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Mathematical Modeling of Hot-Air Drying of Osmo-dehydrated Nectarines

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Abstract: The influence of osmotic pretreatment on nectarines with solutions of glucose syrup and sorbitol and subsequent dehydration at different temperatures (60 °C, 70 °C, or 80 °C) was evaluated. The kinetics of moisture loss during drying was obtained and mathematical models were adjusted to estimate the kinetic parameters. Effective diffusion coefficients were calculated using Fick's second law. All drying kinetics exhibited only a falling-rate period during hot-air drying owing to moisture loss in the osmotic pretreatment. Moisture loss was favoured by the use of sorbitol, whereas the diffusivity of water increased when glucose was used as an osmotic agent. Logarithmic and Midilli et al. models best described the changes in moisture over time, whereas Fick's second law estimated water diffusion coefficient values between 4.96×10^{-9} and 2.43×10^{-8} m^2 s^{-1}. These models may be employed to predict the optimum conditions for osmo-dehydrating nectarines under hot-air drying at the industrial level.

Keywords: drying kinetics, mathematical modeling, osmotic dehydration, diffusion coefficients, nectarines

1 Introduction

Over the past few years, studies on the dehydration of stone fruits such as plums [1, 2], cherries [3, 4], peaches [5], apricots [6, 7] and nectarines [8–10] have been performed owing to the nutritional properties of these fruits and in the interest of obtaining a long shelf-life with the best possible quality. Fruits such as nectarines have a high moisture content and are susceptible to physical and chemical changes that cause their decomposition. Thus, drying represents a good alternative for increasing the commercial life of such fruits. In addition, because nectarines are seasonal fruits, it becomes important to conserve them over long periods so as to make them available out of season and, in this way, to increase their value.

Hot-air drying (HAD) is a method widely used in fruit and vegetable conservation. HAD extends the shelf-life by removing a certain amount of water, such that chemical reactions of deterioration and microbial development in the dehydrated product are reduced. Additionally, other advantages such as weight and volume reduction are obtained, resulting in a reduction in transportation and food storage costs [11–14]. During drying, several factors affect the performance of the drier and the quality of the product. Physical and chemical changes can cause certain desired characteristics in the products, but they can also decrease the amount of nutrients in the fruit and change their organoleptic properties. However, suitable drying conditions could lead to products with improved nutritional value and extended shelf-life [15, 16].

During HAD, different stages are evidenced depending on product structural characteristics and the ways in which water is contained within. In addition, the process conditions such as product area, temperature, humidity, air velocity, time, influence of vegetal tissue, product load, and the use of pretreatments [17, 18] can have a significant influence on the quality of the final product. Therefore, knowing the water movement during drying and its relation to the process variables is essential for establishing optimal HAD conditions [19–22]. During the initial contact between the food solid and the heating medium, the temperature of the solid increases, thus eliminating superficial moisture. This phase occurs very quickly and, in general, it is not recorded. As the process continues, the solid undergoes a constant loss of moisture, showing linear tendencies, where free water, when it is present, is eliminated by capillarity. In this phase, resistance to heating and mass transfer is controlled by the gaseous phase [16]. As a consequence, the amount of water that moves from the interior of the food does not change with time; this is known as the constant-rate period. This phase ends at a critical moisture content

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[16, 18, 21, 23]. Then, a decrease in the rate of moisture loss occurs, showing linear and/or exponential behaviour until attaining the balance moisture; this is known as the falling-rate period. Here, water is retained or bound to the solid components such that it resists movement from the inside of the interphase; water elimination in the solid is controlled by diffusion mechanisms. Therefore, moisture loss decreases considerably, increasing the drying times in order to achieve stable moisture levels in the product. This phase represents an important part of drying time, and so understanding and predicting this phase becomes relevant for optimizing the drying process in terms of the length of drying time and the consumption of energy [16, 18, 21, 23].

In order to decrease the moisture and reduce the process time and energy consumption [14, 24–26], pretreatments of the solids have been implemented before drying, such as osmotic dehydration (OD) or the use of sugars (sucrose, fructose, glucose, sorbitol, corn syrups) [6, 27], biopolymers (pectin, starch, maltodextrin) [28], or salt [29, 30]. OD allows for the decrease in water activity in the product through mild process conditions. Also, the flavour and colour of the fruit are enhanced with respect to HAD [2, 4, 31–36].

Mathematical modeling of drying processes in solids is complex owing to the high moisture content present in solids such as fruits and vegetables [35] and also because of structural changes that occur during dehydration that promote contraction and shrinkage of the solid's tissue during drying. Mathematical models applied in food dehydration can be classified as theoretical, semi-theoretical, and empirical models [37, 38]. Theoretical models employ simultaneous equations of heat and mass transfer with food properties such as particle geometry, contraction, moisture diffusion coefficient and critical moisture content. The models explain the physical changes that occur during the process, quantifying both external and internal resistances. Mass transfer during solid dehydration can be explained using a fundamental model such as Fick's second law for non-steady-state diffusion in a symmetric solid, assuming this is controlled by diffusion phenomena. Crank [39] has presented solutions for this problem. On the other hand, semi-empirical and empirical models are derived from statistical adjustments, and they provide proper representation of the experimental results of the drying process by describing the moisture content loss as a function of time. However, they do not explain the physical changes that occur during drying. Despite these disadvantages, these models have proven to be practical, although it must be considered that semi-theoretical or empirical models do not usually allow for the simulation of experiments carried out under different conditions in order to identify the model's parameters [11, 14, 35, 40].

Therefore, the objective of the present work was to evaluate the influence of solute type, temperature and solid–liquid ratio in the osmotic pretreatment of nectarines prior to carrying out HAD at different air temperatures on the moisture loss, drying rate, and effective diffusion coefficient. A secondary objective was to develop empirical models to describe the dehydration process under different conditions and to determine the drying constant of the models.

2 Materials and methods

2.1 Sample characterization and preparation

Nectarines of the variety Caldesi (*Prunus persica* var. *nectarina*) were used. These were purchased in a local market (Olavarria, Argentina). The nectarines were stored for 10 days at a temperature of 5 °C and a relative humidity (RH) of 90 % until used. Before the test, samples selected by size and quality were washed and dried with absorbent paper. They were then peeled and the stones were removed. Finally, they were manually cut into 1.59 mm pieces (average weight 3.2 g). The batch was characterized by measuring the initial moisture content (X_0) of the fresh fruit (4.602 ± 0.177 g water g dry solid^{-1}) by using standard method 22.013 of the AOAC [41], the initial content of the soluble solids (14.50 %) as established by standard method 22.024 with an Abbe refractometer (accuracy ± 0.01) [41], and the water activity (0.971 ± 0.009) using an AquaLab water activity meter (model 3TE, Washington, DC, USA) according to the hygrometric method 978.18 [41].

2.2 Hot-air drying

OD was carried out over a 2 h period – the period of high water removal rate [42] – by immersing 200 g sample lots in glucose syrup ($C_6H_{12}O_6$) or sorbitol ($C_6H_{14}O_6$) solutions. These respective solutions were prepared at 40 % and 60 % (w/w) in distilled water from 82 % (w/w) glucose syrup and 67 % (w/w) sorbitol using a 2 L Erlenmeyer flask and fruit/syrup ratios of 1/4 and 1/10. The samples were kept in the solutions by using a stainless steel mesh to prevent flotation. Two temperatures were tested, 25 °C and 40 °C, with constant shaking at 331 rpm (5.5 s^{-1}). All the experiments were conducted in duplicate.

