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Optimization of osmotic pretreatment of tomato slices using response surface methodology and further hot-air drying

Amanda Umbelina de Souza[1], Jefferson Luiz Gomes Corrêa[1], Ronaldo Elias de Mello Junior[1], Paula Giarolla Silveira[1], Kamilla Soares de Mendonça[2] and João Renato de Jesus Junqueira[3*]

[1]Departamento de Ciência de Alimentos, Universidade Federal de Lavras, Cx. Postal 3037, 37200-000, Lavras, Minas Gerais, Brazil. [2]Departamento de Ciências Agrárias, Instituto Federal de Educação, Ciência e Tecnologia de Minas Gerais, Campus Bambuí, Fazenda Varginha, Bambuí, Minas Gerais, Brazil. [3]Faculdade de Ciências Farmacêuticas, Alimentos e Nutrição, Universidade Federal de Mato Grosso do Sul, Cidade Universitária, Campo Grande, Mato Grosso do Sul, Brazil. *Author for correspondence. E-mail: joao.junqueira@ufms.br

ABSTRACT. Tomato is one of the most cultivated vegetables, playing important role in the human feed. Due to its characteristics and composition, tomatoes present reduced shelf life, and preservative techniques are required. In this study, response surface methodology was used to optimize process conditions during the osmotic dehydration (OD) of tomato slices, through the desirability function. Optimization factors were absolute pressure (21-89 kPa), vacuum application period (7-15 min), and osmotic solution water activity (0.893-0.943), while investigated responses were sodium incorporation (NaI), water loss (WL), solid gain (SG), weight reduction (WR), and osmodehydrated product water activity (ODa_w). The optimized conditions were achieved, and a further hot-air drying (HAD) was conducted at different temperatures and air velocities. During the OD, lower absolute pressure, and osmotic solution water activity led to lower NaI and higher WL and WR. Shorter drying time and higher diffusivity were obtained at higher temperature and air velocity, during the HAD. The dried tomato slices with sodium incorporation reduction were evaluated with regard to the final water activity, rehydration and color, in which no significant differences ($p > 0.05$) were observed between the treatments.

Keywords: pulsed vacuum osmotic dehydration; sodium uptake; central composite design; dried tomato.

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Introduction

The tomato (*Lycopersicon esculentum*) is one of the most important worldwide crops used for human consumption, presenting ascorbic acid, carotenoids, and phenolic compounds, which are related to health benefits (Akter et al., 2019; Tan et al., 2021). Its perishability is associated with high moisture content and water activity, thus preserving techniques are required.

The hot air-drying is a usual preservation technique, producing dried tomatoes, which are appreciated for their sensorial, functional and nutritional properties (Orikasa et al., 2018). Several studies show that pretreatments prior to the hot air-drying assists in the fresh product characteristics maintenance, reduction in the exposure to high temperatures and economic savings (Amami et al., 2017; Cano-Lamadrid et al., 2017; Sampaio et al., 2015).

Among the pretreatments, the osmotic dehydration (OD) can be applied to obtain products with intermediate moisture content and different characteristics, reducing further drying time and contributing to the energy efficiency process (Ramya & Jain, 2017). An intensification on the mass transfer could be achieved with the application of pressure reduction at the OD onset: pulsed vacuum osmotic dehydration (PVOD) (Moreno et al., 2016; Utkucan & Kemal, 2016).

During the OD, the mass transfer countercurrent flow (water from the product to the solution, and solutes from the solution to the product) leads to an incorporation of osmotic agents, which may modify the sensorial and nutritional characteristics (Abrahão & Corrêa, 2021). A synergistic effect when two or more osmotic agents are used has been shown. Sucrose and sodium chloride are the most employed osmotic solutes, due to their low cost, convenience and effectiveness (Ramya & Jain, 2017).

Despite its efficient process, sodium is related to several diseases, and such a reduction (or even substitution) in processed foods is desired (Junqueira et al., 2017a; Taladrid, Laguna, Bartolomé, & Moreno-

Arribas, 2020). Corrêa, Ernesto, and Mendonça (2016) observed a reduction of about 50% in the sodium incorporation (NaI) during the PVOD of tomato slices in ternary solution.

