\lambda_n a)\right] = 0 \quad (6)$$

Eq. (2) allows the calculation of the eigenvalues λ_n.

Finally, an infinite series is obtained, which is an expression that shows the variation or evolution of dimensionless concentration in relation to dimensionless time:

$$< C_\Theta > = \frac{3}{(1-a^3)} \sum_1^\infty \left\{ \frac{C_i}{b} \left[\int_a^1 R^2 \Phi_{m(R)} dR \right]^2 - \frac{EA_0}{{\lambda_n}^2 - A_1} \left[e^{\left({\lambda_n}^2 - A_1\right)\Theta} - 1 \right] \int_a^1 R^2 \Phi_{m(R)} dR \right\} e^{-{\lambda_n}^2 \Theta} \quad (7)$$

However, for long process times ($\Theta \gg 0$) we can neglect the terms greater than 1 of the infinite series and therefore it is possible to work with the first term. Thus:

$$< C_\Theta > = \frac{3}{(1-a^3)} \left\{ \frac{C_i}{b} \int_a^1 R^2 \Phi_{1(R)} dR - \frac{EA_0}{{\lambda_1}^2 - A_1} \left[e^{\left({\lambda_1}^2 - A_1\right)\Theta} - 1 \right] \right\} e^{-{\lambda_1}^2 \Theta} \int_a^1 R^2 \Phi_{1(R)} dR \quad (8)$$

For more details concerning the mathematical modelling, see Appendices content [42].

The following function was minimized by the least squares method, to obtain effective coefficients in flesh (D_F) and skin (D_S), and the eigenvalues λ_1. The iterative nonlinear regression method was used using Microsoft Excel® software.

$$S = \sum_{i=1}^N \left(\langle C_{exp} \rangle - \langle C_{calc} \rangle \right)^2 \quad (9)$$

2.4. Statistical analysis

Tukey test was used in ANOVA analysis, with a significance level of 0.05, using the IBM® SPSS® software (V22.0, IBM Corp., NY, USA). The results are presented as mean ± standard deviation (SD) for n = 3.

3. Results and discussion

Figure 2 was constructed with data from the first six hours per day of treatment and shows the two main counter-current flows fundamentally the outflow of water from the cherries into the solution and to a lesser extent the entry of soluble solids into cherry flesh, for the three treatments. Before placing the cherries in the hypertonic solutions, the soluble solids values were 0.5 °Brix for the cherry flesh. Then, during the first six hours, the soluble solids increased until an average of 16.41 °Brix. On the second day, when the syrups reached 35 °Brix, the nominal value increased on average 29.67 °Brix. On the third day, soluble solids continued to increase to an average of 42.65 °Brix. On the fourth day, the increase in soluble solids was 51.63 °Brix. The last day the soluble solids in the flesh allowed an average of 55.5 °Brix, in syrup with 65 °Brix. For the three treatments T0, T1 and T2 the behaviour was similar throughout the treatment time. The most important increases were reported in the first three days where 80% of soluble solids incomed into the flesh; then the rest of the time, the income of soluble solids into the cherry flesh was 20% of the total soluble solids and it occurred at a slower velocity. This could be due, because the flesh was more saturated with syrup, and the syrup was more viscose.

On the other hand, the initial moisture content for the cherry flesh was 98% for the three formulations. The moisture was decreasing with the passage of time because of the water outlet, which occurs in the phenomena of osmotic dehydration, when they are placed in a hypertonic solution of syrup. Moreover, as can be seen in Figure 2, the decrease in water for all treatments was similar until day three in consistency with the income of soluble solids in the cherry flesh. On day three, the three treatments have lost an average of 43% of water and have gained 79% of the total soluble solids. In the last two days, remains a water loss of 23% and 11 °Brix of solids, that they represent 20% of the final soluble solids. This could be attributed to the increase in syrup's viscosity and the saturation of the porous matrix with it, which would possibly decelerate the outflow of water molecules from the system. However, if each of the treatments is considered individually, T0 acts as the more osmodehydrating formulation, superior to T1 and T2. The latter could be explained by the increase in lactitol in the formulation, which would provide more moisturizing characteristics, as has been named and referenced in Zumbé et al. [43] and J. L. Multon [44].

At the final time of treatment, T0 had a final value of 23% moisture, T1 of 33% and T2 of 42%. This could indicate that sucrose has a greater osmo-dehydrating power when it is found alone in solution, than when it is combined with lactitol in different proportions [43].