The osmo-dehydrated samples were dried in a laboratory forced convection oven at an air speed of 0.92 ± 0.03 m s^{-1} at temperatures of 60 °C, 70 °C, or 80 °C ± 0.5 °C until reaching levels of water activity lower than 0.750 in order to obtain microbiological stability [43]. During the process, drying kinetics were determined experimentally in duplicate by measuring the weight and moisture loss at regular intervals (0.25, 0.5, 0.75, 1, 1.5, 2, 3, 4, and 5 h) using an external balance (analytical scales, METTLER AE240, accuracy ± 0.0001 g). Moisture content is expressed on a dry basis.

2.3 Mathematical modeling of drying

Drying kinetics obtained experimentally were adjusted using a simplified model in order to determine the effective diffusion coefficients of water (D_w) and theoretical models, which allowed us to obtain the adjustment constants.

2.4 Effective diffusion coefficients of water

During the falling-rate period, the effective diffusion coefficient may be determined using the solution of Fick's second law in an unstable state, assuming the material has an infinite laminar geometry [39]:

$$\frac{X_t - X_\infty}{X_0 - X_\infty} = \sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} \exp\left(-(2n+1)^2 \frac{\pi^2 D_w}{4l^2} t\right) \quad (1)$$

where X_t is the moisture at time t (g water g dry solid^{-1}), X_0 the initial moisture (g water g dry solid^{-1}), X_∞ the moisture in equilibrium (g water · g dry solid^{-1}), and l the semi-thickness (m).

Equation (1) was used under the following assumptions: constant diffusivity, initial concentration of uniform moisture, external resistance to negligible mass transfer, and a constant solid/liquid ratio. D_w was determined by locating the moisture content and critical time on the drying-rate curves at the beginning of the falling-rate period. The falling-rate period was determined by plotting $\ln(X_c X^{-1})$ as a function of time (t), from which the value of D_w was obtained from the slope of the straight line (eq. (2)). The effective diffusivity of moisture was determined by applying the procedures suggested by Geankoplis [16] and Mazza and Lemaguer [44], with some modifications:

$$\ln \frac{X_c}{X} = D_w \times t\left(\frac{\pi}{2l}\right) - \ln \frac{8}{\pi^2} \quad (2)$$

where l is the semi-thickness of the material expressed in meters.

2.5 Drying curves predicting using mathematical equations

The mathematical equations used in the semi-theoretical and empirical models to describe the drying kinetics of osmo-dehydrated nectarines are shown in Table 1. The HAD kinetics of the osmo-dehydrated nectarines were adjusted by 10 mathematical equations. The modeling of the data was performed through analysis of non-linear regression using Systat 2007, which allowed calculation of the goodness of the adjustment of the theoretical models [50].

For the adjustments, moisture values experimentally obtained were expressed as the moisture ratio (XR) according to the following expression:

Table 1: Mathematical equations used for the adjustment of drying kinetics of osmo-dehydrated nectarines.

Models	Equations	References
Newton (Lewis)	$XR = \exp(-Kt)$	[45]
Page	$XR = \exp(-Kt^N)$	[46]
Page modified	$XR = \exp(-(Kt)^N)$	[47]
Henderson and Pabis	$XR = A\exp(-Kt)$	[45]
Logarithmic model	$XR = A\exp(-Kt) + C$	[48]
Two-term model	$XR = A\exp(-Kt) + B\exp(-K_1 t)$	[45]
Two-term exponential model	$XR = A\exp(-Kt) + (1-A)\exp(-KAt)$	[47]
Wang and Singh	$XR = 1 + At + Bt^2$	[45]
Verma et al.	$XR = A\exp(-Kt) + (1-A)\exp(-Gt)$	[11]
Midilli et al.	$XR = A\exp(-Kt^N) + Bt$	[49]

Note: XR is the moisture ratio predicted by the models and t is the time; K is the constant of the drying rate (s^{-1}) and N; A; C; B; K_1; G are the experimental constants of the models.

$$XR = \frac{X(t) - X_\infty}{X_0 - X_\infty} \approx \frac{X(t)}{X_0} \quad (3)$$

The equation of the moisture ratio was simplified to $X(t)\, X_0^{-1}$ because X_∞ is relatively small as compared to $X(t)$ or X_0 [12, 51]. For modeling, time (t) was expressed in seconds.

2.6 Statistical analysis

To determine the influence of the osmotic treatment and drying temperature on moisture, drying speed, mass transfer, and the constants of the various adjusted models, an analysis of variance was carried out (ANOVA) with a significance level (SL) of 5 %. The statistical analysis was performed using the Infostat software [52].

The goodness of fit between the experimental data and the theoretical values predicted by the models were evaluated by the correlation coefficient (r) (eq. (4)), the reduced chi-square (χ^2) (eq. (5)), and the root mean square of error (RMSE) (eq. (6)). The statistical indicators χ^2 and RMSE in the table are expressed in percentages (%):

$$r = \sqrt{\frac{\sum_{i=1}^{N} \left(XR_{\mathrm{pre},i} - \overline{XR}_{\mathrm{pre}}\right)^2}{\sum_{i=1}^{N} \left(XR_{\mathrm{exp},i} - \overline{XR}_{\mathrm{exp}}\right)^2}} \quad (4)$$

$$\chi^2 = \left(\frac{\sum_{i=1}^{N} \left(XR_{\mathrm{exp},i} - XR_{\mathrm{pre},i}\right)^2}{(N-n)}\right) \times 100 \quad (5)$$

$$\mathrm{RMSE} = \left(\sqrt{\frac{\sum_{i=1}^{N} \left(XR_{\mathrm{exp},i} - XR_{\mathrm{pre},i}\right)^2}{N}}\right) \times 100 \quad (6)$$

where N is the number of observations, n is the number of constants in the model, XR_{exp} is the experimental moisture ratio, and XR_{pre} is the theoretical or predicted moisture ratio. The lowest values of χ^2 and RMSE, together with the highest values of r (≈1.0), were selected as optimum criteria in order to evaluate the fit quality of the models used.

3 Results and discussion

Table 2 shows the moisture content values (X) of dehydrated nectarines by direct osmosis as a result of different experimental conditions (type of osmotic agent, concentration, fruit/syrup ratio and time) and the moisture content values and water activity values (a_w) of nectarines dehydrated by osmosis followed by HAD, recorded at the end of the drying period.

Table 2: Moisture content values (X) (g water g dry solid^{-1}) and water activity values (a_w) of nectarines dehydrated by combined methods (OD + HAD).

