

Optimization of osmotic dehydration of tomatoes in a ternary system followed by air-drying

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Abstract

Osmotic dehydration and air drying technology represent a technique that can reduce post-harvest loss of fruits and vegetables. In this work the influence of osmotic solution composition (water/sugar/salt) and temperature on the osmotic dehydration of tomatoes (*Lycopersicon esculentum*) were examined. Tomatoes with and without skin were studied. The process of osmotic dehydration followed by air-drying was studied and modeled, so it could be optimized aiming the reduction of total processing time. The results showed the advantage of two different processes for the tomatoes with skin and without skin. Tomatoes without skin are processed faster using air-drying without submitting the fruit to osmotic dehydration. Whereas, the tomatoes with skin dry faster when submitted to an osmotic solution consisting of 35% of sucrose and 5% of salt at 60 °C prior to air-drying.

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1. Introduction

Osmotic dehydration is an interesting technique to be used as a pre-treatment prior to air-drying. From a biological point of view several fruits and vegetables, tomatoes included, are perishable and present significant loss by decomposition after cropping. So tomatoes can be dried to save part of the production that would not be readily consumed providing an extension of shelf-life, lighter weight for transportation and requiring less storage space.

Tomatoes are the second most cultivated vegetable in the world with a worldwide production exceeding 100 million tons per year (FAOSTAT, 2004). Tomatoes are important not for their commercial value but also because they are part of the diet of many cultures. Drying tomatoes is

not only important to preserve this vegetable but also to produce dried tomatoes, product that has become very popular in several parts of the world as an appetizer and for taking part in several foodstuffs and recipes.

Conventional air-drying is a simultaneous heat and mass transfer process accompanied by phase change. It is also a high cost process due to its energy requirement. A pre-treatment such as osmotic dehydration can be employed to reduce the initial water content of the vegetable and as a consequence requiring less air-drying time. Besides reducing the overall drying time, the osmotic dehydration also inhibits enzymatic activity, retains the fruit natural color (without sulfide addition) and helps to retain volatile aromas during the subsequent drying (Pokharkar, Prasad, & Das, 1997).

Osmotic dehydration consists of the immersion of the fruit in a hypertonic aqueous solution leading to loss of water through the cell wall membranes of the fruit and

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Nomenclature

A_i	surface area of phase i (m^2)	X_f	final fruit moisture on wet bases (g_{water}/g)
C_i^j	mass concentration of j in phase i (g/m^3)	<i>Greek letters</i>	
D	effective diffusivity (m^2/h)	α	shrinking factor of the fruit
H	moisture content (g_{water}/g)	β	resistance parameter
K_m	effective mass transfer coefficient ($1/h m^2$)	δ	height of the fruit (m)
M	mass (g)	ρ	density (g/m^3)
M_S	mass (dry basis) (g)	<i>Subscripts</i>	
R	drying rate at the constant-rate period ($g/h m^2$)	eq	equilibrium
SG	solid gain (%)	FR	fruit
t	time (h)	OS	osmotic solution
V_i	volume of phase i (m^3)	ODD	osmotic dehydration device
w_i	initial fruit mass (g)	<i>Superscripts</i>	
w_f	final fruit mass (g)	S	solute
WR	water reduction (%)	W	water
WL	water loss (%)		
X_i	initial fruit moisture on wet basis (g_{water}/g)		

subsequent flow along the inter-cellular space before diffusing into the solution (Serenó, Moreira, & Martínez, 2001).

Many articles have addressed osmotic dehydration of several fruits and vegetables using binary systems (water/sugar). In this work, the influence of osmotic solution composition of a ternary system (water/sugar/salt) and the influence of temperature on water removal and on total processing time were investigated for tomato dehydration. The combined process (osmotic dehydration followed by air-drying) was modeled and optimized searching for the operating condition that minimizes total processing time.

Many papers on osmotic dehydration and air-drying of fruits have been published lately (Agnelli, Marani, & Mascheroni, 2005; Alves, Barbosa, Antonio, & Murr, 2005; Babalis & Belessiotis, 2004; Corzo & Gomes, 2004; Demirel & Turhan, 2003; Fito, 1994; Shi, Maguer, Wang, & Liptay, 1997; Shidu, Collins, & Penfield, 1995; Tsamo, Bilame, Ndjouenkeu, & Nono, 2005) but few consider ternary osmotic solution, evaluates and optimizes the combined drying process using a phenomenological model (Fernandes, Rodrigues, Gaspareto, & Oliveira, 2006; Spiazzi & Mascheroni, 1997; Yao & Le Maguer, 1996).

