Original article

A Optimisation of convective drying of carrots using selected processing and quality indicatorsJuliana Gamboa-Santos,¹ Ana C. Soria,² Tiziana Fornari,¹ Mar Villamiel^{1*} & Antonia Montilla¹¹ Instituto de Investigación en Ciencias de la Alimentación (CIAL) (CSIC-UAM), CEI (CSIC + UAM), Nicolás Cabrera, 9. 28049, Madrid, Spain² Instituto de Química Orgánica General (CSIC), Juan de la Cierva, 3. 28006, Madrid, Spain

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Summary The effect of drying temperature (40–65 °C) and air rate (2–6 m s⁻¹) on the formation of Maillard reaction indicators and vitamins content of carrots dehydrated by convection has been investigated. The range of assayed processing conditions, based on a previous central composite face design (CCD), led to moderate changes in the studied parameters, even under the most severe conditions. In addition, the drying kinetic of the process was studied taking into account the experimental quantitation of shrinkage, which allowed the determination of a first drying period with a constant rate of water evaporation per unit of exchange surface. The slope of the first drying period, the moisture loss during first hour of drying and the level of quality parameters (Maillard reaction indicators and vitamins) were correlated with processing conditions with high accuracy. For the prototype here used, the optima temperature and air rate to maximise the desirability function (0.77) were 46 °C and 4.9 m s⁻¹.

Keywords 2-furoylmethyl-aminoacids, carrot, convective drying, drying kinetic, Maillard reaction, response surface methodology, shrinkage, vitamins.

Introduction

Nowadays, the trends in food technology are addressed to the intake of nutritive and appealing foods, which provide some health benefits to the consumers. Due to the present “style of life”, dried foods and particularly vegetables, have a predominant position in the market of many countries and this is expected to increase even more over the next decade (Zhang *et al.*, 2006). Longer shelf-life, product diversity and volume reduction are the main reasons for the popularity of dried vegetables (Lewicki, 2006).

Carrot (*Daucus carota* L.) constitutes an important vegetable for human nutrition due to its high vitamin, fibre and other valuable nutrients content and to its organoleptic properties. It is used fresh or dehydrated in the elaboration of a number of foodstuffs, such as soups, salads, sauces, prepared meals and snacks. The importance of carrot is reflected by its global production, which was estimated at 27 million metric tonnes in 2004 (Brunke, 2006).

Dried vegetables are mainly obtained using hot air drying (Lewicki, 2006), being temperature, air-flow rate

and sample thickness the main parameters affecting the characteristics of the final product (Doymaz, 2004). This process may cause irreversible chemical, physical and sensorial changes. At the low water activity and temperature conditions reached during drying, the Maillard reaction (MR), which involves reducing carbohydrates and free amino groups of amino acids, peptides and proteins, can take place (Cardelle-Cobas *et al.*, 2005). Thus, 2-furoylmethyl-amino acids (2-FM-AA), formed at the early stages of MR, have been suggested as sensitive indicators in several dehydrated vegetables (Sanz *et al.*, 2001; Cardelle-Cobas *et al.*, 2005). These indicators have also been found in carrot submitted to different drying processes, such as solar drying (Rufián-Henares *et al.*, 2008), industrial and laboratory convective drying (Soria *et al.*, 2009; Wellner *et al.*, 2011) and ultrasound-assisted convective drying (Soria *et al.*, 2010). In this concern, particularly interesting is the case of the formation of 2-furoylmethyl-lysine (furosine), as its early detection can prevent advanced stages of the MR in which important losses of nutritive value due to the participation of lysine are produced (Corzo-Martínez *et al.*, 2012). Other irreversible changes in the dried product can be related to vitamin losses and modification in texture, rehydration capability, flavour, colour and appearance (Lewicki, 2006).