OD		**HAD**					
Osmotic treatment	***X***	**60 °C**		**70 °C**		**80 °C**	
		X	***a*w**	***X***	***a*w**	***X***	***a*w**
g-40 %-r1/4–25 °C	2.845 ± 0.014	0.035 ± 0.024	0.723 ± 0.008	0.024 ± 0.008	0.552 ± 0.010	0.005 ± 0.002	0.503 ± 0.007
g-40 %-r1/4–40 °C	2.517 ± 0.000	0.127 ± 0.027	0.697 ± 0.001	0.033 ± 0.017	0.603 ± 0.005	0.013 ± 0.019	0.581 ± 0.005
g-40 %-r1/10–25 °C	3.036 ± 0.295	0.202 ± 0.027	0.738 ± 0.004	0.103 ± 0.035	0.686 ± 0.001	0.004 ± 0.045	0.576 ± 0.003
g-40 %-r1/10–40 °C	2.863 ± 0.422	0.343 ± 0.225	0.678 ± 0.003	0.191 ± 0.109	0.663 ± 0.004	0.026 ± 0.005	0.640 ± 0.005
g-60 %-r1/4–25 °C	2.617 ± 0.000	0.102 ± 0.021	0.750 ± 0.010	0.031 ± 0.009	0.649 ± 0.006	0.006 ± 0.010	0.612 ± 0.004
g-60 %-r1/4–40 °C	2.852 ± 0.723	0.099 ± 0.008	0.742 ± 0.010	0.041 ± 0.072	0.650 ± 0.009	0.005 ± 0.016	0.576 ± 0.003
g-60 %-r1/10–25 °C	1.960 ± 0.000	0.029 ± 0.000	0.702 ± 0.008	0.017 ± 0.005	0.536 ± 0.004	0.002 ± 0.000	0.535 ± 0.001
g-60 %-r1/10–40 °C	2.582 ± 0.000	0.048 ± 0.036	0.681 ± 0.003	0.012 ± 0.029	0.590 ± 0.005	0.006 ± 0.008	0.571 ± 0.004
s-40 %-r1/4–25 °C	2.872 ± 0.116	0.197 ± 0.005	0.620 ± 0.001	0.068 ± 0.001	0.594 ± 0.001	0.062 ± 0.027	0.568 ± 0.006
s-40 %-r1/4–40 °C	2.587 ± 0.000	0.239 ± 0.005	0.643 ± 0.002	0.183 ± 0.001	0.595 ± 0.002	0.153 ± 0.021	0.556 ± 0.006
s-40 %-r1/10–25 °C	2.550 ± 0.012	0.237 ± 0.138	0.593 ± 0.001	0.116 ± 0.044	0.459 ± 0.000	0.063 ± 0.014	0.435 ± 0.004
s-40 %-r1/10–40 °C	2.559 ± 0.000	0.519 ± 0.227	0.689 ± 0.004	0.215 ± 0.003	0.559 ± 0.002	0.133 ± 0.008	0.426 ± 0.002
s-60 %-r1/4–25 °C	2.228 ± 0.708	0.530 ± 0.226	0.612 ± 0.004	0.319 ± 0.102	0.586 ± 0.008	0.296 ± 0.175	0.490 ± 0.005
s-60 %-r1/4–40 °C	2.083 ± 0.516	0.152 ± 0.246	0.639 ± 0.001	0.130 ± 0.026	0.512 ± 0.008	0.098 ± 0.004	0.467 ± 0.002
s-60 %-r1/10–25 °C	1.903 ± 0.779	0.081 ± 0.053	0.584 ± 0.006	0.018 ± 0.037	0.497 ± 0.003	0.004 ± 0.011	0.449 ± 0.005
s-60 %-r1/10–40 °C	2.045 ± 0.217	0.275 ± 0.029	0.632 ± 0.006	0.190 ± 0.092	0.573 ± 0.002	0.131 ± 0.053	0.514 ± 0.004

Notes: Osmotic agent: g, glucose; s, sorbitol, concentration of the osmotic agent = 40 %; 60 %.
Ratio: Fruit/osmotic agent = r1/4 = ratio 1–4; r1/10 = ratio 1–10, temperature osmotic = 25 °C; 40 °C.
Drying temperature = 60 °C; 70 °C; 80 °C.

Once the fresh fruit (4.602 g water g dry solid^{-1}) was dehydrated by osmosis, the fruit exhibited intermediate moistures between 1.903 and 3.036 g water g dry solid^{-1}, depending on the type and concentration of the osmotic agent, fruit/syrup ratio and dehydration temperature. With the osmotic treatment, it was found that by using a 60 % w/w sorbitol solution, a fruit/syrup ratio of 1/10, and a dehydration temperature of 25 °C, the product contained 1.903 ± 0.779 g water g dry solid^{-1}, whereas the degree of dehydration was lower when a 40 % w/w glucose solution, a fruit/syrup ratio of 1/10 and a dehydration temperature of 25 °C were used.

Upon HAD, the final moisture of the nectarines varied between 0.002 and 0.530 g water g dry solid^{-1}. The lowest moisture osmo-dehydrated nectarines were those immersed in a 60 % w/w glucose solution with a fruit: syrup ratio of 1/10 dehydrated at 25 °C followed by HAD at 80 °C. Higher moisture was recorded for the samples immersed in 60 % w/w sorbitol with a fruit/syrup ratio of 1/4 dehydrated at 25 °C followed by HAD at 60 °C. This decrease in the final moisture content of the osmo-dehydrated nectarines caused a decrease in the water activity (a_w) values, as shown in Table 2. Once the fresh fruit ($a_w = 0.971$) was dehydrated by osmosis followed by HAD, the water activity ranged between 0.426 and 0.750 for the osmo-dehydrated nectarines in 40 % w/w sorbitol with a fruit:syrup ratio of 1/10 dehydrated at 25 °C followed by HAD at 80 °C, whereas high water activity was recorded for the samples in 60 % w/w glucose with a fruit/syrup ratio of 1/4 dehydrated at 25 °C followed by HAD at 60 °C.

Table 3 shows the data analysis for moisture values and water activity according to the influence of the independent variables (osmotic agent, concentration, ratio fruit:osmotic agent, osmotic time, temperature of OD, temperature of HAD). During the HAD of the osmo-dehydrated nectarines, moisture was affected significantly ($p < 0.0001$) by all linear effects and most of the interactions between the studies variables, whereas water activity was significantly affected ($p < 0.0001$) by the type of osmotic agent and the drying temperature.

During OD, moisture content loss was enhanced by the use of more concentrated solutions and by an increase in the proportion of solution in relation to the sample. Similar results were reported by Araujo et al. [8] in OD of nectarines, Khoji and Hesari [6] and Ispir and Togrul [7] in OD of apricots and by Ferrari et al. [53] in OD of pears. In addition, the samples osmo-dehydrated in sorbitol showed

Table 3: ANOVA for moisture values (X), water activity (a_w) and effective diffusion coefficient values of water (D_w) of nectarines dehydrated by combined methods (OD + HAD).

Variables	X			a_w			D_w		
	df	F	p	df	F	p	df	F	p
Time (min)	9	2314.41	<0.0001	–	–	–	–	–	–
Osmotic agent	1	32.46	<0.0001	1	34.13	<0.0001	1	84.30	<0.0001
Concentration (% w/w)	1	399.11	<0.0001	1	0.47	0.4986	1	6.11	0.0200
Ratio fruit/osmotic agent	1	10.57	0.0012	1	2.39	0.1337	1	0.28	0.6018
Temperature of OD (°C)	1	16.90	<0.0001	1	1.66	0.2088	1	10.12	0.0037
Temperature of HAD (°C)	2	260.50	<0.0001	2	34.43	<0.0001	2	35.00	<0.0001
Time × osmotic agent	9	28.28	<0.0001	–	–	–	–	–	–
Time × concentration	9	15.87	<0.0001	–	–	–	–	–	–
Time × ratio fruit/osmotic agent	9	1.83	0.0618	–	–	–	–	–	–
Time × temperature of OD	9	0.45	0.9081	–	–	–	–	–	–
Time × temperature of HAD	18	6.42	<0.0001	–	–	–	–	–	–
Osmotic agent × concentration	1	1.89	0.1699	1	0.17	0.6857	1	4.14	0.0518
Osmotic agent × ratio fruit/osmotic agent	1	18.76	<0.0001	1	1.67	0.2068	1	3.78	0.0623
Osmotic agent × temperature of OD	1	28.88	<0.0001	1	0.39	0.5367	1	0.23	0.6376
Osmotic agent × temperature of HAD	2	10.64	<0.0001	2	0.18	0.8379	2	5.74	0.0083
Concentration × ratio fruit/osmotic agent	1	228.53	<0.0001	1	0.97	0.3325	1	20.55	0.0001
Concentration × temperature of OD	1	0.20	0.6584	1	0.17	0.6813	1	2.08	0.1607
Concentration × temperature of HAD	2	11.80	<0.0001	2	0.04	0.9581	2	0.12	0.8915
Ratio fruit/osmotic agent × temperature of OD	1	120.72	<0.0001	1	1.63	0.2130	1	4.74	0.0385
Ratio fruit/osmotic agent × temperature of HAD	2	2.43	0.0890	2	0.04	0.9587	2	0.91	0.4138
Temperature of OD × temperature of HAD	2	1.42	0.2419	2	0.09	0.9177	2	0.69	0.5106