Table 1. Effective diffusion coefficients for soluble solids in skin and cherry flesh for the three treatments.

Treatment	T0*	T1*	T2*
D_F (m^2/s)*	$1.78\ 10^{-09} \pm 1.59\ 10^{-09}$ a	$8.21\ 10^{-10} \pm 5.80\ 10^{-10}$ a	$3.58\ 10^{-10} \pm 3.10\ 10^{-10}$ a
D_S (m^2/s)*	$3.02\ 10^{-10} \pm 2.69\ 10^{-10}$ a	$1.40\ 10^{-10} \pm 9.85\ 10^{-11}$ a	$3.38\ 10^{-11} \pm 2.92\ 10^{-11}$ a

Results are stated as means ± SD (n = 3). Mean values for each treatment do not differ significantly ($p > 0.05$).

* D_F: effective diffusion coefficient in cherry flesh. D_S: effective diffusion coefficient in cherry skin. T0: control treatment. Sucrose 100%. T1: treatment 1. Sucrose 75% - lactitol 25%. T2: treatment 2. Sucrose 50% - lactitol 50%.

Table 2. Effective diffusion coefficients for the case of water in skin and cherry flesh for the three treatments.

Treatment	T0*	T1*	T2*
D_F (m^2/s)*	$1.22\ 10^{-07} \pm 8.40\ 10^{-08}$ a	$5.38\ 10^{-08} \pm 3.76\ 10^{-08}$ ab	$6.42\ 10^{-09} \pm 4.38\ 10^{-09}$ b
D_S (m^2/s)*	$2.08\ 10^{-08} \pm 1.43\ 10^{-08}$ a	$9.14\ 10^{-09} \pm 6.38\ 10^{-09}$ ab	$1.09\ 10^{-09} \pm 7.44\ 10^{-10}$ b

Results are stated as means ± SD (n = 3). Mean values with different letters in the same row differ significantly ($p < 0.05$).

* D_F: effective diffusion coefficient in cherry flesh. D_S: effective diffusion coefficient in cherry skin. T0: control treatment. Sucrose 100%. T1: treatment 1. Sucrose 75% - lactitol 25%. T2: treatment 2. Sucrose 50% - lactitol 50%.