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During the last years, due to the increased consumer's awareness for better quality, safety and nutritional value of foods, drying research has been addressed towards the improvement of existent and/or emergent processing technologies, which give rise to final products with improved characteristics. One of the most common approaches to guarantee optimal quality of the final product is through careful process design. Thus, by means of tools, such as modelisation and optimisation of the process, the efficiency of the drying can be improved. A number of studies related to the modelisation of drying kinetics of carrot using convective dryers (Mulet, 1994; Singh & Gupta, 2007; Zielinska & Markowski, 2010), semi-industrial continuous convective dryers (Aghbashlo *et al.*, 2009), or convective dryers assisted by ultrasound (García-Pérez *et al.*, 2007; Carcel *et al.*, 2011) have been conducted. In those studies, the selection of optimal conditions to obtain premium quality products is carried out by taking into account the interaction of selected processing parameters. In this sense, response surface methodology (RSM) is widely recognised as an important tool for process and product improvement. RSM enables to determine the relationship between the experimental factors (experimental drying variables) that simultaneously optimise the analysis variables (quality parameters) and maximise the desirability function (Myers *et al.*, 2004). In several recent publications, RSM has been used for different drying procedures of artichoke and soybean (Icier, 2010), potato (Eren & Kaymak-Ertekin, 2007) and berries (Mitra & Meda, 2009). In carrots, RSM has been used for the optimisation of osmotic dehydration (Kargozari *et al.*, 2010; Singh *et al.*, 2010; Sutar & Prasad, 2011) and fluidised bed processes (Mudahar *et al.*, 1989; Nazghelichi *et al.*, 2011). Aghbashlo *et al.* (2011) analysed the variation in the kinetic of carrot drying with the independent variables time, air temperature, air velocity and cube size. Finally, Frías *et al.* (2010) used RSM to study the effect of convective air drying of carrot on vitamin C and β -carotene retention; however, in that study the drying kinetics was not studied. Moreover, to the best of our knowledge, no previous data have been reported in the literature on the optimisation of convective drying of carrots based on 2-FM-AA data, as sensitive quality parameters.

In this study, the effect of processing conditions (drying temperature and air rate) of a prototype by convection on quality indicators (Maillard reaction indicators and vitamins) and drying kinetic of sliced carrot have been reported. To this aim, an experimental design using a central composite face design (CCD) was first carried out and, then, the selected drying and quality parameters were related using a RSM to find the optima processing conditions leading to dehydrated carrots of the best quality.

Materials and methods

Samples

Fresh carrots (*D. carota* L. var. Nantesa) were purchased from a local market in Madrid (Spain). The selection of carrots was based on similar size, optimum colour and ripeness stage. After sorting, they were stored at 4 °C for, as maximum, 5 days. Before processing, carrots were washed in tap water to remove dust and other residues and were peeled and sliced (4.0 ± 0.5 mm thickness and 24.0 ± 0.4 mm diameter). Sliced carrot samples were blanched in boiling water for 1 min (sample:water ratio was 1:12), cooled to room temperature in cold water and then dried with tissue paper to remove superficial water.

Drying equipment

Blanched carrot samples were dried by convection using a computer controlled (Edibon Scada Control and Data Acquisition Software) air tray dryer (SBANC, Edibon Technical Teaching Units, Spain; Figure S1). This system consists of three main sections: (i) fan unit with air rate control (AVE), (ii) temperature control (seven temperature sensors: ST1, ST4 and ST6 (dry bulb); ST2, ST5 and ST7 (wet bulb) and ST3 sensor of electrical resistance (AR)) and (iii) drying compartment (load cell with four drying trays). Although AR (°C) was the setpoint temperature, ST7 (°C) was chosen as representative of the process temperature, as it was the wet bulb measurement closest to the sample. The air flow was parallel to the sample and the air rate was selected using the AVE (m s^{-1}) sensor. Experimental air-flow rate ($\text{m}^3 \text{h}^{-1}$) was verified at the output nozzle (area = 0.01 m^2) using a thermo-anemometer (TESTO, 425, Lenzkirch, Germany). During the drying process, the weight of the samples was automatically monitored by the load cell of the system (SF, Figure S1). In addition, carrot samples were weighted at 1 h intervals using an external digital balance for control of accuracy of data (SOE-HNLE, Murrhardt, Germany).