Note: df, degree of freedom.

a higher degree of dehydration in relation to those treated in glucose syrup, as was observed in Table 2. Despite the similarity in the molecular weights of sorbitol and glucose, other variables influenced the behaviour of the osmotic agents, such as viscosity, a_w, and the ionic behaviour, which will change the interaction between solutes with water and with the solid matrix of the food [54–59].

In the HAD of osmo-dehydrated nectarines, X showed temperature dependence, i.e., the moisture content of the osmo-dehydrated nectarines decreased as the drying temperature increased. The results were dependent on the osmotic treatment, which is consistent with the results obtained by Pavkov et al. [9] during the drying of previously osmo-dehydrated halved nectarines. The same trend is shown by the water activity of osmo-dehydrated nectarines (Table 2), i.e., a_w decreased with increasing HAD temperature. Convective drying of osmo-dehydrated nectarines allowed for the reduction of a_w levels from 0.971 to less than 0.750 through water elimination and the incorporation, to a lesser extent, of soluble solids. Thus, stable products could be obtained from the microbiological perspective [30, 43].

Figures 1 and 2 show the kinetics of moisture content as a function of time for nectarines convection dried at

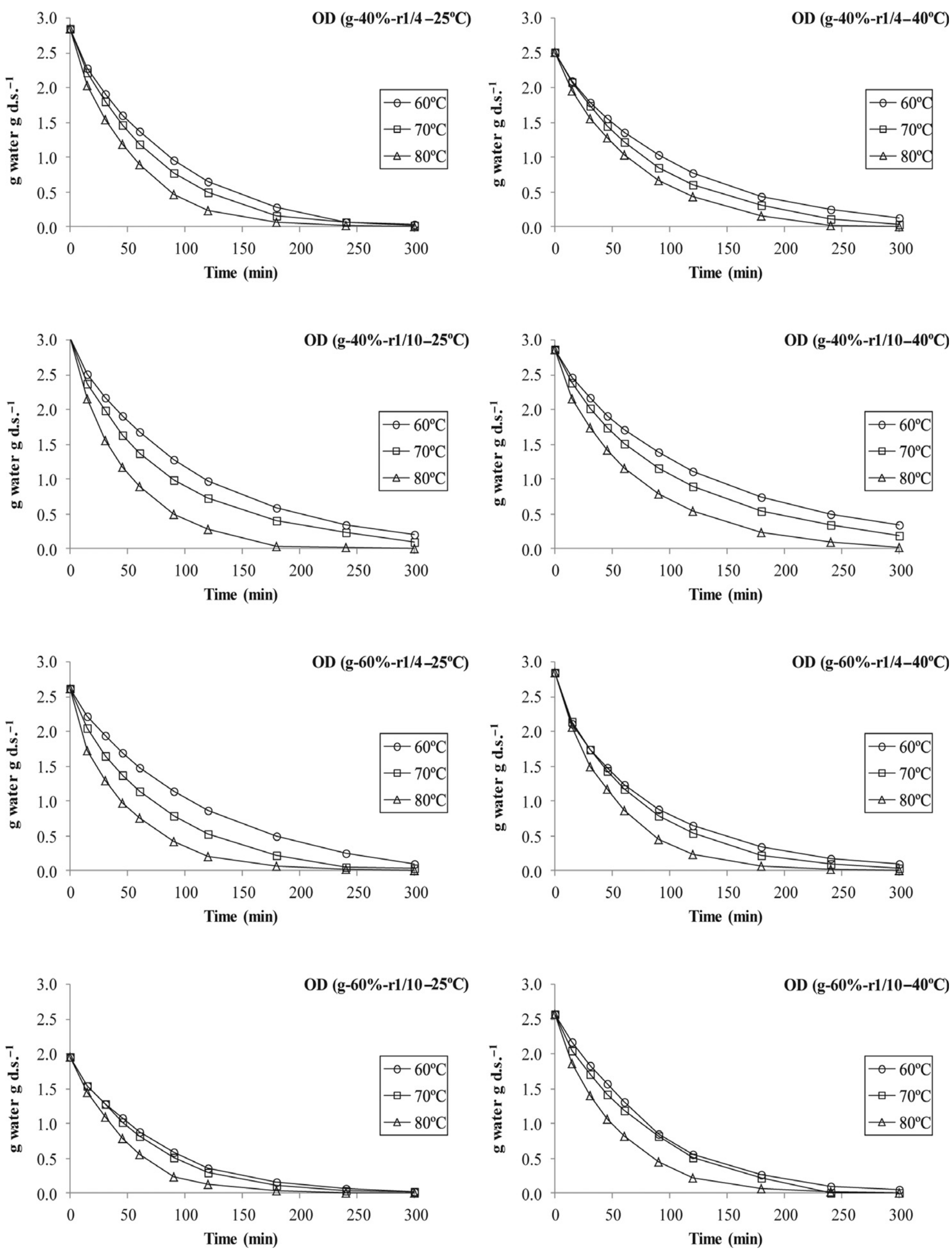

Figure 1: Moisture kinetics of hot-air dried nectarines at 60 °C, 70 °C, or 80 °C in glucose syrup solution.