In this sense, the objective of this study was to optimize the osmotic process (aiming sodium incorporation reduction) for obtaining dried tomatoes, evaluating the factors: absolute pressure (AP), vacuum application period (VA) and the osmotic solution water activity (OSa_w). The optimum operating conditions of PVOD were defined with respect to the sodium incorporation (NaI), water loss (WL), solid gain (SG), weight reduction (WR), and osmodehydrated product water activity (ODa_w). In a second step, the optimized condition was carried out prior to the hot air-drying (HAD), and the effects of air temperature and velocity on the drying kinetic, effective diffusivity, rehydration, water activity, and color of the dried tomato were analyzed.

Material and methods

Material

The tomatoes (*Lycopersicon esculentum*) Carmem cv. were purchased in a local market (Lavras, Minas Gerais State, Brazil) and were selected based on appearance, firmness, and size. The seedless fruits were characterized with respect to the proximate composition (AOAC, 2016), water activity (a_w) (Aqualab, 3-TE model, Decagon Devices Inc., Pullman, WA, USA), and color parameters (Minolta, Model CR-400, Osaka, Japan) (Araújo et al., 2020). The results are presented in Table 1.

Table 1. Quality properties of fresh seedless tomato.

Moisture content [g 100 g^{-1}]	94.46 ± 0.32
a_w [-]	0.994 ± 0.003
Lipids [g 100 g^{-1}]	0.03 ± 0.05
Protein [g 100 g^{-1}]	0.50 ± 0.02
Ash [g 100 g^{-1}]	0.02 ± 0.00
L^*	41.77 ± 1.40
a^*	17.59 ± 0.39
b^*	19.05 ± 0.34
C_{ab}	24.49 ± 1.68
°h	45.56 ± 2.13

All data were obtained by quadruplicate analyses and expressed as mean ± standard deviation.

The tomatoes were washed in tap water and halved; the seeds were removed. The fruits were sliced (30.0 mm diameter × 6.87 ± 0.80 mm thick) by using a stainless-steel mold. The tomato skin was maintained, since its removal causes significant nutritional losses, and Heredia, Peinado, Rosa, Andrés, and Escriche (2012) and Souza, Medeiros, Magalhães, Rodrigues, and Fernandes (2007) concluded that the skin removal did not affect the processing time (OD and drying).

Osmotic solution preparation and PVOD

The osmotic solution was prepared with distilled water, sucrose ($C_{12}H_{22}O_{11}$) and sodium chloride (NaCl). The sucrose concentration was adjusted according to the experimental design, based on the osmotic solution water activity (OSa_w). The sodium chloride was maintained constant at 0.05 kg kg^{-1} solution.

The PVOD experiments were performed in a chamber with temperature and pressure control (Biasinox, Lambari, Brazil). The total PVOD time was 120 min., the temperature was set at 30.0°C and the fruit:solution ratio was 1:10 (w/w). The absolute pressure (AP) and the vacuum application time (VA) were defined according to the experimental design.

Experimental design

The experimental design was defined according to a Central Composite Rotational Design (CCRD) (Table 2), with 3 repetitions at the central point, 6 axial points and a complete factorial 2^3, totalizing 17 runs.

Statistical models were obtained by using the Statistica 8.0® software (Statsoft Inc., Tulsa, USA). The resulting experimental data obtained from the factorial design were fitted into a second-order equation (Equation 1):

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum \sum_{ij}^{k} \beta_{ij} x_i x_j \quad (1)$$

where Y is the predicted value for response variable (NaI, WL, SG, WR and ODa_w), AP, VA, and OSa_w are independent variables; β_i is the linear adjustable constant; β_{ii} is the quadratic adjustable constant, and β_{ij} is the interaction adjustable constant.

The ANOVA statistical test was developed with a confidence level of 95%, which includes the statistical significance of each term of the adjustable model (p-value), the estimated effects in each term (β_i) and the correlation coefficient (R^2). The complete models were used to predict the best PVOD condition.

Table 2. Experimental conditions for pulsed vacuum osmotic dehydration of tomatoes determined by central composite rotational design with the variable responses.