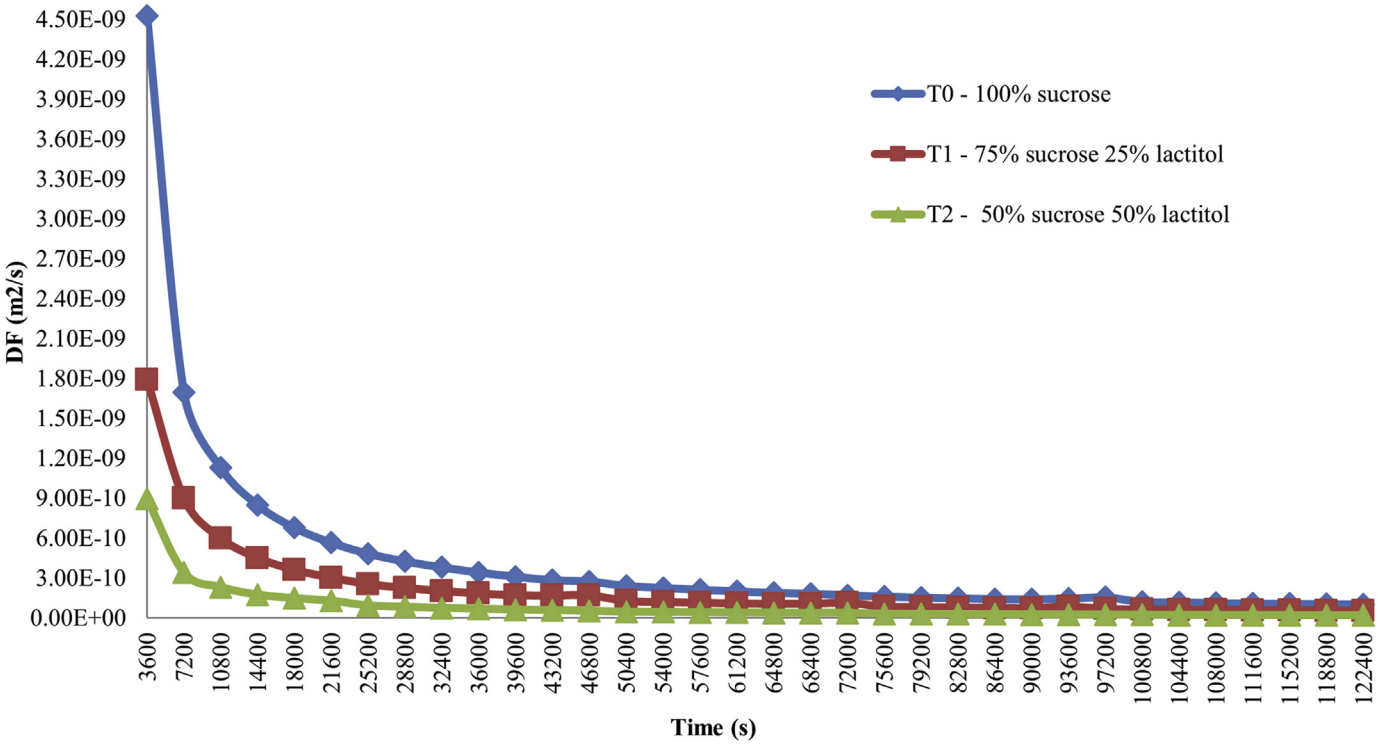

Figure 3. Comparison of effective diffusion coefficients for soluble solids in cherry flesh for the three treatments in relation to time.

It can also be noted that the different osmotic dehydrating power between the different formulations was on average 10% at the end of the treatment. This is consistent with what was found by Zumbé et al. [43] who tabulated lactitol's hygroscopicity with 90% in contrast to 84% of sucrose, at equilibrium relative moisture, at a temperature of 20 °C in powder form and Multon [44] who said all polyalcohol have humectants characteristics. In other words, as the amount of lactitol in the formulation increases, the water is retained more intensely, thus the osmotic dehydration of the fruit is less. The experimental values could suggest a different form of diffusion of the sucrose molecule in relation to that of lactitol.

Table 1 presents the average values of effective diffusion coefficients for the case of soluble solids in skin and cherry flesh, for the three treatments. For flesh diffusion, for treatment T0, the effective diffusion