Moisture content and drying kinetic curves

The kinetic curves representing the variation in the moisture content of carrots with convective drying time were calculated as follows:

$$X(t) = (W(t) - DM)/DM \quad (1)$$

Where X : moisture content ($\text{kg H}_2\text{O kg}^{-1} \text{ DM}$) determined according to Geankoplis (1998); t : drying time (h); W_i : sample weight (kg); DM : dry matter (kg) determined according to A.O.A.C. (1990a).

A polynomial approximation ($n = 3$) to the drying curve was proposed to fit the drying process. In agreement with Górnicki & Kaleta (2007), the first part of the drying curve was described by applying a linear regression model, assuming that a constant drying rate occurred during the first stage of process. Then, the drying rate decreased during the second or fall drying rate period. In the present study, the end of the first constant drying period was considered by means of parameter t^* , defined as the period of time for which a linear regression of the drying curve can be attained with a $R^2 \geq 0.99$. In this point, the sample reached the critical moisture content (X^*). The slope (S) ($\text{kg H}_2\text{O kg}^{-1} \text{ DM min}^{-1}$) of this trend line was also considered in the studied model.

Determination of shrinkage

To analyse the influence of shrinkage in the drying rate of the process, the thickness (l) and diameter (d) of carrots subjected to drying, were measured in triplicate (slices were selected at random) at 30 min-intervals using a vernier calliper (Mitutoyo Corp., Japan; error ± 0.05 mm). Then, the real exchange surface area (A) was calculated as follows:

$$A = \pi d(d/2 + l) \quad (2)$$

In the previous equation, it is assumed that the cylindrical shape of carrots is maintained throughout the drying process; this assumption was supported by experimental observation of carrot slices, until the very last part of the falling-rate drying period.

The water flux (q_t) averaged over the exchange surface area of carrot slice was calculated as previously defined by May & Perre (2002):

$$q_t = -\frac{DM}{A} \frac{dX(t)}{dt} \quad (3)$$

where $dX(t)/dt$ is the drying rate ($\text{kg H}_2\text{O kg}^{-1} \text{ DM min}^{-1}$), which was calculated from the experimental drying curves.

Analysis of 2-furoylmethyl-amino acids

For determination of 2-FM-AA, 0.25 g of carrots were hydrolysed with 4 mL of HCl 8 M for 23 h at 110 °C under inert atmosphere (helium), using a Pyrex screw-cap vial with polytetrafluoroethylene-faced septa (Soria *et al.*, 2010). The resulting hydrolysate was filtered (paper filter Whatman no. 40) and 0.5 mL were purified in a Sep-Pack C₁₈ cartridge (Millipore, MA) pre-treated with 5 mL of methanol and 10 mL of water. The filtrate was eluted with 3 mL of 3 M HCl.

The 2-FM-AA corresponding to lysine (furosine) and arginine were determined using ion-pair Reversed-

phase-High-performance liquid chromatography (RP-HPLC) (Resmini & Pellegrino, 1991) using a C₈ column (250 mm length $\times$ 4.6 mm internal diameter, Alltech, Lexington, KY) at 37 °C. A binary gradient composed of phase A (4 mL L⁻¹ acetic acid) and phase B (3 g L⁻¹ KCl in phase A solution) was used. The elution program was as follows: 0–12 min: 100% A; 20–22.5 min: 50% A and 50% B; 24.5–30 min: 100% A. The flow rate was 1.2 mL min⁻¹ and injection (50 μ L) was carried out using a manual Rheodyne valve. Detection was done at 280 nm in a LCD Analytical SM 4000 detector.