Test	AP (X_1) [kPa]	VA (X_2) [min.]	OSa_w (X_3) [-]	NaI [g kg^{-1}]	WL [%]	WR [%]
1	35 (-1)	7 (-1)	0.903 (-1)	0.034	29.62	22.9
2	35 (-1)	7 (-1)	0.932 (+1)	0.056	20.48	13.1
3	35 (-1)	13 (+1)	0.903 (-1)	0.036	28.02	22.4
4	35 (-1)	13 (+1)	0.932 (+1)	0.072	20.99	14.6
5	75 (+1)	7 (-1)	0.903 (-1)	0.042	28.24	22.8
6	75 (+1)	7 (-1)	0.932 (+1)	0.077	24.79	15.5
7	75 (+1)	13 (+1)	0.903 (-1)	0.045	31.84	26.7
8	75 (+1)	13 (+1)	0.932 (+1)	0.074	24.91	19.9
9	21 (-1.68)	10 (0)	0.918 (0)	0.044	23.81	17.8
10	89 (+1.68)	10 (0)	0.918 (0)	0.053	26.91	21.5
11	55 (0)	5 (-1.68)	0.918 (0)	0.056	27.79	22.5
12	55 (0)	15 (+1.68)	0.918 (0)	0.052	28.12	21.8
13	55 (0)	10 (0)	0.893 (-1.68)	0.041	28.14	23.5
14	55 (0)	10 (0)	0.943 (+1.68)	0.104	18.83	13.8
15	55 (0)	10 (0)	0.918 (0)	0.056	26.54	22.7
16	55 (0)	10 (0)	0.918 (0)	0.052	26.96	20.5
17	55 (0)	10 (0)	0.918 (0)	0.054	27.98	22.6

Optimization

Simultaneous response optimization was developed according to the methodology proposed by Derringer and Suich (1980). It was also performed by the Statistica 8.0® software (Statsoft Inc., Tulsa, USA), to obtain an optimum solution for each experimental design, minimizing NaI and maximizing WL and WR, combined into an overall composite function (the desirability function – D(x)), Equation 2

$$D = \left(d_1 \times d_2 \times d_3 \times \ldots \times d_n\right)^{1/n} \tag{2}$$

where D is the global desirability value and d_i are the responses.

Mass transfer parameters

Water loss (WL), solid gain (SG) and weight reduction (WR) were calculated in accordance with Equations. 3, 4, and 5, respectively

$$WL = \frac{\left(M_0 X_{w0}\right) - \left(M_t X_{wt}\right)}{M_0} \times 100 \tag{3}$$

$$SG = \frac{\left(M_t X_{st}\right) - M_0\left(1 - X_{w0}\right)}{M_0} \times 100 \tag{4}$$

$$WR = \frac{M_0 - M_t}{M_0} \times 100 \tag{5}$$

where X_{w0} is the initial moisture content (on wet basis) [kg water kg^{-1}], X_{wt} and X_{st} are the water and soluble solids content, respectively, at any time, and M_0 and M_t are the initial and final sample mass [kg], respectively.

Hot-air drying (HAD)

The optimized PVOD condition was employed as a pretreatment before the hot air-drying (HAD). The equipment was a tunnel dryer (Eco Engenharia Educacional, MD018 model, Brazil), with the tested air temperatures of 50 and 70°C, and the air velocities of 0.5 and 1.5 m s^{-1}.

In each batch, 0.100 ± 0.006 kg of osmodehydrated tomato was dried. The final moisture content was set at 0.15 ± 0.01 [kg H_20 kg^{-1} dry basis (d.b.)]. The sample mass was monitored during the drying, using a digital balance (Marte Cientifica, AD33000 model, Brazil). The drying experiments were carried out in triplicate.

Drying kinetic

During the HAD, the moisture was recorded, and the moisture ratio (MR) was calculated according to Equation. 6.

$$MR = \frac{X_t - X_e}{X_0 - X_e} \approx \frac{X_t}{X_0} \quad (6)$$

where MR is the moisture ratio [dimensionless], X_t is the moisture content at a specific time [kg water kg^{-1}], X_0 is the initial moisture content [kg water kg^{-1}]. The X_e is the moisture content in equilibrium conditions [kg water kg^{-1}] in which the value is much lower than X_t and X_0. Therefore, its value was neglected (Faruq, Zhang & Fan, 2019; Macedo, Silva Araújo, Vimercati, Saraiva, & Teixeira, 2021).

Based on Fick's second law, the analytical solution of the unidirectional unsteady state diffusion equation is given by Equation. 7:

$$MR = \left(\frac{8}{\pi^2} \sum_{i=0}^{\infty} \frac{1}{(2i+1)^2} \exp\left(-(2i+1)^2 \pi^2 D_{eff} \frac{t}{4L^2} \right) \right) \quad (7)$$

where D_{eff} is the effective diffusivity [m^2 s^{-1}], t is the time [s], and L is the characteristic length (half of the thickness) [m].