2. Materials and methods

2.1. Preparation of samples

Tomatoes (*Lycopersicon esculentum* variety industrial long life) were bought from the producer (Natal, Brazil). First, the tomatoes were washed with water and then cut to obtain triangles of 0.04 m in height and 0.05 m in width (average values). The tomatoes were cut in half obtaining a dome and then each half was cut in four equal parts obtaining a triangular shaped sample. The initial moisture content was determined by direct heating in a drying oven at

105 °C for 48 h according to AOAC method 931.04 (AOAC, 1990). The initial concentration of solute (°Brix) was determined by refractometry.

In the experiments which skinless tomatoes were investigated whole tomatoes were immersed for 1 min in boiling NaOH solution (3% w/w), rinsed with water at ambient temperature and the skin had peeled off.

The osmotic solution used in each experiment was prepared mixing food grade sucrose and food grade marine salt with distilled water. The osmotic solution to fruit weight ratio was kept at 4:1, because previous studies showed that the osmotic dehydration process should run under an osmotic solution to fruit weight ratio of at least 4:1 to maintain the operating conditions constant and to avoid excessive dilution of the osmotic solution (Fernandes et al., 2006; Teles et al., 2006). Excessive dilution of the osmotic solution can lead to decreasing mass transfer coefficient throughout the experiment and longer processing periods. Each experimental group was randomly formed by 50 samples. Experiments were done in triplicate.

2.2. Osmotic dehydration

Two sets of experiments were carried out, one to search for the best operating conditions (optimal salt and sucrose content of the osmotic solution) and one to study the osmotic dehydration dynamics and the influence of temperature on the osmotic dehydration at the best operating conditions.

In the set of experiments carried out to search for the best operating conditions, the sugar and salt content of each run were set following a 2^2 experimental planning shown in Table 1. All runs of this set of experiments were carried out at 30 °C. A 2^2 experimental planning was used because the relationship of sugar and salt concentrations in

Table 1
Experimental planning used to search for the best osmotic solution

Run	Temperature (°C)	Sugar (w/w %)	Salt (w/w %)
1	30.0	25	5
2	30.0	25	10
3	30.0	35	5
4	30.0	35	10

practically linear on water removal and solid gain when sugar concentrations between 0% and 40% (w/w) and salt concentrations between 0% to 10% (w/w) are used. Sugar concentrations over 40%, especially over 50% will generate a non-linear relationship between sugar and salt concentration on water removal and salt concentration (Heredia, Barrera, & Andrés, 2006; Rodrigues & Fernandes, 2007; Souza, 2002).

Each experimental group was immersed in the osmotic solution during a period of 0.5, 1, 2, 3 h (conditions are presented in Table 1). The osmotic dehydration was carried out in separate 0.5 L perforated baskets immersed in a 4 L osmotic dehydration apparatus to avoid interference among the samples. The osmotic dehydration apparatus was cylindrical and had a height to total diameter ratio equal to unit. Experiments were performed under constant mechanical agitation (150 rpm) to maintain a uniform temperature and concentration throughout the experiment. Agitation was provided by a four blade impeller with blades at a 45° angle and a total diameter to impeller diameter equal to 3. With the current apparatus configuration and level of agitation the external resistance of mass transfer can be assumed negligible with regard to the internal resistance. The process temperature was controlled using a thermocouple and a heating plate.

After removal from the solution, the dehydrated samples were drained to remove the excess solution. Weight and moisture content were measured individually. The concentration of the solution was monitored during the runs determining the osmotic solution soluble solids content (°Brix) using a refractometer.

Weight and moisture content of the samples were used to calculate the response variables of the experimental planning: weight reduction (WR), water loss (WL) and solid gain (SG), according to the following equations:

$$WR (\%) = \frac{w_i - w_f}{w_i} \cdot 100 \quad (1)$$

$$WL (\%) = \frac{(w_i \cdot X_i - w_f \cdot X_f)}{w_i} \cdot 100 \quad (2)$$

$$SG (\%) = \frac{[w_f \cdot (1 - X_f) - w_i \cdot (1 - X_i)]}{w_i} \cdot 100 \quad (3)$$

In the set of experiments carried out to study the dynamics of the osmotic dehydration process and the effect of temperature, the samples were kept in the osmotic solution for a period of 0.5, 1.0, 1.5, 2.0 and 3.0 h. Four levels of temperature between 30 and 60 °C were studied. The operating conditions for this set of experiments are presented in Table 2.