Quantification was performed using the external standard method, using a commercial standard of furosine (Neosystem Laboratoire, Strasbourg, France). Values were expressed as mg kg⁻¹ protein and all the analyses were performed in duplicate.

To analyse the protein content of carrot samples under study, total nitrogen (TN) was determined using the Kjeldahl method (A.O.A.C. 1990b). Protein content was calculated using 6.25 as conversion factor ($\text{TN} \times 6.25$).

Optimisation of carrot drying by response surface methodology

The effect of two independent factors, air rate and temperature, on the convective drying of blanched sliced carrots (80 g) for up to 6 h was studied using a central composite face design (CCD, Statgraphic 5.0, Statistical Graphics Corporation, Rockville, MD, USA). A total of ten experiments (2^2 points of a factorial design, four star points and two centre points to estimate the experimental error), were carried out in randomised order. Setpoint parameters, AR and AVE (Figure S1), of assays selected from the experimental design are listed in Table 1.

Four dependent variables were taken into account to optimise the convective drying of carrot by means of RSM: linear time (t^* , min), the slope of the linear function of the constant drying rate period (S , $\text{kg H}_2\text{O kg}^{-1} \text{ DM min}^{-1}$), the weight loss at the first hour of processing (W_L , %) and the content of 2-FM-Lys + 2-FM-Arg (mg kg⁻¹ protein). In addition, the level of vitamin C and β -carotene, determined in these samples by Frías *et al.* (2010), were also included in the process optimisation. Each analytical response was evaluated using a one-way analysis of variance (ANOVA), using Fisher's Significant Difference test (LSD, 95%) (Statgraphics Centurion XV, Statistical Graphics Corporation, Rockville, MD, USA).

The analysis was based on the F-test and on the percentage of explained variance (R^2_{adj}), which provides a measurement of how much of the variability in the observed response values could be explained by the experimental factors and their interactions (Myers

Table 1 Assay conditions (prototype setpoint and experimentally measured) of the experimental design for optimisation of convective drying of carrot

Assay	Prototype setpoint		Experimental data	
	Temperature (AR, °C)	Air rate (AVE, m s ⁻¹)	Temperature (ST7, °C)	Air flow-rate ± SD (m ³ h ⁻¹)
A1	62	2.0	52.5	67.3 ± 12.4
A2	50	5.4	43.6	198.8 ± 12.5
A3	64	4.0	52.5	154.3 ± 12.5
A4	53	2.6	43.6	93.0 ± 8.8
A5 ^a	>80	5.4	61.4	198.8 ± 12.5
A6	64	4.0	52.5	154.3 ± 12.5
A7	80	4.0	65.0	154.3 ± 12.5
A8	72	6.0	52.5	218.8 ± 11.4
A9	72	2.6	61.4	93.0 ± 8.8
A10	43	4.0	40.0	154.3 ± 12.5

^aConditions excluded from experimental design as they were unfeasible to be obtained with the prototype used for convective drying. AR, electrical resistance; AVE, air rate control of fan unit; ST7, temperature of wet bulb closest to the sample (± 0.5 °C accuracy).

et al., 2004). The overall effect of the six dependent factors was used to obtain a desirability function that represents the effect of the processing conditions on the final product quality and on the efficiency of drying. It is based on the idea that the “quality” of a process has multiple quality characteristics (Reis *et al.*, 2008). The method finds operating conditions that provide the “most desirable” response values. For processing conditions, a desirability function assigns numbers between 0 (completely undesirable value) and 1 (completely desirable or ideal response). To obtain process optimised, the models that presented an adjusted determination coefficient ($R^2_{adj} \geq 70\%$) were submitted to simultaneous optimisation, in accordance with the procedures outlined by Granato *et al.* (2010).