Uniform initial moisture content, concentration symmetry, and the equilibrium content at the surface, are the initial and boundary conditions (Crank, 1975).

The D_{eff} were obtained by using the software Statistica 8.0 (Statsoft Inc., Tulsa, USA), with equation parameters estimated using a non-linear regression procedure. In order to evaluate the goodness of fit, the higher adjusted correlation coefficient (R^2) and the lower sum square error (SSE) were considered.

Quality analysis

Quality analyses were performed using osmodehydrated and/or dried tomatoes. The analyses were performed in at least three repetitions.

Moisture content and a_w

The moisture content of the fruits was determined using a drying oven (SL104/40; Solab, Piracicaba, Brazil) until constant weight (AOAC, 2016). The a_w was determined at 25°C using an electronic hygrometer (Aqualab, 3-TE model; Decagon Devices, Inc., Pullman, WA, USA).

Sodium quantification

For the sodium quantification, the osmodehydrated tomato slices were dried at 70°C for 24h. The dried samples were mashed, and the powder material was subjected to nitric-perchloric acid digestion. The sodium content was determined by atomic emission spectrometry (Malavolta, Vitti, & Oliveira, 1997). The NaI was obtained from the ratio of the sodium content in the osmodehydrated samples and the sodium content in fresh samples.

Color parameters

The color of the dried tomato samples was determined by measurement with the colorimeter equipment (Minolta Camera CO., model CR 400, Osaka, Japan). The device uses the CIElab scale to measure L^* (black to white), a^* (green to red) and b^* (blue to yellow) parameters. The color parameters were used to calculate the chroma (C_{ab}) and the hue angle (°h), according to Equations 8 and 9 (Purkayastha, Nath, Deka, & Mahanta, 2013).

$$C_{ab} = \sqrt{a^2 + b^2} \quad (8)$$

$$^{\circ}h = \tan^{-1}\left(b/a \right) \quad (9)$$

Rehydration ratio (RR)

The rehydration of the dried tomato slices was evaluated at 25°C. Approximately 5 g of sample was placed in 100 mL of distilled water. The samples were weighed for 20, 30, 40, and 50 min. and the RR was obtained from the ratio between the rehydrated weight sample [kg] and the dried weight sample [kg] (Doymaz & Özdemir, 2014).

Statistical analysis

The results were analyzed by one-way analysis of variance (ANOVA) at the 95% probability level, using the software Statistica 8.0® (Statsoft Inc., Tulsa, USA). In the case of significant effects ($p \leqslant 0.05$) the means were compared using Tukey's test.

Results and discussion

PVOD

Table 3 shows the effects of independent variables on water NaI, WL, and WR of osmodehydrated tomatoes. The results indicated a linear effect between AP and OS_{aw} as well as the quadratic effect of OS_{aw} significantly affected the all the independent variables ($p < 0.05$).

According to the Table 3, it is possible to notice that the independent variables have higher effects on WL than in NaI. The variable with higher influence is OSa_w. The lower the OSa_w, the higher the WL and the lower the NaI. The OSa_w decrease indicates higher osmotic pressure gradient between the food and the solution, increasing the WL.

As the concentration of sodium chlorine was maintained constant, OSa_w increase means higher the rate NaCl/sucrose, i.e., higher sodium availability. The second and the third influencer variable is AP and VA, respectively. The use of vacuum (lower AP) for some minutes in the beginning of the osmotic dehydration is expected to: increase the contact between the solution and the food in the food inner; and increase the transfers between the phases. In the present work, lower AP did not increase NaI.

Table 3. Analysis of the main effects for the factors absolute pressure (AP), vacuum application period (VA) and osmotic solution water activity (OSa_w) on the responses sodium incorporation (NaI), water loss (WL), weight reduction (WR), and osmodehydrated from the central composite design for the osmotic pretreatment of tomato slices.