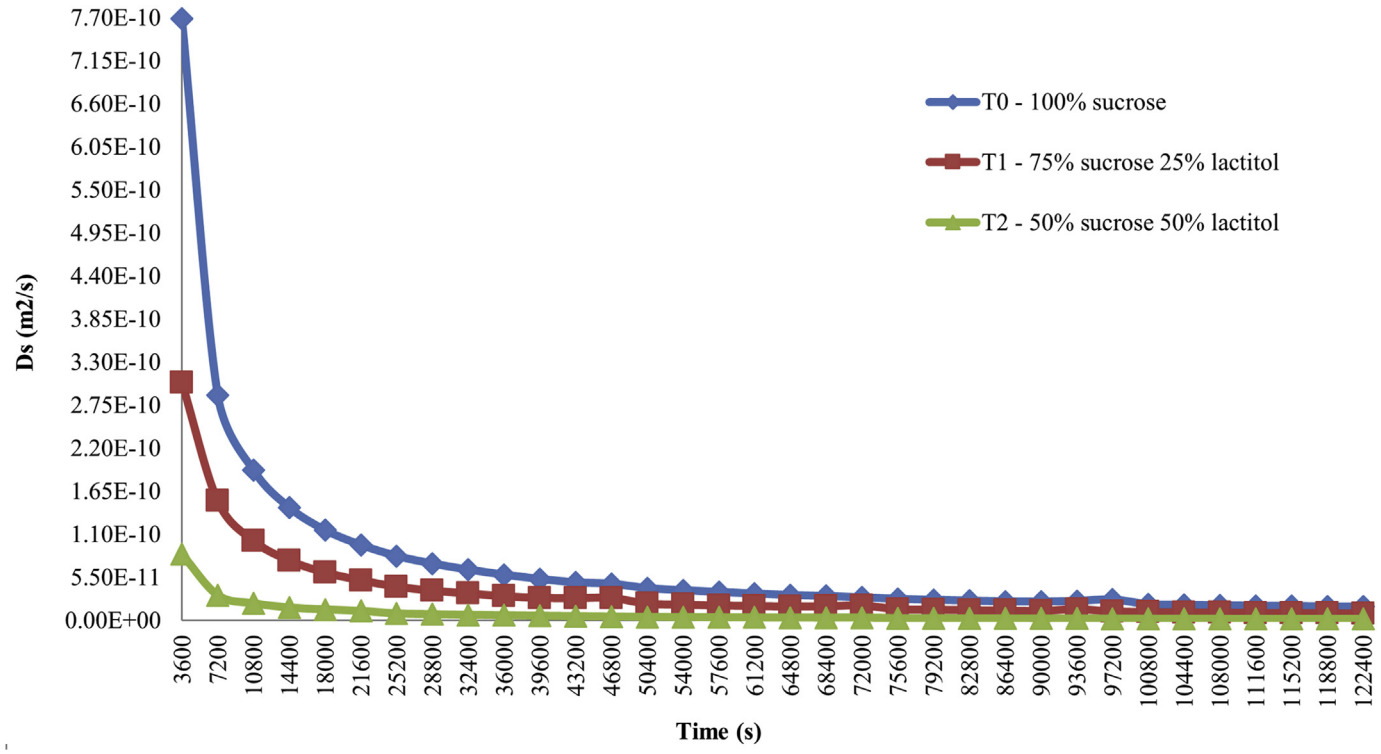

Figure 4. Comparison of effective diffusion coefficients for soluble solids in cherry skin for the three treatments in relation to time.

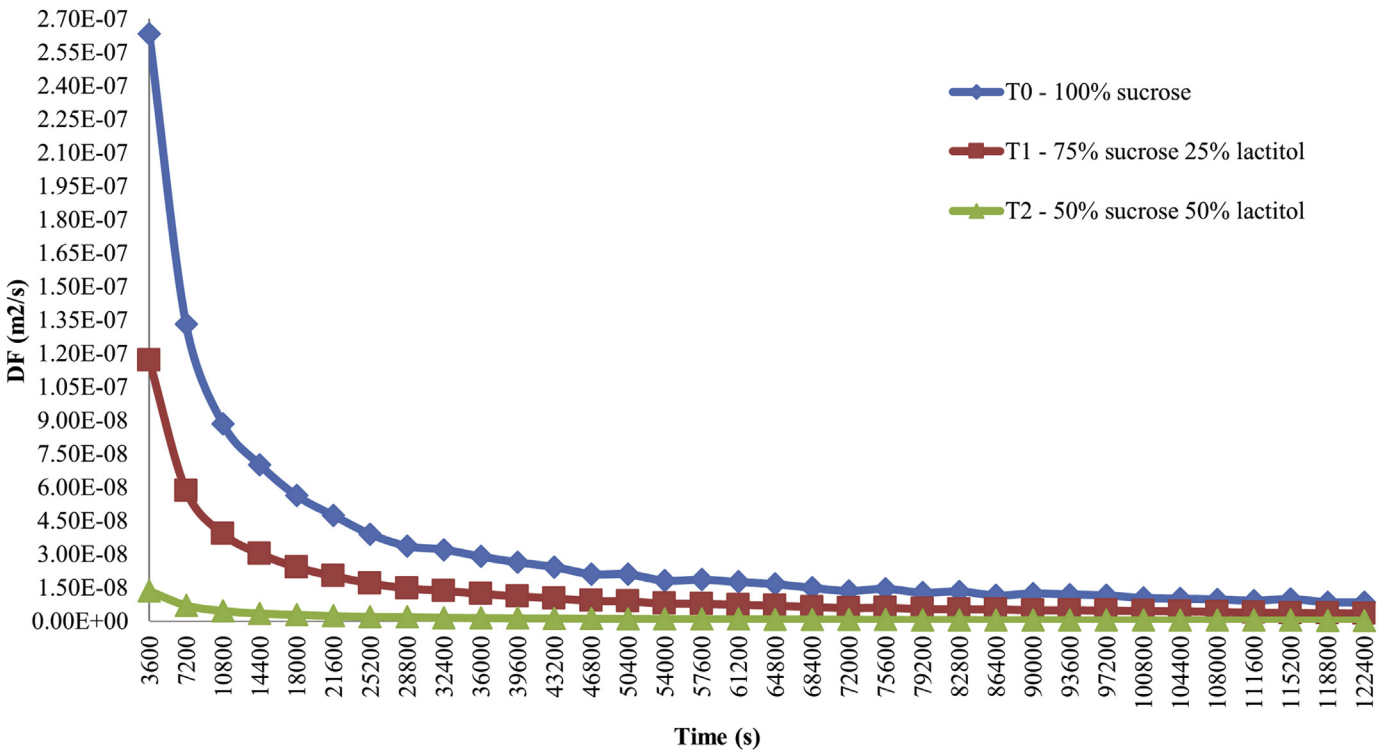

Figure 5. Comparison of effective diffusion coefficients for water in cherry flesh for the three treatments in relation to time.

coefficient is higher than for treatments T1 and T2. Further, the difference between effective coefficients in flesh was not significant ($p > 0.05$).