Table 2
Operating conditions used in the dynamic studies

Run	Temperature (°C)	Sugar (w/w %)	Salt (w/w %)
<i>Tomatoes with skin</i>			
1	30.0	35	5
2	40.0	35	5
3	50.0	35	5
4	60.0	35	5
<i>Tomatoes without skin</i>			
5	30.0	35	5
6	40.0	35	5
7	50.0	35	5
8	60.0	35	5

2.3. Air-drying

After removal from the osmotic solution, the dehydrated samples were drained to remove the solution in excess and transferred to a fixed bed dryer. The air moisture content was determined by psychrometry methods (dry and wet bulb temperature).

The fixed bed air-dryer used in the experiments was built of wood and covered with aluminum foil measuring 1.3 m in height and 0.34 m in width and length. Heated air was injected at the base of the dryer through a 4.0 CV blower at an average superficial velocity of 0.087 m/s. Air was heated by electrical resistances (250, 500 and 1000 W) that can be turn on simultaneously or individually to control air temperature (Fig. 1).

Air-drying was carried out at 60 °C, condition which the diffusion coefficient is high and does not compromise the quality of the product (Pena, 1999). Each group sample was set in one dryer shelf and kept drying for 8 h. Every 30 min the samples were weighed to calculate the moisture content by mass balance.

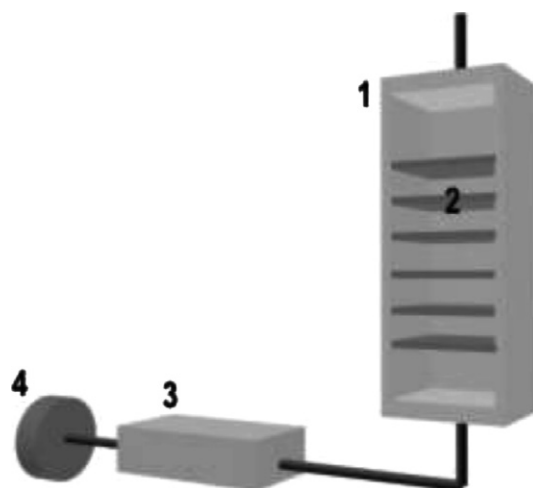


Fig. 1. Experimental setup for air-drying: (1) fixed bed dryer; (2) shelves with the samples; (3) heating box and (4) blower.

3. Mathematical model

Mathematical models of the osmotic dehydration and of the air-drying process were developed to enable the optimization of the combined operation searching for the minimum processing time. The model developed for the osmotic dehydration process considered the mass transfer between the fruit and the osmotic solution (water, sucrose and salt).

The mass balance for the fruit considered the loss of water from the fruit to the osmotic solution and the mass transfer of sugar and salt from the osmotic solution to the fruit. The β parameter introduced in Eq. (5) accounts for the saturation of the surface of the sample with soluble solids that can increase the local concentration of soluble solids. High β parameter values indicate that the surface of the sample is saturated rapidly and that the osmotic pressure equilibrium is also achieved more rapidly.

$$\frac{dM_{FR}^W}{dt} = -K_m^W A_{FR} (C_{FR}^W - C_{OS}^W) V_{FR} \quad (4)$$

$$\frac{dM_{FR}^S}{dt} = -K_m^S A_{FR} \cdot (C_{FR}^S \beta - C_{OS}^S) V_{FR} \quad (5)$$

During osmotic dehydration the fruit presents a considerable shrinkage, which needs to be considered by the mathematical model to better represent the process and to increase the confidence of the mass transfer coefficients. In the model the shrinkage effect was set to be proportional to the water mass change in the fruit, according to Eq. (6). For tomatoes, the estimated shrinkage factor was 0.82, obtained by the volume decrease during the experiments. The fruit superficial area was assumed to decrease at a proportional rate following the decrease in volume of the sample. This proportionality showed to be a good approximation of the phenomena (Fernandes et al., 2006).

$$\frac{dV_{FR}}{dt} = \alpha \frac{dM_{FR}^W}{dt} \quad (6)$$

The mass balance for the osmotic solution included the gain of water that is removed from the fruit and the loss of sugar and salt to the fruit. As the material balances were based on mass balances the amount of water leaving the fruit is equal to the amount of water entering the osmotic solution. The opposite occurs with the mass balance of sugar and salt, where the amount of solids entering the fruit is equal to the amount of solids leaving the osmotic solution.

