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Influence of Drying by Convective Air Dryer or Power Ultrasound on the Vitamin C and β-Carotene Content of Carrots

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Convective air drying and power ultrasound effects on vitamin C and β-carotene contents in carrots were studied. For convective air drying, a central composite face-centered design fitting temperature between 40 and 65 °C and air flow rate between 2 and 6 × 10^{-1} m/s were used; previously, carrots were blanched. Likewise, ultrasound drying was performed on both unblanched and blanched carrots at 20, 40, and 60 °C for 120, 90, and 75 min, respectively. Blanching had a sharp effect on vitamin C and β-carotene degradation (80−92% retentions, respectively), and convective air drying led to further losses (32−50% and 73−90% retentions, respectively). According to the response surface model, a combination of 40 °C and 6 × 10^{-1} m/s will maximize vitamin C retention in dried carrots, whereas 40 °C and 3.3 × 10^{-1} m/s will ensure the highest β-carotene content. Ultrasound drying caused higher vitamin C and β-carotene retention (82−92% and 96−98%, respectively) than convective air drying. Blanched carrots dehydrated by ultrasound showed retentions of 55% and 88% of vitamin C and β-carotene, respectively. Ultrasound drying at 20 °C for 120 min caused the maximum vitamin C and β-carotene contents. Therefore, power ultrasound may be considered a valuable tool to obtain high nutritive dehydrated carrots.

KEYWORDS: Dehydrated carrots; air drying; ultrasound; blanching; vitamin C; β-carotene

INTRODUCTION

Carrots are among the most common vegetables for human nutrition since they present high nutritive value and health properties, mainly due to their high content in β-carotene, vitamin B complex, vitamin C, fiber and minerals (*1*). The maximum retention of their vitamin content is of utmost importance for the preservation of their attractive appearance and for their dietary value. Carrots have a water content of 80−90%, hence, it is susceptible to moisture loss, which consequently leads to wilting and a loss of fresh appearance.

Preservation of carrots can prevent the huge wastage, increase their shelf life and provide a good source of vitamins in the off-season at reasonable prices. Drying is one of the oldest methods of food preservation and represents a very important aspect of food processing to minimize biochemical, chemical and microbiological deterioration of food products over a long period of time (*2*). Dehydrated vegetables also undergo substantial weight and volume reduction, which minimizes packaging, storage and transportation costs (*3*). The application of different pretreatment methods, such as hot water blanching before drying, guarantees the inactivation of enzymes responsible for the deterioration reactions, shortens time of drying, increases drying rate and improves the quality and acceptability of the final product (*4*). This pretreatment also enhances the rehydration capacity (*5*) and facilitates moisture removal during drying caused by the changes in tissue structure that lead to structural softening (*6*). Blanching also improves some quality parameters of dehydrated carrots such as texture, water uptake and reconstitution rate of the rehydrated product (*7*, *8*).

Dehydrated carrots are used as an ingredient in instant soups or meals, not only in the cuisine for home purposes, food services and commercial restaurants but also as healthy oil-free snack foods that can be developed if their nutritional value is preserved (*9*).

Over the last two decades, many studies have been carried out to process carrots by sun drying (*10*), air drying (*11*), microwave drying (*12*), vacuum drying (*9*), a combination of the aforementioned (*13*), or pulsed electric field (*14*). Convective air-drying is the choice process to dehydrate foodstuffs in the food industry to improve carrot stability (*15*, *16*), and the quality of the dehydrated product will depend on the type of dryer, the processing parameters and also the pretreatments of the dried vegetables (*17*).

The application of novel technologies, such as ultrasonic dehydration, permits the removal of moisture content at mild temperatures. Ultrasound wave travels through the solid medium causing a rapid series of compressions and expansions which may make the moisture removal easier without producing a liquid phase change, and produces cavitation which may be beneficial for the removal of moisture strongly attached without significantly heating the product preserving heat-sensitive food constituents (*18*, *19*). Dehydration by power ultrasound also limits the extent of the Maillard reaction in dehydrated vegetables, one of the thermal quality control indicators (*20*), giving rise to dehydrated foods of premium quality (*21*). In addition, the ultrasound has a lethal effect on microorganisms and thus has potential as a food preservation treatment (*22*).