With this, one of the two important flows that are generated in osmotic dehydration is evident, that is, the entry of a flow of soluble solids from the hypertonic solution that surrounds the cherries. Furthermore, the greater osmo-dehydrating effect generated by treatment T0, which contains only sucrose, can be observed compared to the remaining treatments T1 followed by T2, which contain sucrose and lactitol in different proportions.

The same occurs with the diffusion coefficients in skin; however, the values are 1 order of magnitude lower compared to the effective coefficients in the flesh, whilst the difference between effective coefficients in skin was not significant ($p > 0.05$). This could be due to the resistance and barrier to diffusion of sucrose and lactitol molecules offered by the skin of cherries. A similar finding was described by Maldonado et al. [26, 27, 31] where the difference in diffusivity could be due to a more impermeable structure in fruit skin (natural barrier) against the diffusion of compounds.

Table 2 presents the average values of the effective diffusion coefficients for water, in the skin and flesh of the cherries, for the three treatments. It can be observed that for the flesh diffusion, for the T0 treatment, the effective diffusion coefficient is higher than for the T1 and T2 treatments, showing one of the two main flows that are generated in osmotic dehydration, in this case, the flow of water out of the cherry, and then incorporated into the surrounding hypertonic solution. Furthermore, diffusion coefficients in flesh are significantly different ($p < 0.05$), for certain comparisons between treatments. This could indicate that the diffusion between species and treatments is differential. In addition, osmo-dehydrating effect for T0 is much higher, followed by the remaining treatments T1 followed by T2.

A similar behaviour for diffusion coefficients in skin was found; nevertheless, the values are 1 order of magnitude lower compared to the effective coefficients in flesh, while diffusion coefficients in skin are significantly different ($p < 0.05$), for certain comparisons between treatments. Additionally, this could be due to the resistance and barrier effect to the diffusion of water molecules, offered by the cherries skin. The fruits epidermis tend to have tissues composed of cells that are large and tighter than cells of the cell parenchyma, which are of the isodiametric type and are more closely arranged [45]. This characteristic of the epidermis, in addition the cuticle layer, which covers fruits such as cherries and others, present a barrier effect to the diffusion of substances through it and is different from the diffusion in the mesocarp. Maldonado et al. [31] and Zuritz and Maldonado [25] found this when studying sodium diffusivity in olives.

On the other hand, it can be observed that if the effective diffusion values of Table 1 are compared, the conclusion is reached that the water coefficients in skin and flesh are 2 order of magnitude greater than the coefficients, in skin and flesh of cherries, for soluble solids [31].

Furthermore, it is distinguished that the effective coefficients for water in flesh are 3 orders of magnitude greater than the effective diffusion coefficients for soluble solids in the skin. This difference for water, of 1 and up to 3 orders of magnitude, could probably be due to its smaller size and molecular weight, compared to the sizes and weights of sucrose and lactitol, adding the barrier effect that the skin of the cherries. This is consistent with the results obtained by da Conceição Silva et al. [46], whose values range from 10^{-12} m^2/s to 10^{-08} m^2/s in skin and flesh respectively, and those obtained with M B Maldonado, Zuritz, & Miras [27], where values of 1.88 10^{-13} m^2/s to 2.22 10^{-10} m^2/s were obtained in skin and flesh of olives, respectively.

Figure 3 shows the evolution of the effective diffusion coefficients for soluble solids in cherry flesh, for the three treatments in relation to time. These effective coefficients in cherry flesh, compared with the coefficients in skin, are 1 order of magnitude higher. This is possibly due to the barrier effect offered by the fruit epidermis, previously discussed.