$$\frac{dM_{OS}^W}{dt} = -\frac{dM_{FR}^W}{dt} \quad (7)$$

$$\frac{dM_{OS}^S}{dt} = -\frac{dM_{FR}^S}{dt} \quad (8)$$

$$\frac{dV_{OS}}{dt} = \frac{1}{\rho^W} \cdot \frac{dM_{FR}^W}{dt} \quad (9)$$

The model for the air-drying process follows the traditional equations for drying, considering the constant-rate period and the falling-rate period. The equation for the

falling-rate period is a simplification of Fick's second law considering a long processing period (Perry & Green, 1999). During the experiments where the osmotic dehydration was used as pre-treatment, the moisture content of the fruit after dehydration was always lower than the transition point between the constant-rate period to the falling-rate period and only Eq. (11) was used. Eq. (10) was used solely to calculate the initial stage of the air-drying process without osmotic dehydration pre-treatment.

$$\frac{dH}{dt} = -\frac{RA_{FR}}{M_S} \quad (10)$$

$$\frac{dH}{dt} = -\frac{\pi^2}{4\delta^2} D(H-H_{eq}) \quad (11)$$

Experimental data were used to estimate the effective mass transfer coefficients of the osmotic dehydration process and the effective diffusion coefficient of the air-drying process. The parameters of the models were adjusted using a parameter estimation procedure that was built in FORTRAN, which was based on the minimization of the sum of squared errors. The mathematical model equations were solved by numerical integration using the Runge–Kutta method. The *F*-test was used as a criterion to validate the model where the level of significance of the model was established comparing the listed *F*-values and the calculated *F*-values for each operating condition.

3.1. Process optimization

Once the model was validated it was used to optimize the total processing time to dry the fruit by osmotic dehydration followed by air-drying. The optimization was done using the method of Levenberg–Marquardt and a computer program was built in FORTRAN using the minimization of the total processing time as objective function. The optimization was carried out within the limits of temperature studied herein (30–60 °C).

The drying process considered herein comprehends the osmotic dehydration process followed by air-drying. Total processing time can be optimized to reduce the drying process to a minimum, which can reduce cost and increase overall productivity. The osmotic dehydration should be used while the water loss rate is higher than the water removal rate that would be obtained with the air-drying process. When the water loss rate in the osmotic dehydration becomes lower than the rate that would be obtained in the air-drying process, the fruit should be transferred from the osmotic dehydration to the air-drying equipment, where the fruit stays till the final moisture content is achieved (Fig. 2).

4. Results and discussion

4.1. Search for the best osmotic solution composition

The results obtained for the osmotic dehydration carried out according to the experimental planning showed in

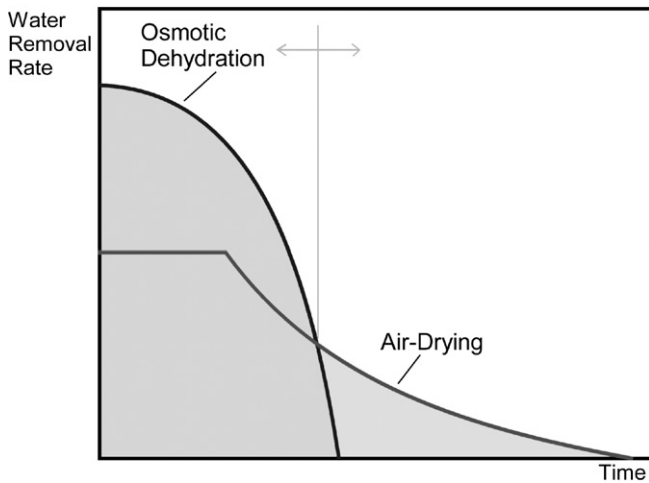


Fig. 2. Illustrative scheme of the water removal rate in osmotic dehydration and air-drying and the optimum time to change from osmotic dehydration to air-drying.

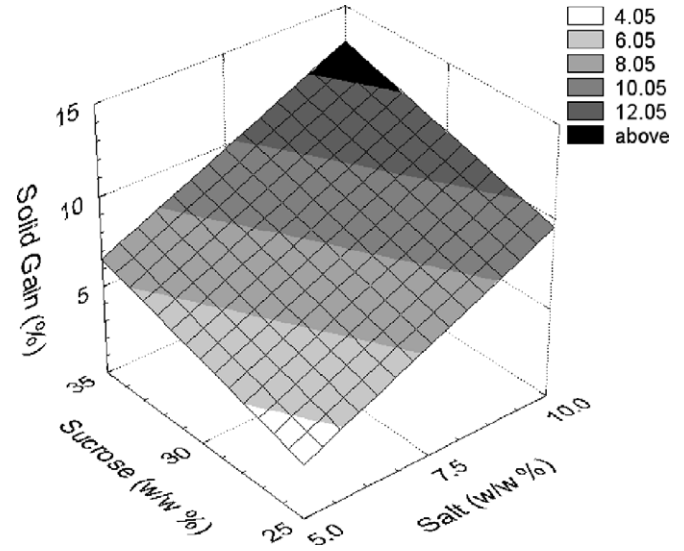


Fig. 4. Solid gain as a function of sucrose and salt concentration.