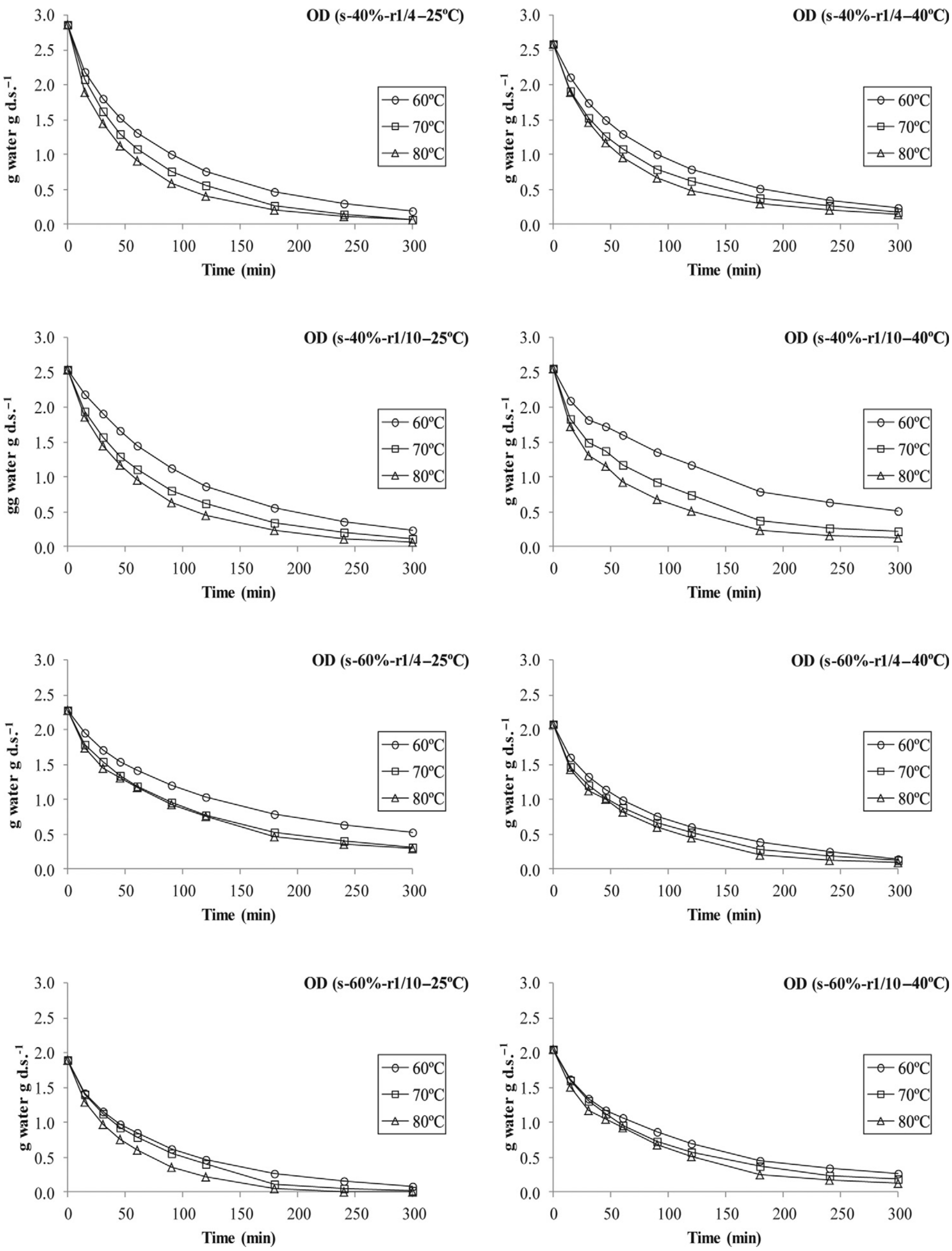

Figure 2: Moisture kinetics of hot-air dried nectarines at 60 °C, 70 °C, or 80 °C in sorbitol solution.

different temperatures after osmotic treatment in glucose syrup and sorbitol, respectively. For all conditions, the moisture decreased continually with increasing time and drying temperature. This is evidenced in the figures, which show that the slopes of the curves increase with increasing temperature. These results coincide with those obtained by Pavkov et al. [9], Sacilik and Elicin [12], Van Arsel et al. [17], Kaleta and Górnicki [35], Akpinar et al. [60], Akpinar et al. [61], and Lahsasni et al. [62].

As regards the osmotic treatment, the use of sorbitol together with an increase in the concentration of the hypertonic solution from 40 % to 60 % w/w and the use of a fruit/syrup ratio of 1/10 resulted in a higher degree of dehydration of the nectarines. At the same time, it is observed that a higher degree of dehydration occurred at 25 °C than at 40 °C (Figure 2). This effect may be attributed to the collapse in the cell structure when conditions are extreme, such as at high temperatures, causing partial expulsion of the osmotic solution with gas release. The pores then contract and, consequently, the free volume needed for water release is reduced [63].

The osmotic treatment favoured moisture loss in the samples of 21–29 %. This fact indicates that all the treatments presented only a falling-rate period during drying.

The lack of a constant rate period of drying indicates that diffusion governed the drying process [18]. These results were also reported by Togrul [14], Lahsasni et al. [62], Senadeera et al. [64], Sankat and Castaigne [65], Doymaz [66], Riva et al. [67] and Wang and Xi [68].

4 Mathematical modeling of drying

4.1 Effective diffusion coefficients of water

Only the falling-rate period was present during the drying of the nectarines, which indicates that water movement was limited by resistance to the water mass transfer from inside the solid to the interphase. It is therefore assumed that even if different mass transfer mechanisms coexist, water elimination is carried out by diffusion. The water diffusivity was estimated adequately by Fick's second law model. Tables 3 and 4 show the results of the variance according to the influence of the independent variables for the effective diffusion coefficients and the effective diffusion coefficient values of water, respectively. The effective diffusion coefficients of water values ranged from 4.96×10^{-9} to 2.43×10^{-8} m^2 s^{-1}. It is observed that

Table 4: Effective diffusion coefficient values of water of nectarines dehydrated by combined methods (OD + HAD).

	Effective diffusion coefficient (D_w) (m^2 s^{-1})		
Osmotic treatments	**60 °C**	**70 °C**	**80 °C**
g-40 %-r1/4–25°C	1.57×10^{-08}	1.69×10^{-08}	2.22×10^{-08}
g-40 %-r1/4–40°C	1.02×10^{-08}	1.40×10^{-08}	1.88×10^{-08}
g-40 %-r1/10–25°C	9.39×10^{-09}	1.14×10^{-08}	2.32×10^{-08}
g-40 %-r1/10–40°C	7.39×10^{-09}	9.18×10^{-09}	1.57×10^{-08}
g-60 %-r1/4–25°C	1.09×10^{-08}	1.59×10^{-08}	2.10×10^{-08}
g-60 %-r1/4–40°C	1.15×10^{-08}	1.48×10^{-08}	2.22×10^{-08}
g-60 %-r1/10–25°C	1.48×10^{-08}	1.70×10^{-08}	2.43×10^{-08}
g-60 %-r1/10–40°C	1.41×10^{-08}	2.02×10^{-08}	2.12×10^{-08}
s-40 %-r1/4–25°C	9.08×10^{-09}	1.26×10^{-08}	1.31×10^{-08}
s-40 %-r1/4–40°C	8.23×10^{-09}	8.97×10^{-09}	9.82×10^{-09}
s-40 %-r1/10–25°C	8.34×10^{-09}	1.04×10^{-08}	1.27×10^{-08}
s-40 %-r1/10–40°C	5.49×10^{-09}	8.55×10^{-09}	1.03×10^{-08}
s-60 %-r1/4–25°C	4.96×10^{-09}	6.75×10^{-09}	7.07×10^{-09}
s-60 %-r1/4–40°C	8.76×10^{-09}	9.29×10^{-09}	1.08×10^{-08}
s-60 %-r1/10–25°C	1.04×10^{-08}	1.63×10^{-08}	2.16×10^{-08}
s-60 %-r1/10–40 °C	6.97×10^{-09}	8.23×10^{-09}	9.60×10^{-09}

Note: Osmotic agent: g, glucose; s, sorbitol, concentration of the osmotic agent = 40 %; 60 %; ratio: fruit/osmotic agent = r1/4 = ratio 1–4; r1/10 = ratio 1–10; temperature: osmotic = 25 °C; 40 °C; drying temperature = 60 °C; 70 °C; 80 °C.

water diffusion was favoured by the glucose syrup at a concentration of 60 % w/w, a fruit:syrup ratio of 1/10, and a dehydration temperature of 25 °C followed by air drying at 80 °C, where the diffusion of water was lower when treatment was performed in sorbitol at a concentration of 60 % w/w, a fruit/syrup ratio of 1/4, and a dehydration temperature of 25 °C followed by air drying at 60 ° C (Table 4).