Variables	NaI				WL				WR			
	Effect	Stand. error	t(7)	p-value	Effect	Stand. error	t(7)	p-value	Effect	Stand. error	t(7)	p-value
Average	0.054	0.003	18.566	<0.001[a]	27.228	0.619	43.973	<0.001[a]	22.044	0.877	25.125	<0.001[a]
AP (L)	0.008	0.003	2.973	0.021[a]	2.293	0.579	3.963	0.005[a]	2.628	0.820	3.205	0.015[a]
AP (Q)	-0.005	0.003	-1.754	0.123	-1.061	0.630	-1.683	0.136	-1.776	0.893	-1.989	0.087
VA (L)	0.002	0.003	0.606	0.564	0.474	0.583	0.813	0.443	1.192	0.827	1.442	0.193
VA (Q)	-0.001	0.003	-0.477	0.648	0.772	0.652	1.184	0.275	-0.056	0.923	-0.061	0.953
OS_{aw} (L)	0.033	0.003	12.252	<0.001[a]	-6.049	0.575	-10.519	<0.001[a]	-6.867	0.815	-8.427	<0.001[a]
OS_{aw} (Q)	0.011	0.003	3.932	0.006[a]	-2.278	0.615	-3.707	0.008[a]	-2.361	0.871	-2.711	0.030[a]
AP (L) by VA (L)	-0.005	0.004	-1.273	0.244	1.203	0.759	1.584	0.157	1.825	1.076	1.697	0.134
AP (L) by OS_{aw} (L)	0.001	0.004	0.405	0.697	1.435	0.759	1.890	0.101	0.863	1.075	0.802	0.449
VL (L) by OS_{aw} (L)	0.002	0.004	0.538	0.607	-0.349	0.759	-0.460	0.660	0.586	1.075	0.545	0.603

[a]Statistically significant with 90% of confidence ($p < 0.05$).

In a ternary solution of NaCl and a large carbohydrate molecule osmotic dehydration, the use of vacuum makes greater the incorporation of the large molecule instead of the ion dissociated salt (Corrêa et al., 2016). As pointed, it was expected that the vacuum use (lower AP) would increase the WL and the WR, but it was not observed. Other works showed that the vacuum use does not always increase the transfers between the phases (Viana, Corrêa, & Justus, 2014).

The polynomial model was obtained and is present in the Table 4. The NaI values ranged from 0.034 to 0.104 g sodium kg^{-1} osmodehydrated sample (d.b.). Lower AP and OSa_w favored an increase in the NaI (Figure 1 and

Table 4). Such a result corroborates Corrêa et al. (2016), which observed that vacuum pulse could reduce the sodium incorporation in osmodehydrated tomato slices.

On the other hand, according to Table 4, the reduced pressure did not favor the WL and the WR, while a decrease in the OSa_w favored it. The WL ranged from 18.83 to 31.84% and the WR ranged from 13.10 to 26.70% (Table 2). The NaCl concentration was constant in all treatments, and the higher OSa_w leads to lower WL and WR, once the chemical gradient potential amid the solution and the fruit is reduced (Derossi, Severini, Del Mastro, & De Pilli, 2015; Junqueira et al., 2017a).

Table 4. Real model for the sodium incorporation, water loss and weight reduction in osmodehydrated tomatoes.

Variable	Model	R^2	Fcal	p-value
NaI	$21.801-0.001(AP)-6.431\times10^{-6}(AP)^2-0.016(VA)-8.038\times10^{-5}(VA)^2-48.317(OSa_w)+26.754(OSa_w)^2-3.750\times10^{-5}(AP\times VA)+0.002(AP\times OSa_w)+0.022(VA\times OSa_w)$	0.965	21.196	<0.001
WL	$-4252.561-2.116(AP)-0.001(AP)^2+2.349(VA)+0.043(VA)^2-9637.808(OSa_w)-5418.176(OSa_w)^2+0.010(AP\times VA)+2.473(AP\times OSa_w)-4.009(VA\times OSa_w)$	0.957	17.416	0.001
WR	$-4354.582-1.207(AP)-0.002(AP)^2-6.755(VA)-0.003(VA)^2+9917.025(OSa_w)-5614.718(OSa_w)^2+0.015(AP\times VA)+1.488(AP\times OSa_w)+6.735(VA\times OSa_w)$	0.934	10.949	0.002

The regression coefficient in featured indicates statistically significant effects ($p < 0.05$).