Table 1 are presented in Figs. 3 and 4. Analysis of variance of the regression models are presented in Table 3 and the analysis of perturbation caused by factors are presented in Table 4. All statistical analysis was performed at a level of confidence of 95%.

Water loss was favored by increasing concentrations of salt and sucrose and the analysis of perturbation of factor (Table 4) showed that the main factor that contributed for water loss was sucrose concentration. The addition of sucrose into the osmotic solution increased considerably the water mass transfer from the fruit to the osmotic solution, leading to significant increase of water loss. The water loss resulting when using an osmotic solution consisting of 25% w/w of sucrose and 5% w/w of salt is 14.0% (for 2 h of osmotic dehydration), while with 35% w/w of sucrose and same salt content is 23.7% (69.2% more) (Fig. 3). The effect of salt addition was slight since when immersing the tomatoes in an osmotic solution consisting of 35% w/w of

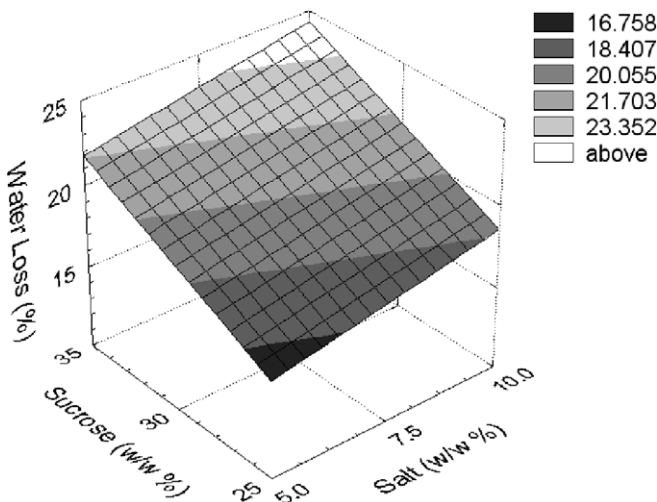


Fig. 3. Water loss as a function of sucrose and salt concentration.

Table 3
Analysis of variance for weight reduction, water loss and sugar gain

Source of variation	Sum of squares	Degrees of freedom	Mean square	F-value
<i>Weight reduction</i>				
Regression	64.66	2	32.33	14.03
Residual	11.52	5	2.30	
Total	76.18			$F_{2,5} = 5.79$
<i>Water loss</i>				
Regression	80.80	2	40.40	6.64
Residual	30.42	5	6.08	
Total	111.22			$F_{2,5} = 5.79$
<i>Sugar gain</i>				
Regression	109.00	2	54.50	112.60
Residual	2.42	5	0.48	
Total	111.42			$F_{2,5} = 5.79$

Table 4
Analysis of perturbation of response variables (WL, WR and SG) caused by factors

Independent variable	β	SE	B	SE	t(5)	p
<i>Water loss</i>						
Mean	–	–	–1.15	5.914	–0.194	0.853
Salt	0.3487	0.2339	0.52	0.348	1.491	0.196
Sucrose*	0.7778	0.2339	0.58	0.174	3.325	0.020
<i>Solid gain</i>						
Mean*	–	–	–12.2	1.668	–7.313	0.0007
Salt*	0.8708	0.0659	1.30	0.098	13.213	0.0000
Sucrose*	0.4689	0.0659	0.35	0.049	7.115	0.0008
<i>Weight reduction</i>						
Mean	–	–	2.05	3.640	0.563	0.598
Salt*	–0.5185	0.1739	–0.64	0.214	–2.981	0.031
Sucrose*	0.7615	0.1739	0.47	0.107	4.379	0.007

* Significant at 95% of confidence level.

sucrose and 10% w/w of salt the water loss decreases to 22.4%.

The solid gain increased with increasing sucrose and salt concentration. Salt concentration affected significantly the gain of solids whereas sucrose concentration presented only slight influence over solid gain (Fig. 4). This result was also evidenced by the higher value of the β -value for salt showed in Table 4. This means that due to the smaller molecule size, more salt than sucrose enters the fruit. As an outcome, the fruit may present a salty flavor if high salt concentrations are used. During this study, the tomatoes samples were tasted and an osmotic solution with up to 5% w/w of salt was considered to be the maximum amount of salt that can be added to the osmotic solution not to chance the natural taste of the tomatoes.