D_w values were significantly affected ($p < 0.05$) by the type of osmotic agent, the concentration, osmotic temperature, drying temperature and the interactions between the variable fruit:syrup ratios with concentration and osmotic temperature and type of osmotic agent with the drying temperature (Table 3). Owing to the influence of the variables involved in the osmotic treatment on the D_w, values, it is observed that water diffusion was favoured by the glucose syrup, as described previously (Table 4).

For the samples osmotically treated under the same experimental conditions, the values of D_w increased with increasing drying temperature. Similar results were published by Maskan et al. [69] for grapes, Akpinar et al. [70] for slices of potato, Sanjuan et al. [18] for the drying of red peppers at 50–70 °C and Keqing [22] for the air drying of osmo-dehydrated pears. In these studies, it was also found that the temperature significantly affected the effective diffusion coefficients of water during air drying, and a direct relation between the increase of D_w values and the drying temperature was reported. Fick's second law satisfactorily predicts water movement during osmotic pretreatment of nectarines, which explains the 95.06–99.98 % variation in the experimental data.

The effective diffusion coefficients found for the osmo-dehydrated nectarines are consistent with those of some reports, such as those described by Wang et al. [37] for dried apples (1.91×10^{-9} to 3.93×10^{-9} m^2 s^{-1}) and Velic et al. [71] for apples dried at 60 °C (1.79×10^{-9} to 4.45×10^{-9} m^2 s^{-1}).

4.2 Fitting of the drying curves using mathematical equations

Tables 5 and 6 show the adjustment of drying kinetics through the use of 10 mathematical models. The tables also show the values of the statistical indicators (r, χ^2, RMSE) obtained for the 48 treatments. The r values were between 0.750556 and 0.999995. The ranges were 0.000005–0.026241 for χ^2 and 0.000618–0.045818 for RMSE. These results show that the models studied accurately described the HAD kinetics of osmo-dehydrated nectarines.

Table 5: Mathematical model of drying kinetics of osmo-dehydrated nectarines by the equations of Newton, Page, Page modified, Henderson and Pabis, and the logarithmic model.

T	Newton			Page			Page modified			Henderson and Pabis			Logarithmic		
	r	χ^2	*RMSE*	*r*	χ^2	RMSE	*r*	χ^2	RMSE	*r*	χ^2	RMSE	*r*	χ^2	RMSE
1	0.998	0.026	0.48	0.999	0.047	0.62	0.999	0.047	0.62	0.998	0.04	0.56	1.000	0.03	0.44
2	0.999	0.012	0.32	0.999	0.019	0.39	0.999	0.019	0.39	0.999	0.01	0.32	1.000	0.01	0.30
3	0.999	0.010	0.29	1.000	0.014	0.34	1.000	0.014	0.34	0.999	0.01	0.29	1.000	0.01	0.27
4	1.000	0.029	0.51	1.000	0.008	0.25	1.000	0.008	0.25	1.000	0.03	0.49	1.000	0.05	0.59
5	0.999	0.005	0.20	0.999	0.007	0.24	0.999	0.007	0.24	0.999	0.01	0.21	1.000	0.02	0.37
6	0.999	0.014	0.36	0.999	0.018	0.38	0.999	0.018	0.38	0.999	0.01	0.32	1.000	0.04	0.51
7	0.999	0.049	0.66	1.000	0.008	0.26	1.000	0.008	0.26	1.000	0.05	0.64	1.000	0.06	0.63
8	0.997	0.091	0.91	1.000	0.003	0.14	1.000	0.003	0.14	0.999	0.19	1.23	1.000	0.16	1.06
9	0.999	0.020	0.42	0.999	0.009	0.27	0.999	0.009	0.27	0.999	0.05	0.61	0.999	0.08	0.74
10	0.999	0.070	0.79	1.000	0.001	0.07	1.000	0.001	0.07	1.000	0.10	0.89	1.000	0.04	0.56
11	0.998	0.078	0.84	1.000	0.001	0.11	1.000	0.001	0.11	1.000	0.14	1.05	1.000	0.10	0.85
12	0.998	0.056	0.71	0.999	0.011	0.30	0.999	0.011	0.30	1.000	0.10	0.88	1.000	0.16	1.06
13	0.999	0.013	0.35	0.999	0.022	0.42	0.999	0.022	0.42	0.999	0.01	0.34	1.000	0.04	0.52
14	0.999	0.029	0.51	0.999	0.027	0.47	0.999	0.027	0.47	0.999	0.03	0.47	1.000	0.07	0.72
15	0.998	0.062	0.75	0.999	0.020	0.40	0.999	0.020	0.40	1.000	0.14	1.05	1.000	0.17	1.10
16	0.995	0.185	1.29	1.000	0.015	0.34	1.000	0.015	0.34	1.000	0.31	1.57	1.000	0.30	1.44
17	0.999	0.052	0.68	1.000	0.015	0.35	1.000	0.015	0.35	1.000	0.08	0.78	1.000	0.11	0.88
18	1.000	0.008	0.27	1.000	0.009	0.26	1.000	0.009	0.26	1.000	0.01	0.27	1.000	0.01	0.30
19	1.000	0.011	0.32	1.000	0.016	0.36	1.000	0.016	0.36	1.000	0.01	0.34	1.000	0.01	0.29
20	0.999	0.012	0.33	1.000	0.010	0.28	1.000	1.613	3.59	1.000	0.04	0.56	1.000	0.03	0.44
21	0.998	0.029	0.51	0.999	0.009	0.26	0.999	0.009	0.26	0.999	0.13	1.02	0.999	0.13	0.97
22	0.999	0.033	0.54	1.000	0.008	0.25	1.000	0.008	0.25	1.000	0.09	0.83	1.000	0.06	0.65
23	0.997	0.031	0.53	0.997	0.055	0.66	0.997	0.055	0.66	0.997	0.05	0.62	0.999	0.04	0.51
24	1.000	0.009	0.29	1.000	0.011	0.29	1.000	0.011	0.29	1.000	0.01	0.28	1.000	0.01	0.31
25	0.989	0.313	1.68	1.000	0.001	0.06	1.000	0.001	0.06	0.999	0.58	2.15	1.000	0.33	1.53
26	0.991	0.206	1.36	1.000	0.004	0.18	1.000	0.004	0.18	0.999	0.53	2.06	0.999	0.47	1.82
27	0.986	0.234	1.45	1.000	0.001	0.07	1.000	0.001	0.07	0.998	0.79	2.52	1.000	0.56	1.97
28	0.992	0.247	1.49	1.000	0.008	0.25	1.000	0.008	0.25	0.999	0.49	1.97	1.000	0.20	1.18
29	0.981	0.417	1.94	1.000	0.008	0.26	1.000	0.008	0.26	0.997	0.99	2.81	1.000	0.41	1.70
30	0.979	0.288	1.61	0.999	0.032	0.50	0.999	0.032	0.50	0.994	1.02	2.86	1.000	0.24	1.30
31	0.999	0.039	0.59	0.856	2.576	4.54	1.000	0.003	0.15	1.000	0.08	0.80	1.000	0.02	0.33
32	0.992	0.209	1.37	1.000	0.002	0.13	1.000	0.002	0.13	0.999	0.45	1.90	1.000	0.31	1.48
33	0.993	0.146	1.15	0.754	2.394	4.38	1.000	0.000	0.06	0.999	0.43	1.85	1.000	0.29	1.43
34	0.994	0.422	1.95	0.988	0.376	1.73	0.999	0.041	0.57	0.999	0.36	1.70	1.000	0.19	1.15
35	0.985	0.563	2.25	0.998	0.046	0.61	0.998	0.046	0.61	0.998	0.73	2.42	0.999	0.54	1.94
36	0.978	0.486	2.09	0.998	0.020	0.40	0.998	0.020	0.40	0.997	1.07	2.93	0.999	0.73	2.25
37	0.992	0.454	2.02	1.000	0.008	0.25	1.000	0.008	0.25	0.999	0.57	2.13	1.000	0.15	1.02
38	0.985	0.531	2.19	1.000	0.003	0.17	1.000	0.003	0.17	0.998	0.78	2.50	1.000	0.26	1.34
39	0.984	0.599	2.32	0.999	0.014	0.34	0.999	0.014	0.34	0.998	0.80	2.54	1.000	0.35	1.55
40	0.990	0.350	1.77	1.000	0.003	0.17	1.000	0.003	0.17	0.999	0.57	2.13	1.000	0.42	1.72
41	0.982	0.513	2.15	1.000	0.010	0.29	1.000	0.010	0.29	0.997	0.35	1.68	1.000	0.63	2.11
42	0.986	0.403	1.91	0.998	0.038	0.55	0.998	0.038	0.55	0.999	0.70	2.37	0.999	0.57	2.00
43	0.992	0.253	1.51	1.000	0.006	0.22	1.000	0.006	0.22	0.999	0.45	1.91	1.000	0.39	1.65
44	0.996	0.108	0.98	0.997	0.070	0.75	0.997	1.535	3.50	0.998	0.12	0.96	0.999	0.24	1.29
45	0.996	0.088	0.89	0.998	0.028	0.47	0.998	0.028	0.47	0.999	0.18	1.21	0.999	0.28	1.40
46	0.986	0.508	2.14	1.000	0.011	0.30	1.000	0.011	0.30	0.998	0.74	2.44	1.000	0.29	1.43
47	0.987	0.347	1.77	1.000	0.007	0.24	1.000	0.007	0.24	0.998	0.70	2.37	1.000	0.24	1.30
48	0.988	0.372	1.83	0.999	0.029	0.49	0.999	0.029	0.49	0.998	0.61	2.20	0.999	0.41	1.70