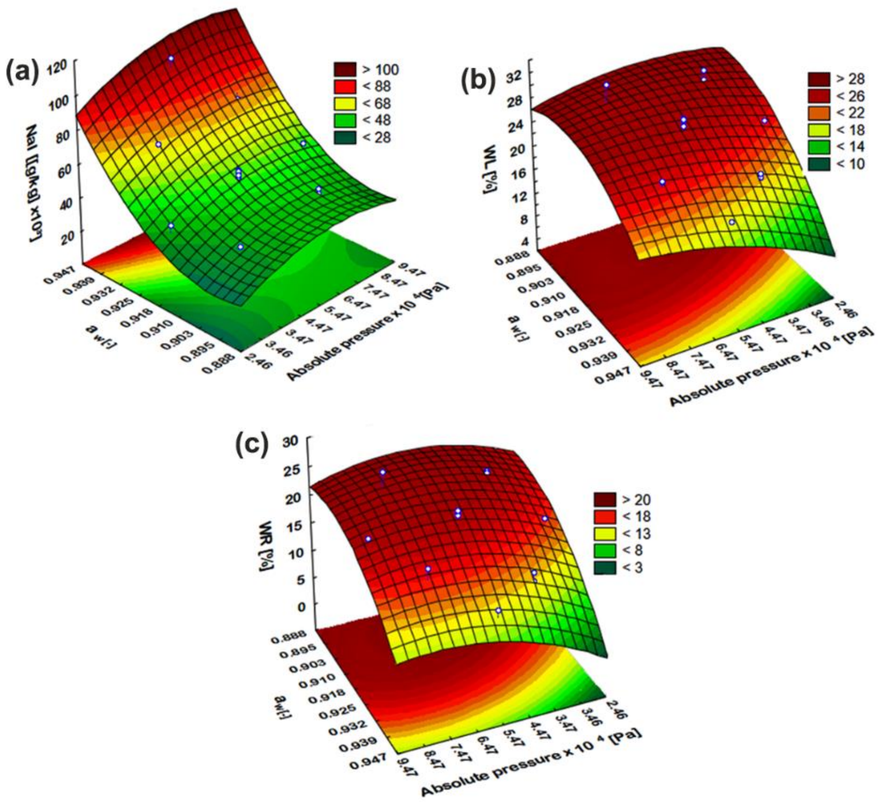

Figure 1. Response surfaces for Sodium Incorporation [g kg^{-1}] × 10^3 (a), Water Loss [%] (b), and Weight Reduction [%] (c) as a function of absolute pressure of system [Pa] and water activity of ternary solution of sucrose and sodium chloride [-].

No statistical difference was shown for SG and ODa_w, and the mean values were 5.72 ± 0.85% and 0.961 ± 0.004, respectively.

The AP reduction during osmotic processes, promotes the removal of internal gases in the intercellular gaps. After the restoration of atmospheric pressure, the tissue (pores) is filled with osmotic solution. Usually, this process enhances the mass transfer parameters, due to the extension of contact surface (Abalos, Naef, Aviles, & Gómez, 2020; Oliveira, Corrêa, Silveira, Vilela, & Junqueira, 2021).

Souza et al. (2007) studied the OD of tomatoes using ternary solutions (water + sucrose + sodium chloride), and observed that an increase in the osmotic solution concentration led to an increase in the incorporation of solids. Moreover, those authors worked with a NaCl concentration variable, and concluded that the influence of NaCl was higher than that of the sucrose, mainly due to the ionic characteristics (easing the penetration into the tissues).

According to Table 4, the VA had no significant influence on the obtained responses. During the PVOD of pineapple, Ramallo and Mascheroni (2013), did not observe a relation amid the VA and mass transfer parameters. Junqueira, Corrêa, Mendonça, Mello Júnior, and Souza, (2018) evaluated the PVOD of beetroot, carrot and eggplant slices, and observed that some vegetables (with porous structure) are more sensitive to the VA, favoring the WL and SG. Similar reports were observed by Ferrari, Arballo, Mascheroni, and Hubinger (2011) and Corrêa, Pereira, Vieira, and Hubinger (2010), during the PVOD of melon and guavas, respectively. Such difference is related to the food structure.

The second-order polynomial equation was fitted to the experimental data (Table 4), as shown by the response surfaces (Figure 1), and the linear coefficients of AP, and the linear and quadratic coefficients of OSa_w were significant ($p < 0.05$) for NaI, WL and WR. There was no significant difference ($p \geqslant 0.05$) in the other quadratic terms and the interaction between them. The ANOVA indicates the equation suitability ($R^2 > 0.94$), for the evaluated responses.