According to the results presented in Tables 3 and 4 and in Figs. 3 and 4 sucrose concentration is the variable that most affects the studied responses (WR, WL and SG). The regression models for the surface responses are given by Eqs. (12)–(14). The ANOVA analysis shown in Table 3 show that the calculated F -values for all surface responses were higher than the listed F -values, and therefore the regression models are significant at a 95% confidence level.

$$\text{WL (\%)} = -1.15 + 0.58 \text{ Sucrose} + 0.52 \text{ Salt} \quad (12)$$

$$\text{WR (\%)} = 2.05 + 0.47 \text{ Sucrose} - 0.64 \text{ Salt} \quad (13)$$

$$\text{SG (\%)} = -12.2 + 0.35 \text{ Sucrose} + 1.30 \text{ Salt} \quad (14)$$

In an osmotic dehydration process the higher the water loss the better is the dehydration process. However, high solid gain affects the quality and sensory characteristics of the tomatoes. Analyzing the surface responses and how the operating condition affect the response variables (water loss, weight reduction and solid gain) the best operating conditions were found using an osmotic solution consisting of 35% w/w of sucrose and 5% w/w of salt.

4.2. Dynamic studies

The dynamic studies were carried out with the best osmotic solution composition found in the first set of experiments. The mass transfer coefficients observed in the osmotic dehydration were estimated from the experimental and are presented in Table 5.

The validations of the model are presented in Figs. 5 and 6. The model has represented very well the data points as observed in the figures and by the high R^2 values. The F -values for all experiments were above the listed F -values for a 95% level of confidence confirming the validity of the model. Further validation of the model was carried out simulating a run never used during the estimation of the mass transfer coefficient. Fig. 7 shows that response of the model is satisfactory and has fitted accordingly the experimental results ($R^2 = 0.98$, significant at 95% of confidence level based on F -test results).

The mass transfer coefficients for water and solids of the tomatoes without skin were higher than the mass transfer

Table 5

Mass transfer coefficients, water loss and water loss to sugar gain ratio for the osmotic dehydration of tomatoes

Process temperature (°C)	Mass transfer coefficient for water (1/h m ²)	Mass transfer coefficient for solids (1/h m ²)	Resistance parameter	Water loss (%)	Water loss to sugar gain ratio
<i>Tomatoes without skin</i>					
30	298.1	105.2	2.079	43.9	0.193
40	249.9	67.2	1.383	36.3	0.108
50	380.7	71.1	1.140	51.4	0.143
60	570.4	89.3	1.244	54.3	0.161
<i>Tomatoes with skin</i>					
30	220.0	205.9	2.770	31.3	0.079
40	230.0	25.0	0.971	28.4	0.056
50	374.6	63.9	5.281	43.3	0.057
60	421.3	81.3	2.127	48.1	0.048

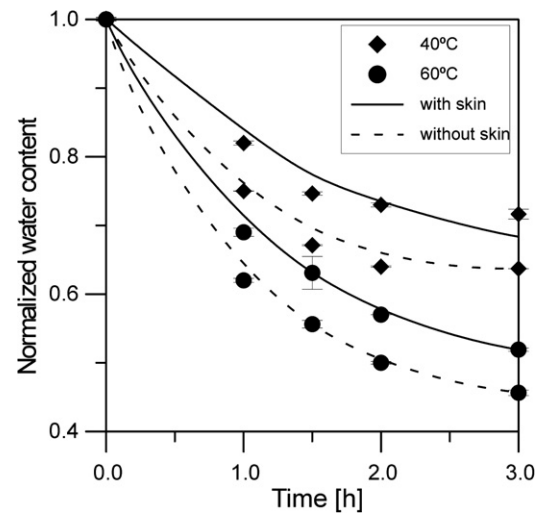


Fig. 5. Normalized water content for tomatoes with and without skin osmo-dehydrated at 40 °C and 60 °C. Regressions R^2 between 0.996 and 0.999; significant within 95% of confidence.

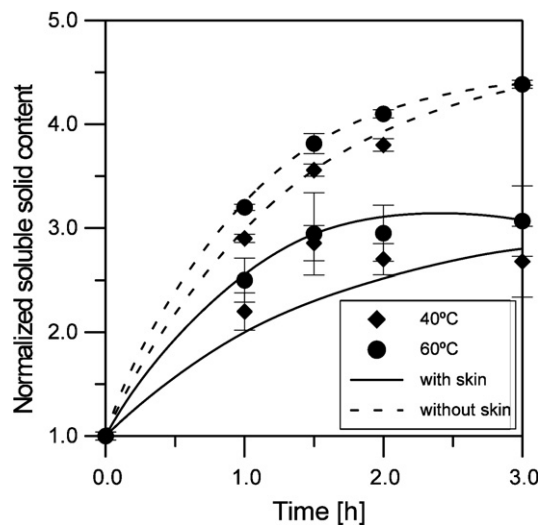


Fig. 6. Normalized soluble solids content for tomatoes with and without skin osmo-dehydrated at 40 °C and 60 °C. Regressions R^2 between = 0.973 and 0.998; significant within 95% of confidence.