Results and discussion

Drying kinetic curves

Table 1 lists the experimental conditions (ST7 and air-flow rate) corresponding to setpoint values (AR and AVE) taken from experimental design. Assay 5 (AR > 80 °C and AVE = 5.4 m s⁻¹) was removed from the experimental design, as the proposed combination of processing conditions was unfeasible to be accomplished using prototype described under “Drying equipment” subsection. ST7 registered temperatures from 40 to 65 °C that were obtained by setting AR at temperatures within the range 43–80 °C. A close match was found between AVE values (2–6 m s⁻¹) and experimental air rate data (in the range 1.9–6.1 m s⁻¹) calculated from air-flow rate measured using a

thermoanemometer. Blanched carrot samples (with an initial DM of 10.5%) processed under the operating conditions listed in Table 1 showed percentages of DM between 84.1 and 89.2. These values are close to those considered as appropriate to preserve the microbiological quality of dehydrated vegetables (~85%, Belitz & Grosch, 1997). These values corresponded to an initial moisture content of 9.65 ± 0.34 kg H₂O kg⁻¹ DM for blanched carrot samples and, after drying, the moisture content was in the range 0.44–0.99 kg H₂O kg⁻¹ DM.

For each of the assays listed in Table 1 (except for assay A5), variation in the moisture content of the sample as a function of time was calculated from data collected at 1 h intervals for up to 6 h. Figure 1 depicts the experimental measurements and the corresponding polynomial fit. As expected, the moisture decreased with drying time for all drying processes resulting in different curves depending on the processing conditions of each assay. In general, as it has been described in the literature (Geankoplis, 1998), both the constant rate period and the falling-rate period, described in the drying of solids under constant conditions, were experimentally observed. In the initial period, a vegetable like carrot with high moisture content shows a constant rate of drying. This is due to the fact that evaporation initially takes place near the surface, and water is easily transported to the surface by diffusion. Therefore, the rate of drying would be the same than the rate of free water evaporation. In such conditions, the interface temperature remains constant and the heat is completely used for water evaporation (Geankoplis, 1998).

In the second, falling-rate period, the decrease in drying rate might be related to the reduction in porosity of the material due to shrinkage, with the progress of drying increasing the resistance to movement of water (Lagunez-Rivera *et al.*, 2007; Singh & Gupta, 2007). In this period, the diffusion of internal moisture to the solid surface is the rate-limiting step, when compared with the rate at which the surface moisture is swept away; therefore, it is the period of diffusion-controlled drying (Carcel *et al.*, 2007).

Different studies report fruit or vegetable (including carrot) dehydration, with these two periods (Saravacos & Charm, 1962; Dissa *et al.*, 2008). However, many studies consider that there is no stage of constant rate or it has been assumed that the first period is negligible because of the changes in water content are not linear after a short period from the beginning of drying; therefore, the entire drying process is considered to occur in the range of falling-rate period (Mulet, 1994; García-Pérez *et al.*, 2007; Doymaz, 2008; Arslan & Mehmet, 2010). These contradictory reported results could be related, among other factors, to the importance of considering the shrinkage and shape changes

Figure 1 Drying curves at different air-flow rates and temperatures (Table 1) for carrot samples.

during the first period of drying. Thus, during the constant rate period, the shrinkage can be neglected and the conditions of external mass transfer could determine the course of the process (Górnicki & Kaleta, 2007). However, May & Perre (2002) and Pabis & Jaros (2002) stated that in the case of foods with a high initial moisture content, the kinetic model must incorporate the shrinkage factor for better describing the drying results.