Note: T, treatments.

Table 6: Mathematical model of drying kinetics of osmo-dehydrated nectarines by the equations of the two-term model, two exponential terms, Wang and Sing, Verma et al. and Midilli et al.

T	Two terms			Two exp. terms			Wang and Sing			Verma et al.			Midilli et al.		
	r	χ^2	RMSE	*r*	χ^2	RMSE	*r*	χ^2	RMSE	*r*	χ^2	RMSE	*r*	χ^2	RMSE
1	0.998	0.08	0.69	0.999	0.04	0.57	0.984	0.47	1.95	0.998	0.04	0.54	1.000	0.269	1.27
2	0.999	0.02	0.37	0.999	0.02	0.37	0.961	0.78	2.50	0.999	0.01	0.32	1.000	0.212	1.13
3	0.999	0.02	0.31	1.000	0.01	0.33	0.837	1.83	3.82	0.999	0.01	0.29	1.000	0.104	0.79
4	1.000	0.00	0.15	1.000	0.02	0.39	0.990	0.36	1.70	1.000	0.00	0.12	1.000	0.014	0.29
5	0.999	0.02	0.34	0.999	0.01	0.23	0.981	0.47	1.93	0.999	0.01	0.21	1.000	0.020	0.35
6	0.999	0.02	0.31	0.999	0.02	0.40	0.955	0.89	2.67	0.999	0.01	0.28	1.000	0.108	0.81
7	1.000	0.01	0.21	1.000	0.02	0.43	0.991	0.35	1.68	1.000	0.00	0.07	1.000	0.030	0.43
8	0.999	0.18	1.04	1.000	0.00	0.20	0.966	0.87	2.63	0.999	0.02	0.41	1.000	0.067	0.63
9	0.999	0.03	0.45	0.999	0.02	0.39	0.807	2.16	4.16	0.999	0.01	0.23	0.999	0.143	0.93
10	1.000	0.07	0.66	1.000	0.01	0.23	0.996	0.22	1.34	1.000	0.02	0.38	1.000	0.002	0.11
11	1.000	0.11	0.83	1.000	0.01	0.21	0.987	0.46	1.92	1.000	0.03	0.43	1.000	0.051	0.55
12	1.000	0.06	0.62	0.999	0.03	0.49	0.944	1.15	3.04	1.000	0.00	0.15	1.000	0.028	0.41
13	0.999	0.04	0.49	0.999	0.02	0.40	0.993	0.25	1.40	0.999	0.02	0.34	1.000	0.001	0.09
14	0.999	0.03	0.39	0.999	0.04	0.53	0.968	0.78	2.50	0.999	0.01	0.31	1.000	0.196	1.08
15	1.000	0.11	0.83	0.999	0.04	0.57	0.751	2.59	4.55	1.000	0.00	0.16	1.000	0.474	1.69
16	1.000	0.30	1.34	1.000	0.02	0.37	0.956	1.18	3.07	1.000	0.01	0.24	1.000	0.143	0.93
17	1.000	0.04	0.51	0.999	0.03	0.53	0.950	1.07	2.92	1.000	0.00	0.10	1.000	0.146	0.94
18	1.000	0.01	0.23	1.000	0.01	0.28	0.820	1.98	3.98	1.000	0.01	0.22	1.000	0.128	0.88
19	1.000	0.03	0.40	1.000	0.01	0.34	0.971	0.60	2.19	1.000	0.02	0.34	1.000	0.134	0.90
20	1.000	0.06	0.59	1.000	0.01	0.23	0.959	0.69	2.36	1.000	0.02	0.38	1.000	0.077	0.68
21	0.999	0.23	1.17	1.000	0.01	0.23	0.802	1.87	3.87	0.999	0.02	0.41	1.000	0.055	0.58
22	1.000	0.17	1.01	1.000	0.01	0.21	0.987	0.26	1.45	1.000	0.03	0.46	1.000	0.020	0.34
23	0.997	0.07	0.63	0.997	0.05	0.61	0.980	0.54	2.08	0.997	0.05	0.60	0.999	0.252	1.23
24	1.000	0.01	0.22	1.000	0.01	0.31	0.847	1.81	3.80	1.000	0.01	0.22	1.000	0.200	1.10
25	0.999	0.58	1.87	0.999	0.06	0.69	0.966	1.09	2.96	0.999	0.07	0.71	1.000	0.006	0.19
26	0.999	0.53	1.78	0.999	0.02	0.44	0.913	1.74	3.74	0.999	0.05	0.60	1.000	0.020	0.34
27	0.998	0.83	2.23	0.997	0.06	0.67	0.814	2.62	4.58	0.998	0.05	0.57	1.000	0.018	0.33
28	0.999	0.49	1.71	0.999	0.03	0.46	0.980	0.70	2.37	0.999	0.12	0.92	1.000	0.147	0.94
29	0.997	1.15	2.63	0.995	0.13	1.01	0.944	1.49	3.45	0.997	0.16	1.06	1.000	0.034	0.45
30	0.994	1.12	2.59	0.993	0.09	0.85	0.912	1.73	3.72	0.994	0.20	1.17	1.000	0.143	0.93
31	1.000	0.02	0.34	1.000	0.02	0.38	0.994	0.24	1.38	1.000	0.02	0.42	1.000	0.009	0.24
32	0.999	0.44	1.62	0.999	0.02	0.39	0.956	1.17	3.06	0.999	0.06	0.65	1.000	0.023	0.38
33	0.999	0.41	1.57	1.000	0.01	0.29	0.912	1.64	3.63	0.999	0.04	0.55	1.000	0.023	0.37
34	0.999	0.33	1.42	0.999	0.14	1.04	0.996	0.44	1.88	0.999	0.05	0.56	1.000	0.571	1.85
35	0.998	0.76	2.13	0.995	0.21	1.30	0.966	1.36	3.30	0.998	0.05	0.57	0.999	1.088	2.55
36	0.997	1.16	2.64	0.992	0.24	1.38	0.901	2.21	4.21	0.997	0.07	0.72	0.999	0.886	2.31
37	0.999	0.59	1.88	0.998	0.15	1.08	0.995	0.37	1.71	0.999	0.16	1.07	1.000	0.013	0.27
38	0.998	0.83	2.23	0.899	2.42	4.40	0.983	0.79	2.52	0.998	0.14	0.99	1.000	0.042	0.50
39	0.998	0.85	2.26	0.908	2.22	4.21	0.980	0.97	2.78	0.998	0.10	0.85	1.000	0.504	1.74
40	0.999	0.57	1.85	0.999	0.07	0.74	0.970	1.05	2.89	0.999	0.07	0.72	1.000	0.054	0.57
41	0.999	0.93	2.36	0.995	0.25	1.42	0.944	1.66	3.65	0.999	0.06	0.63	1.000	0.276	1.29
42	0.999	0.72	2.08	0.996	0.13	1.02	0.932	1.78	3.77	0.999	0.04	0.50	0.999	0.992	2.44
43	0.999	0.44	1.62	0.999	0.04	0.55	0.956	1.22	3.13	0.999	0.04	0.50	1.000	0.002	0.10
44	0.998	0.08	0.71	0.998	0.03	0.48	0.954	1.14	3.02	0.998	0.03	0.45	0.999	0.650	1.97
45	0.999	0.14	0.92	0.999	0.01	0.27	0.837	2.19	4.19	0.999	0.01	0.25	0.999	0.495	1.72
46	0.998	0.78	2.17	0.996	0.16	1.13	0.984	0.81	2.54	0.998	0.14	1.00	1.000	0.188	1.06
47	0.998	0.73	2.10	0.997	0.08	0.79	0.972	0.94	2.75	0.998	0.14	0.99	0.999	0.020	0.35
48	0.998	0.61	1.92	0.997	0.10	0.91	0.960	1.30	3.23	0.998	0.06	0.62	0.999	0.711	2.07