Even though the quadratic coefficient of AP was significant ($p < 0.05$) for the SG, a lack of adjustment was observed ($F_{tab} > F_{calc}$, and $R^2 < 0.70$). None of the terms were significant for the OD_{aw}. Therefore, such results were not presented, and the optimization was conducted in order to reduce the NaI (desirability closer to 0) and to maximize the WL and WR (desirability closer to 1).

The optimized conditions were: AP = 85 kPa; VA = 15 min., and OSa_w = 0.903. The remaining process time (105 min.) was conducted at atmospheric pressure (101.3 kPa). The ternary osmotic solution was composed of sodium chloride (0.05 kg kg^{-1} solution) and sucrose (0.42 kg kg^{-1} solution). The overall desirability was 0.99.

Hot-air drying

The Figure 2 presents the drying curves of osmodehydrated samples (prepared under optimized conditions). The moisture content of 0.15 ± 0.01 kg H_20 kg^{-1} d.m. was reached in period ranging from 323 ± 14 min. (70°C; 1.5 m s^{-1}) to 847 ± 15 min. (50°C; 0.5 m s^{-1}). As expected, higher temperature and air velocities enhance the drying rates, reducing the process time, by increasing the internal and external mass transfer, respectively (Pavkov et al., 2021; Singh & Talukdar, 2019). At 1.5 m s^{-1}, the drying process was reduced by about 45-48%, compared with the air velocity of 0.5 m s^{-1}.

The effects of higher temperature and air velocity were observed during the drying of bananas (Macedo et al., 2021), figs (Utkucan & Kemal, 2016), apples (Önal, Adiletta, Crescitelli, Di Matteo, & Russo, 2019), potatoes (Singh & Talukdar, 2019) and tomatoes (Doymaz & Özdemir, 2014; Purkayastha et al., 2013; Sampaio et al., 2015).

The D_{eff} values were presented in Table 5, and they ranged from 2.86×10^{-7} to 8.70×10^{-7} m s^{-1}. The R^2 were higher than 0.96, and the SSE lower than 7.29×10^{-3}. The D_{eff} values increased with higher temperatures, due to the vapor pressure enhancement, which favors the moisture diffusion and removal, corroborating the drying behavior presented in Figure 2.

The air velocity also influences the D_{eff} values, increasing the mass flow rate (Bhong & Kale, 2020; Ju et al., 2020; Singh & Talukdar, 2019). Similar reports were obtained by Corrêa, Rasia, Mulet, and Cárcel (2017); Bozkir, Rayman Ergün, Serdar, Metin, and Baysal (2019) and Miraei Ashtiani, Sturm, and Nasirahmadi (2018), during the HAD of pineapple, persimmon and nectarine, respectively.

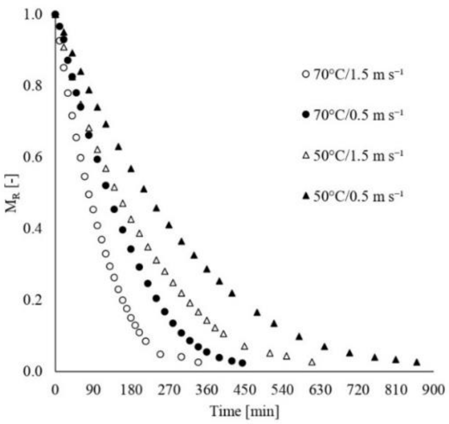

Figure 2. Variation in the MR versus time during the drying of tomato slices.

Table 5. Effective moisture diffusivity (D_{eff}) of the tomato slices during different drying treatments.

Condition	$D_{eff} \times 10^7$ [m² s⁻¹]	R^2	SSE × 10^3
70°C; 1.5 m s^{-1}	8.702	0.972	4.725
70°C; 0.5 m s^{-1}	5.496	0.964	7.291
50°C; 1.5 m s^{-1}	4.580	0.979	3.370
50°C; 0.5 m s^{-1}	2.862	0.968	5.999

Figure 3 presents the rehydration ratio (RR) of the dried tomato slices. This parameter indicates the physical and chemical tissue damages caused by the different treatments (Aral & Bese, 2016). The higher RR values were observed in the first immersion minutes. After the 20 min., an equilibrium was observed, regardless the employed drying treatments.