To analyse the effect of shrinkage on the drying process, Fig. 2 shows, as an example, the water flux (q_t) as a function of the drying time under the conditions of centre point assays (A3, A6), considering not only the slice surface equal to the initial surface, but also the actual slice surface reported in Table S1. As can be deduced from the figure, a constant rate period was observed when shape changes (reduction in slice surface) were considered. The first section of drying curve of A3 assay is also represented in Fig. 2, together with the t^* parameter calculated as the time for which a linear regression of the drying curve can be obtained with

a precision of $R^2 = 0.99$. As can be observed, the value of this parameter reasonably corresponds to the constant rate period observed. Then, the t^* parameter for each assay of carrot drying was calculated (see Table 2) and was included as a dependent variable in the model analysis. The highest values of t^* were found in samples processed under the conditions of assays A1, A4 and A10 (148, 141 and 192 min respectively), which were the mildest of the experimental design; whereas the lowest values of t^* were detected in the most intense assays (A7, 81 min; A8, 85 min). Taking into account the t^* drying time, the remaining critical moisture content (X^*) was calculated (Table 2), and ranged from 2.4 to 3.9 kg H₂O kg⁻¹ DM depending on processing conditions, values similar to those reported by May & Perre (2002) for convective drying of carrots (2.8 kg H₂O kg⁻¹ DM). According to Dissa *et al.* (2008), the value of this remaining moisture can be considered as the critical moisture for each drying process, as it separates both constant and falling-rate periods.

Figure 2 Water flux (q_t) and moisture content (X) vs. time for the first stage of drying curve at the centre point.

Table 2 Values of t^* (linear time), X^* (critical moisture content), S (constant rate period of drying), W_1 (weight loss at the first hour of processing) and concentration of 2-FM-AA (average $\pm$ SD) at the end of the processing of carrot samples.

Assay	t^* (min)	X^* (kg H ₂ O kg ⁻¹ DM)	S (kg H ₂ O kg ⁻¹ DM min ⁻¹)	W_1 (%)	2-FM-Lys + 2-FM-Arg (mg kg ⁻¹ protein)
A1	148	3.5	−0.044	30.5	393 $\pm$ 23
A2	106	3.9	−0.054	36.2	tr
A3	106	3.7	−0.056	37.8	445 $\pm$ 19
A4	141	3.8	−0.042	28.5	tr
A5	—	—	—	—	—
A6	106	3.3	−0.058	37.8	431 $\pm$ 1
A7	81	3.2	−0.080	50.9	1689 $\pm$ 152
A8	85	3.2	−0.074	48.1	1583 $\pm$ 20
A9	105	3.5	−0.058	38.3	705 $\pm$ 35
A10	192	2.4	−0.038	27.2	tr

tr, trace value; DM, dry matter (kg). For RSM optimization, trace values were replaced by an arbitrary numeric value of 0.1

Taking into account the t^* definition, the drying rate during the constant rate period can be calculated for each experimental assay as the slope (S) of the linear regression obtained. The S values obtained are given in Table 2 and are in agreement with the t^* values, namely the higher t^* , the lower value for the slope, that is the lower drying rate. The highest slopes of the drying curves were obtained for assays A7 and A8 (0.080 and 0.074 kg H₂O kg⁻¹ DM min⁻¹ respectively), corresponding to the most severe conditions. Several authors have reported that, in general, drying rates increase with the temperature and air-flow rate for various vegetables, including carrot (Velic *et al.*, 2004; Aghbashlo *et al.*, 2009; Zielinska & Markowski, 2010). However, when the air rate range is narrow (0.5–1 m s⁻¹), hardly any effect on drying rate can be detected (Madamba *et al.*, 1996).

During the constant rate drying period, values between 27 and 51% of weight loss were reached after

1 h of drying (Table 2). The highest W_1 values were observed in the assays carried out under the most severe conditions (A7 and A8), whereas the lowest values for this parameter (about 28%) were obtained at mild processing conditions (A4, and A10).

Effect of drying on quality indicators

As afore-mentioned, the formation of 2-FM-Lys + 2-FM-Arg was selected as quality marker of drying process related to the initial steps of evolution of MR. Table 2 depicts the quantitative data of 2-FM-AA for carrots analysed in the present study after 6 h of dehydration. No formation of 2-FM-AA was detected either in raw or blanched carrots. The highest 2-FM-AA contents (1689 and 1583 mg kg⁻¹ protein) were found in dehydrated carrots after the assays A7 and A8 respectively. The conditions used in these assays were the most severe and also gave rise to the major humidity losses (residual humidity values of 10.8 and 12.7%). The intermediate processing conditions (A1, A3, A6 and A9) provoked the formation of 2-FM-AA within the range 393–705 mg kg⁻¹ protein, and only traces of 2-FM-AA were detected in carrot samples processed after assays A2, A4 and A10.