This could be since sucrose syrup alone moves faster than when it is combined with lactitol in different proportions, since it would increase

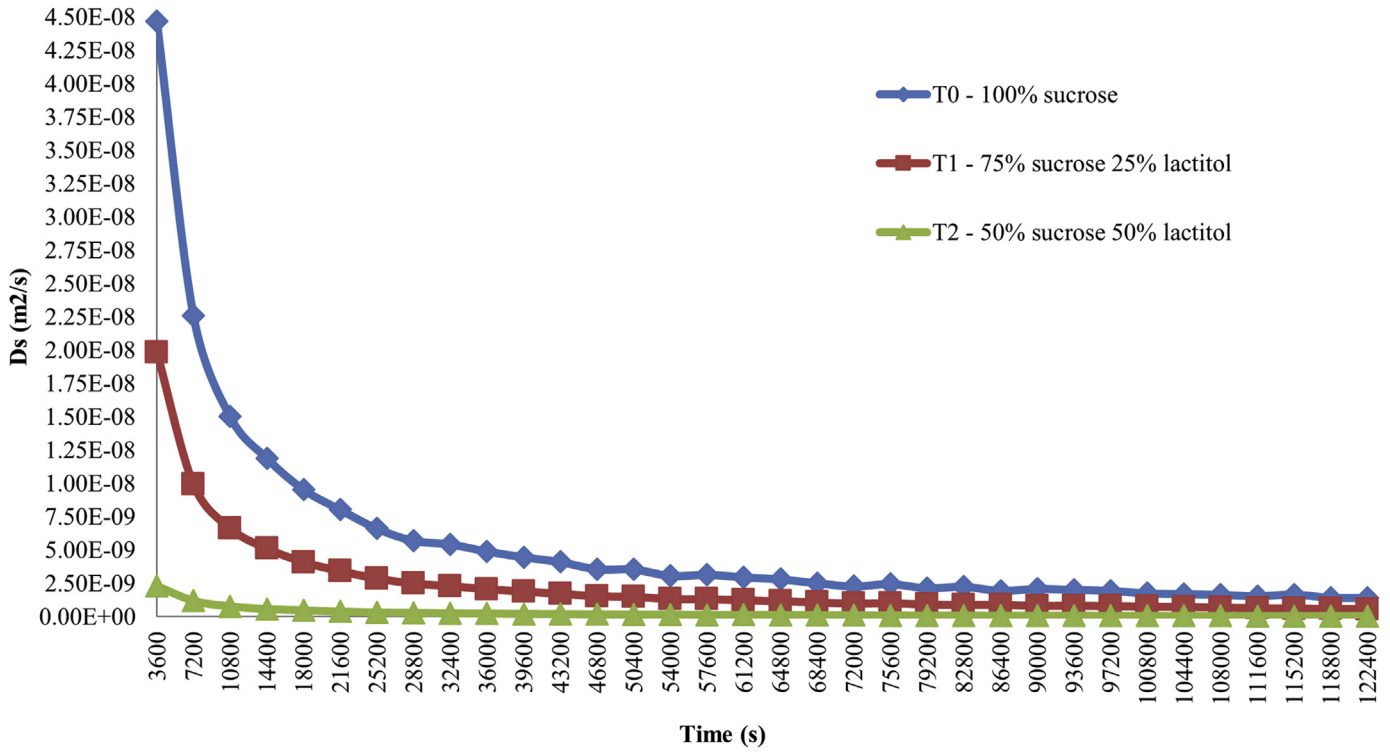

Figure 6. Comparison of effective diffusion coefficients for water in cherry skin for the three treatments in relation to time.

the proportion of free OH^- ion to combine that would decelerate the entrance into the flesh.

Figure 4 shows the evolution of the effective diffusion coefficients for soluble solids in cherry skin, for the three treatments in relation to time. As discussed above, the diffusion of the water molecule is much greater than the diffusion of the sucrose and lactitol molecules (2 orders of magnitude, both for flesh and skin). This difference for water, as mentioned above, is very possibly due to its smaller size and molecular weight, compared to the sizes and weights of sucrose and lactitol.

As can be observed, the effective diffusion coefficients, both for water and for soluble solids, decrease as the phenomenon progresses, and something to be highlighted is how the coefficients approach each other in both cases, for times much greater than zero. Possibly, this could be due to that porous solid permeability decreases, owing to the syrup high viscosity and saturation of the system. Then the solution that impregnated the wall of the canaliculi could increase their tortuosity, increasing the difficulty of moving through them for molecules in their translation form. Therefore, the speed of diffusion of the molecules decreases.