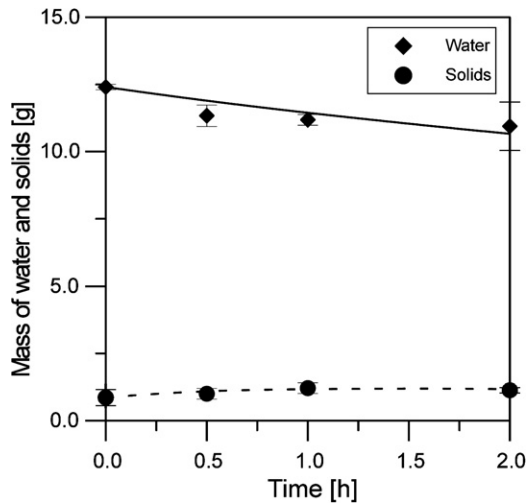


Fig. 7. Mass of water and soluble solids for tomatoes with skin osmotic dehydrated at 30 °C and 25°Brix. Regression $R^2 = 0.98$; significant within 95% of confidence.

coefficients of the tomatoes with skin showing that the tomato skin acts as an additional resistance for water removal from the tomato. High β parameter values indicate that the osmotic pressure equilibrium is achieved more rapidly. After a fast initial period of mass transfer the transfer of water becomes more difficult due to an accumulation of sucrose on the border of the fruit. For skinless tomatoes, the β parameter values were lower than for tomatoes with skin. This may happen because the skin acts as an additional barrier for mass transfer and bigger molecules, such as sucrose, prefer to enter the fruit thru the skinless side saturating this side more rapidly with sucrose causing a decrease in the mass transfer rate.

As expected the temperature had a positive effect on water mass transfer. For tomatoes with skin there was a slight increase (4.5%) on water mass transfer between 30 and 40 °C and a pronounced increase between 40 and 60 °C (83.2%). For tomatoes without skin the increase on water mass transfer was also pronounced between 40 and 60 °C (128.3%). The exception was from 30 and 40 °C where the water mass transfer decreased. Experiments at 30 and 40 °C were carried out for a second time and confirmed the results. At 30 °C the water removal from tomatoes without skin was fast but was also rapidly saturated by sucrose and salt (observed by the high β -value). At 40 °C the saturation of the tomato by sucrose and salt was less pronounced (low β -value) and the fast water removal period was longer than at 30 °C.

From 40 to 60 °C the solid mass transfer increased with increasing temperatures of the osmotic process. At 30 °C the solid mass transfer was very high but was also accompanied by high resistance parameter (β -value). This means that although the tomatoes have gain solids at a fast rate during the initial stages of the osmotic dehydration process, the solids gained are mainly on the surface of the tomatoes and may not have diffused much into the fruit. At higher temperatures the lower resistance parameters

and lower solid mass transfer coefficients indicate that the solids molecules are diffusing into the fruit and are not stopping on the tomato surface blocking solid and water mass transfer.

Water loss (Table 5) was slightly higher when the osmotic dehydration was carried out at 30 °C than at 40 °C (20.9% for tomatoes without skin and 10.2% for tomatoes with skin). This result may indicate that tomatoes may suffer some structural alteration during thermal treatment, changing some of its properties. From 40 to 60 °C, water loss increased 49.6% for tomatoes without skin and 69.4% for tomatoes with skin. As expected, water loss was higher for tomatoes without skin than for tomatoes with skin but the difference decreased with increasing temperature. At 30 °C the difference between the water losses was of 12.6% and at 60 °C the difference was 6.2% indicating that the skin of the tomato is somewhat more affected by temperature which might alter the skin structure.

The water loss to solid gain ratio (Table 5) for tomatoes without skin was higher than for tomatoes with skin. This result was more influenced by the lower water loss than by an increase in solid gain.

Experimental data were used to estimate the water effective diffusivity in the tomatoes during air-drying after the osmotic pre-treatment. The water diffusivity for the drying process without prior pre-treatment was $6.85 \times 10^{-6} \text{ m}^2/\text{h}$ for skinless tomatoes and $2.31 \times 10^{-6} \text{ m}^2/\text{h}$ for tomatoes with skin, showing that the skin reduces the overall water effective diffusivity as expected.