The 2-FM-Lys (furosine) contents of dehydrated carrots analysed in the present study were lower than those previously reported for dehydrated carrots by other authors. Soria *et al.* (2009, 2010) found values from 3580 to 8480 mg kg⁻¹ protein in industrially dried and commercial carrot samples, whereas upper values were obtained by Wellner *et al.* (2011) for commercial carrot products (15408–15529 mg kg⁻¹ protein) and for carrot slices dried at 70, 80 and 90 °C in an oven during 5 h (9040–9890 mg kg⁻¹ protein). Rufián-Henares *et al.* (2008) analysed carrots industrially dehydrated at low temperature (30 °C) during long time (180 h) and they found values of 4030 mg furosine kg⁻¹ protein. Only in carrots dehydrated by power ultrasound at temperatures up to 60 °C, Soria *et al.* (2010) reported values of this quality marker

Table 3 Regression equations for the model fit of the different variables studied during the drying process of carrot

Variables ^a	Fitted model equation	R ² (%)	R ² _{adj} (%)
t*	656.645-15.973·T-7.231·V+0.125·T ² -0.127·T·V-0.0974·V ²	81.8	51.5
S	0.088-0.002·T-0.018·V+1.863E-05·T ² +3.871E-04·T·V+7.169E-04·V ²	98.9	97.1
(kg H ₂ O kg ⁻¹ DM min ⁻¹)			
W ₁ (%)	52.161-1.022·T-10.072·V+0.0103·T ² +0.210·T·V+0.443·V ²	99.5	98.7
2-FM-AA	997.268-28.035·T-239.366·V+0.215·T ² +3.303·T·V+11.920·V ²	97.0	92.1
(mg kg ⁻¹ protein)			
Vitamin C	2.582+0.585·T+3.622·V-0.005·T ² -0.085·T·V+0.053·V ²	99.4	98.3
(mg kg ⁻¹ DM)			
β-carotene	8.169+1.097·T+5.657·V-0.012·T ² -0.030·T·V-0.669·V ²	98.6	96.4
(mg kg ⁻¹ DM)			

^at*, linear time; S, constant rate period of drying, W₁, weight loss at the first hour of processing, 2-FM-AA, 2-furoylmethyl-amino acids.

Figure 3 Response surface plots of each analysed variable as a function of temperature and air-flow rate.

significantly lower than those here analysed (390 mg kg⁻¹ protein).

These results highlight the limited progress of MR during the dehydration process of carrot carried out in our convective system, even under the most severe conditions of temperature and air flow, and the importance of optimising the process to obtain premium quality products, as kinetic of this reaction is strongly dependent on temperature and water content throughout the treatment.

Optimisation of processing conditions by response surface methodology

In order to optimise the drying process, operating conditions (air rate and drying temperature) of assays

1–10 were related by means of RSM with each of the dependent variables under study: parameters derived from drying curves (t*, S and W₁) and quality parameters (2-FM-AA, vitamin C and β-carotene). The equations of the fitted models and the corresponding estimated responses surfaces are shown in Table 3 and Fig. 3, respectively. Together with the equations of the fitted models given in Table 3, the R² and R²_{adj} statistics values are also shown. As it can be observed, with the exception of t*-value, all the variables presented high values of R² and R²_{adj} indicating the goodness of the fits (Granato *et al.*, 2010). The slopes of the constant rate period present high regression values (R² = 98.9% and R²_{adj} = 97.1%), showing that this variable can be maximised in the optimisation by RSM, to attain the shorter times during the drying