The fast rehydration during the first minutes are related to the filling of the porous and cavities with water, due to the diffusion and capillarity (Önal et al., 2019). Due to the prolonged process period, some modifications in the structure are released: the sealing of surface (Xu et al., 2020), the sugar caramelization (mainly the absorbed sucrose during the PVOD) (Corrêa et al., 2017), and the structure decompartimentalization (Junqueira et al., 2017b), which implies water penetration difficulty. A similar result was reported by Liu et al. (2019), during the drying of broccoli florets.

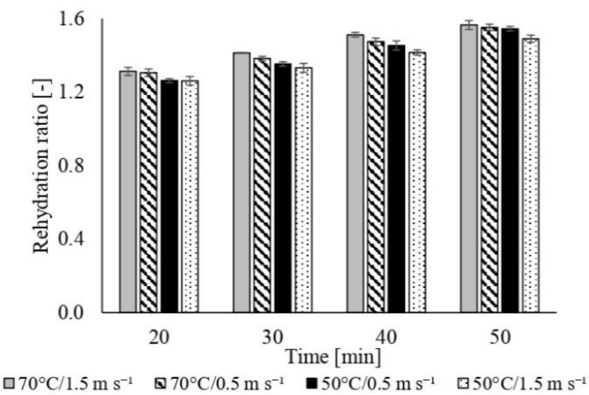

Figure 3. Evolution of rehydration of dried tomato slices.

Table 6 presents the a_w and the color parameters of the dried tomato slices. The a_w was below 0.6, which contributes to the reduction in biochemical and chemical degradative reactions, as well as lipid oxidation, vitamin degradation, nonenzymatic browning and hydrolysis, and controls the microorganism growth and development (Sagrin & Chong, 2013). The treated tomatoes showed significant difference ($p < 0.05$) when compared to fresh tomatoes, however, they did not show any difference with each other. This behavior was expected since the activity values obtained were the target of the study, and were the result of different drying times.

Table 6. Effect of different drying treatments on water activity and color parameters of the dried tomato slices.

Condition	a_w	L^*	C_{ab}	°h
Fresh	0.994 ± 0.003 a	41.77 ± 0.94 a	24.49 ± 1.74 a	37.85 ± 1.62 a
70°C; 1.5 m s^{-1}	0.427 ± 0.019 b	44.39 ± 2.25 a	35.31 ± 0.87 b	34.95 ± 1.78 a
70°C; 0.5 m s^{-1}	0.409 ± 0.041 b	44.49 ± 1.22 a	34.48 ± 3.61 b	37.09 ± 0.54 a
50°C; 1.5 m s^{-1}	0.423 ± 0.014 b	43.40 ± 1.60 a	33.01 ± 1.80 b	35.77 ± 1.53 a
50°C; 0.5 m s^{-1}	0.459 ± 0.052 b	44.11 ± 1.99 a	38.59 ± 1.74 b	37.57 ± 3.06 a

Average value ± standard deviation. Means followed by different letters in the same column indicates a significant difference ($p \leq 0.05$), according to Tukey's test.

The color parameters of the dried tomatoes were not significantly affected by the different treatments (Table 6) ($p > 0.05$). However, it was possible to observe a significant difference in the C_{ab} parameter when compared with fresh tomatoes. This parameter is related to the color intensity, in which the treated tomatoes showed greater intensity than the fresh. This is justified by the concentration of the compounds during the drying process (Vásquez-Parra, Ochoa-Martínez, & Bustos-Parra, 2013). The hue of the tomatoes was not altered with the treatments used, keeping them in a deep red color, which demonstrated color preservation after treatment.

During the HAD of tomato slices, Purkayastha et al. (2013), obtained similar °h values at 50 to 70°C. They concluded that 50°C was the best condition for the best maintenance of the initial color of tomatoes. Furthermore, it suggests that the osmotic pre-treatment in this work corroborates with the attractive red hue of the tomato also at high temperatures due to the protection of the pigments by the solute (Abrahão & Corrêa, 2021).

Conclusion

The OSa_w presented a significant effect on the evaluated variables, followed by AP, promoting higher efficiency on the process. The VA time was not statistically significant under the studied conditions. The desirability index allowed simultaneous evaluation of the results and the optimum conditions, which was defined as: AP = 85 kPa; VA = 15 min., and OSa_w = 0.903. During the HAD of osmodehydrated samples, higher temperature and air velocity led to a reduction in the process time, and higher D_{eff} values.

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