The osmotic dehydration pre-treatment had different effect on the water effective diffusivity of tomatoes with and without skin. In the skinless tomatoes the water diffusivity decreased to $4.23 \times 10^{-6} \text{ m}^2/\text{h}$ (a 38.2% decrease), whereas in the tomatoes with skin the water diffusivity increased 139.9% rising to $5.54 \times 10^{-6} \text{ m}^2/\text{h}$. The temperature used in the osmotic pre-treatment did not influence the diffusivity of water during the air-drying stage.

This result might be explained by two different effects of the transfer of solids from the osmotic solution to the tomatoes. In the skinless tomato sucrose from the osmotic solution has a greater low resistant superficial area to enter into the fruit and will be more uniformly distributed on the entire superficial area. The high solid mass transfer coefficient and the low resistance parameter of the skinless tomato contribute to the formation of a sucrose barrier on the surface of the tomato which can in some cases reduce the effective water diffusivity.

For the tomato with skin, when the fresh tomato is air-dried the moisture content of the fruit will leave preferably by the skinless side which will present a higher water diffusivity than the skin side, as such the tomato with skin will present a lower water diffusivity if compared with the water diffusivity of the skinless tomato. When the osmotic pre-treatment is employed, due to the high osmotic pressure gradient between the fruit and the osmotic solution, sucrose will force its way into the fruit collapsing the cell wall membranes. The effect of the cell wall membrane

collapse is stronger on the hard structures (such as the skin) than on soft structures that already have micro-channels that provide the sucrose molecule with an easier path for diffusion. This effect was shown and proved by Prinivalli, Brambilla, Maffi, Scalzo, and Torreggiani (2006). After 40 min of osmotic dehydration the cell wall membranes start to break, phenomena that increases after 1.5 h of osmotic dehydration (Prinivalli et al., 2006). When the cell wall membranes break the water diffusion within the fruit becomes easier and the effective water diffusivity increases as is observed with the tomatoes with skin. The lower solid mass transfer and the higher resistance parameter of the tomato with skin results in a lower solid gain and as a consequence the sucrose barrier will be less intense and the water effective diffusivity will be higher.

4.3. Process optimization

Table 6 presents the total processing times for the air-drying process operating at 60 °C and for the osmotic dehydration process followed by air-drying operating at 60 °C for all operating conditions employed in the osmotic dehydration experiments. All simulations stopped at the same final fruit moisture content ($0.05 \text{ g}_{\text{water}}/\text{g}_{\text{dry solids}}$). The results show that when a final moisture content of 0.05 g of water per gram of solids is desired, the best option is to submit the tomatoes to air-drying after removal of the skin and that the use of the osmotic dehydration only increases the total processing time. This result shows that not always the osmotic dehydration is an advantage, especially when large amounts of water have to be removed. When the tomato skin is desired the osmotic dehydration becomes interesting since the total processing time reduces from 1203 min to 417 min.

The same behavior was observed when higher final moisture contents are desired. For example, when a final moisture content of 0.20 g of water per gram of solids is desired, the minimal processing time was 287 min obtained with air-drying of skinless tomatoes. And when the tomato

skin is desired the osmotic dehydration still reduces the total processing time (from 850 to 300 min – osmotic dehydration at 60 °C for 62 min).

5. Conclusion

The results showed the advantage of using an osmotic solution consisting of 35% w/w of sucrose and 5% w/w of salt to enhance the water loss from tomatoes and to reduce the gain of solids.

A mathematical model has been developed for the osmotic dehydration process considering the mass transfer between the fruit and the osmotic solution (water, sucrose and salt). The estimated parameters allowed to simulate the drying process and to optimize the system to reduce total processing time.

The results showed that the minimal processing time to dry tomatoes is obtained by removing the tomato skin and submitting the skinless tomato to air-drying. When the tomato skin is desired in the product the osmotic dehydration becomes interesting and its use reduces the total processing time.

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Table 6
Optimum processing times of the final dried product for tomatoes with and without skin

<i>Tomatoes without skin – air-drying</i>	
Total processing time	406 min
<i>Tomatoes with skin – air-drying</i>	
Total processing time	1203 min
<i>Tomatoes without skin – osmotic dehydration followed by air-drying</i>	
Total processing time	473 min
Time in osmotic dehydration	101 min
Time in air-drying	372 min
Osmotic dehydration temperature	60 °C
<i>Tomatoes with skin – osmotic dehydration followed by air-drying</i>	
Total processing time	417 min
Time in osmotic dehydration	64 min
Time in air-drying	353 min
Osmotic dehydration temperature	60 °C

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