Table 4 Predicted and observed values for the desirability function during the different assays of drying of carrots by convection

Assay	Desirability	
	Predicted	Observed
A1	0.61	0.61
A2	0.74	0.78
A3	0.73	0.73
A4	0.51	0.58
A5	–	–
A6	0.73	0.73
A7	0.000	0.000
A8	0.40	0.34
A9	0.59	0.57
A10	0.56	0.41

Figure 4 Estimated response surface (a) and the corresponding contour plot (b) for the desirability function.

process. Consequently, the slope and weight loss at the first hour ($R^2 = 99.5\%$ and $R^2_{adj} = 98.7\%$) of each fit were selected as the representative variables of the drying process together with the quality indicators of dried carrot samples, defined as the 2-FM-Lys +

Table 5 Optima values of the different dependent variables to obtain the maximum desirability value corresponding to 46 °C and 4.9 m s⁻¹

Variables ^a	Values
S (kg H ₂ O kg ⁻¹ DM min ⁻¹)	0.052
W ₁ (%)	35.1
2-FM-Lys+2-FM-Arg (mg kg ⁻¹ protein)	153
Vitamin C (mg kg ⁻¹ DM)	189
β-carotene (mg kg ⁻¹ DM)	376

^aS, constant rate period of drying, W₁, weight loss at the first hour of processing, 2-FM-AA, 2-furoylmethyl-amino acids.

2-FM-Arg content (measured and reported in this study) and the vitamin C and β-carotene contents.

In addition, Table 4 compares the value of the desirability function predicted for assays A1–A10, with the values calculated from the corresponding experimental data. This was defined to minimise the 2-FM-AA concentration and maximise the β-carotene and vitamin C content, the first hour loss weight (W₁) and the rate of the first drying period (S). The corresponding three-dimensional representation of the desirability function obtained is shown in Fig. 4a. This figure illustrates the effect of temperature and air rate on the desirability function. As observed, there is a maximum of predicted desirability (0.77) corresponding to a temperature value of 46 °C and an air rate of 4.9 m s⁻¹. The exact point can be better seen in Fig. 4b, which represents the corresponding contour plot. Among the tested conditions, the highest observed value of desirability function was 0.78, corresponding to A2 assay and 0.73 to the centred points (A3 and A6). Granato *et al.* (2010) obtained a value of desirability of 0.72 when studying the optimisation of the sensory properties of dairy-free emulsions. Other authors, such as Kargozari *et al.* (2010), optimising physical properties of osmotically dehydrated carrot cubes, obtained a desirability value of 0.92. In summary, Table 5 shows the optimal values for the dependent variables obtained by RSM optimisation of the process at 46 °C and 4.9 m s⁻¹.

Conclusion

An experimental design is here proposed to optimise the operating conditions (temperature and air rate) with regard to selected processing (t^* , S and W₁) and quality indicators (advance of MR and loss of vitamins). Furthermore, and to better determine the first drying period with constant rate, which can be described by a linear regression ($R^2 = 0.99$) of the drying curve, experimental quantification of shrinkage has also been carried out. In general, mild changes in the advance of MR and the loss of vitamin C and β-carotene were

observed, even under the most severe conditions assayed, together with moisture loss values within the limits established to guarantee the microbiological stability of the product. RSM analysis of the operating conditions and studied indicators allowed, with high accuracy, the determination of optimal drying parameters (46 °C and 4.9 ms⁻¹). This study underlines the usefulness of optimising the convective drying of carrots to obtain a long shelf-life product with premium quality (the lowest loss of nutritive value) in the shortest time and with the lowest energy requirement.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Drying cabinet (EDIBON) used for the convective drying of carrots.

Table S1. Experimental thickness (l) and diameter (d) (average data $\pm$ standard deviation) and calculated exchange area (A) used to study the influence of shrinkage during drying of carrots under A3 conditions.

6

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