Furthermore, it is known, that lactitol forms hydrogen bonds, and when it is in certain proportions with sucrose it forms a polymer [47, 48]. All this should make it difficult for water molecules to escape from the cherry. Thus, based on the aforementioned, this could evidence the moisturizing power of the polyalcohol, and more specifically, that of the polyalcohol under study, which is lactitol, as Multon [44] and Torreggiani et al. [49] mentioned.

On the other hand, it is observed that during the first 6 h of treatment is where the diffusion phenomenon of the different molecules present, occurs to a greater extent, that is, where the greatest driving force or difference in concentrations occurs. Reason why, the maximum slope and the most marked decrease of the diffusion coefficients takes place. This is consistent with other studies that indicate that the main movement of molecules occurs during the first hours of starting the process [50, 51].

Figure 5 shows a comparison of the effective diffusion coefficients for the case of water, in cherry flesh for the three treatments in relation to time. It can be observed that effective coefficients in cherry flesh, compared to the coefficients in skin, are 1 and up to 2 orders of magnitude higher. This, possibly due to the barrier effect offered by the epidermis of the fruit.

On the other hand, it is observed that the effective diffusion coefficients for water, in the T0 treatment, are higher than for the rest of the treatments. This might be due to a greater quantity of water molecules that leave the porous matrix and become integrated in the hypertonic solution that surrounds the cherries.

Figure 6 shows a comparison of the effective diffusion coefficients for the case of water, in cherry skin, for the three treatments in relation to time. As can be seen in the figures, the treatment that shows the greatest diffusion of the water molecule, both for skin and flesh, is always the T0 treatment, whose composition is entirely sucrose. This indicates that T0 is the one that generates the greatest osmo-dehydrating effect, that is, a greater quantity of water molecules that leave the porous matrix (cherry) [52] and are incorporated into the hypertonic solution that surrounds it.

Then, T1 and T2 treatments follow, where they no longer have an exclusively sucrose composition, but are found in different proportions with lactitol. This indicates that the presence of lactitol in the treatments reduces the osmotic dehydration effect in cherries, compared to the effect achieved with pure sucrose.

Another issue to highlight is the difference achieved in the diffusion coefficients for the T0 treatment in cherry flesh, with the T2 treatment in cherry skin, reaching a difference at the beginning, of 2 orders of magnitude, that is, a value of 2.63 10^{-07} m^2/s in flesh for T0, compared to 2.33 10^{-09} m^2/s in skin for T2, for example. Clearly, the barrier effect exerted by the skin of the cherries would be showing again. This is consistent with what we discovered on previously mentioned by M B Maldonado, Zuritz, & Miras [27] and da Conceição Silva et al. [46] when

they studied the skin and flesh diffusion in different fruits for the epidermic tissues barrier effects.

4. Conclusions

The diffusional phenomena of cherries in osmotic dehydration with different formulations of sucrose and lactitol were quantified. The osmotic dehydration increased the soluble solids into the flesh of cherries and diminished the flesh moisture in all the treatments. All treatments reached 55 °Brix at least and presented a similar behaviour in relation to the increment of soluble solids. In the first 6 h of trials, all reported the main molecular movement for the entry of soluble solids and the outflow of water.

The diffusion coefficients of soluble solids in skin and flesh (including all treatments), was on average $D_{SS} = 5.37\ 10^{-11}\ m^2/s$ and $D_{SF} = 1.24\ 10^{-10}\ m^2/s$ respectively, for the three treatments, and no significant difference was found ($p > 0.05$). While, for water in skin and flesh, it was on average $D_{WS} = 9.27\ 10^{-09}\ m^2/s$ and $D_{WF} = 5.48\ 10^{-08}\ m^2/s$, respectively, and a significant difference ($p < 0.05$) was observed between the treatments. This could indicate that the diffusion between species and treatments is differential. Between the effective diffusion coefficients for soluble solids and water, whether in skin or flesh, the difference is 2 orders of magnitude for water, probably due to its molecular weight. Whereas the effective diffusion coefficients for water and soluble solids in cherry skin are between 1 and 2 orders of magnitude lower compared to the effective diffusion coefficients for both in cherry flesh. This is probably due to the barrier effect exerted by the cherry skin.

Furthermore, when soluble solids saturated the cherry flesh, all effective diffusion coefficients, both for soluble solids and water, decreased as the osmotic dehydration process progressed.

Declarations

Author contribution statement

Mariela Maldonado: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Juan González Pacheco: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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