Note: T, treatments.

When exhaustively comparing the models' behaviour, it should be emphasized that the logarithmic and Midilli et al. [49] models presented the best adjustment, as expressed by values of r close to unity and the small values of χ^2 and RMSE. From the 10 mathematical adjusted equations, it was expected that the Wang and Sing model would present a poorer adjustment because it is not an exponential-type equation. In the same way, the logarithmic, two terms, two-term exponential, Verma et al., and Midilli et al. models represented a better adjustment because they are exponential equations with more terms, which allows for a better representation of the drying curves, which are exponential and asymptotic in time. These results coincide with the ones obtained by Menges and Ertekin [11], Sacilik and Elicin [12], and Rayaguru et al. [72].

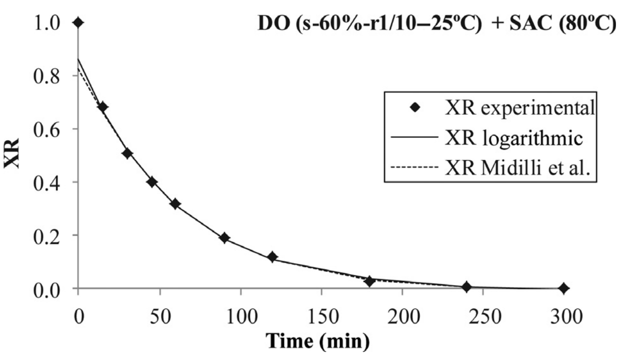

Figure 3: Adjustment of the logarithmic and Midilli et al. models to the data obtained for nectarines osmo-dehydrated in 40 % w/w glucose syrup with a fruit/syrup ratio of 1/10 at 25 °C and hot-air dried at 60 °C.

Figure 3 shows the adjustment of the logarithmic and Midilli et al. models for 1 of the 48 treatments tested, corresponding to nectarines dehydrated by osmosis using a sorbitol solution (60 % w/w) with a fruit/syrup ratio of 1/10 dehydrated at 25 °C followed by air drying at 80 °C. This was the treatment with which the highest rate of dehydration was achieved. In the figure, the absolute moisture values obtained experimentally and the ones predicted by the models mentioned above in terms of time can be observed.

The optimum treatment and the constants and coefficients of the logarithmic and Midilli et al. models, respectively, were as follows:

$$XR = 0.870\ \exp\left(-2.750 \times 10^{-04} t\right) - 0.008 \quad (r = 0.999)$$

$$XR = 0.830\ \exp\left(-1.668 \times 10^{-04} t^{1.057}\right) - 2.973 \times 10^{-07} t \quad (r = 0.999)$$

The moisture ratio of the nectarines at any time during the drying process can be more accurately estimated using these expressions.

5 Conclusions

It was observed that dehydration increased proportionally with increasing drying temperature and that the results depended on the osmotic treatment. The treatment that achieved the greatest moisture reduction was that in which the nectarines were osmo-dehydrated in a 60 % w/w sorbitol solution with a fruit/syrup ratio of 1/10 dehydrated at 25 °C followed by air drying at 80 °C. It was observed that the rate-drying curves did not show a constant drying-rate period. Fick's second law satisfactorily predicted water movement during osmotic pretreatment, explaining the 95.06–99.98 % variation in the experimental data. The mathematical models employed presented a high quality of adjustment. However, the logarithmic and Midilli et al. empirical models best described the drying kinetics, and thus they are recommended for predicting the process conditions at an industrial level. The best treatment that achieved the greatest moisture reduction was when the nectarines were osmo-dehydrated in a 60 % w/w sorbitol solution with a fruit/syrup ratio of 1/10 dehydrated at 25 °C followed by air drying at 80 °C. Future research will show whether such drying conditions also helps maintain the qualities of the fruit.

Abbreviations

OD	Osmotic dehydration
HAD	Hot air drying
X_0	Initial moisture (g water g dry solid^{-1})
a_w	Water activity
X_c	Critical moisture (g water g dry solid^{-1})
X	Moisture (g water g dry solid^{-1})
D_w	Diffusion coefficient of water (m^2 s^{-1})
L	Semi-thickness (m)
XR	Moisture ratio
T	Time (s; min)
K	Constant of drying rate (s^{-1})
N; A; C; B; K_1; G	Experimental constants of the models
X_∞	Moisture in the equilibrium (g water g dry solid^{-1})
R	Correlation coefficient
χ^2	Reduced chi-square
RMSE	Root mean square of error
N	Number of observations
XR_{exp}	Experimental moisture ratio
XR_{pre}	Theoretical or predicted moisture ratio
d.s.	Dry solid

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