β-Carotene is a precursor of vitamin A (retinol) which is involved in the visual process, reproduction, growth, the maintenance of

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Table 1. Effect of Dehydration by Convective Air-Dryer System on the Content of Vitamin C and β-Carotene of Carrots[a]

	convective air drying conditns					
carrots	temp (°C)	air flow rate (10^{-1} m/s)	vitamin C (mg/100 g dm)	retention of vitamin C (%)	β-carotene (mg/100 g dm)	retention of β-carotene (%)
raw			39.73 ± 1.53 h		43.87 ± 1.58 g	
blanched			32.34 ± 0.87 g	81	40.44 ± 0.65 f	92
blanched	40.0	4.0	19.46 ± 1.13 f	49	39.61 ± 1.06 ef	90
blanched	43.6	2.6	18.91 ± 0.85 ef	48	38.95 ± 0.51 e	89
blanched	43.6	5.4	19.99 ± 1.33 f	50	36.64 ± 1.49 c	84
blanched	52.5	2.0	18.02 ± 1.49 de	45	37.88 ± 0.79 d	86
blanched	52.5	4.0	17.04 ± 1.13 cd	43	37.45 ± 0.88 cd	85
blanched	52.5	4.0	17.85 ± 1.17 de	45	37.10 ± 0.68 cd	85
blanched	52.5	6.0	16.31 ± 1.07 bc	41	32.07 ± 0.70 a	73
blanched	61.4	2.6	15.79 ± 1.84 b	40	34.04 ± 0.41 b	78
blanched	65.0	4.0	12.89 ± 0.73 a	32	31.89 ± 1.60 a	74

[a] Mean value ± SD of 6 determinations. The same letters in the same column mean no significant differences ($P \leq 0.05$).

skin and mucous membranes but also has beneficial biological effects such as antioxidant, immunomodulatory and anticarcinogenic properties (*23*). In carrots β-carotene, the predominant carotenoid, is located in the chromoplasts as crystals and stabilized by lipoproteins, and its stability is rather high. The loss of β-carotene is one of the most important phenomena produced during dehydration of carrots; this affects the quality of the dehydrated product to a great extent (*16*). Moreover, the autocatalytic oxidation of β-carotene may be caused by the reduction of moisture content during the dehydration process (*24*, *25*).

Vitamin C is the most heat labile of all the vitamins, and its degradation to diketogulonic acid is a primary cause of loss of this vitamin in dehydrated products (*26*). This acid can then react nonenzymatically with free amino acids to form a red-brown compound that causes discoloration in the dried products (*27*). Vitamin C is a potent antioxidant that prevents cancer by inhibiting the formation of *N*-nitroso compounds in the stomach, and by stimulating the immune system (*28*); it also enhances the bioavailability of iron (*29*). Due to its lability, ascorbic acid is routinely used as an index to measure processing effects on nutrient retention (*30*).

Although there is a large amount of information describing the effect of different dehydration processes on the stability of β-carotene in carrots (*11*, *26*, *31*−*34*), little has been recorded on the drying effect in the vitamin C content, and no information has been found concerning the effect of ultrasound, as an emerging drying treatment, on the vitamin C and β-carotene content.

The objective of this work was to evaluate the effectiveness of convective air-drying and power ultrasound for enhancing the retention of vitamin C and β-carotene of carrots, in an attempt to improve the nutritional quality of dehydrated products.

MATERIALS AND METHODS

Carrots. Good quality fresh carrots (*Daucus carota*, L. var. *Nantesa*) were purchased from a local market and stored in the dark at 4 °C for a maximum period of five days previous to dehydration. Just before processing, the carrots were washed in water and sliced into 4 mm thickness and 24 mm diameter. Some raw carrot slices were freeze-dried (LyoBeta 15, Telstar) and finely ground using a thermostatized laboratory grinder (IKA A10, Jankie & Kunkel) and kept under a N_2 atmosphere at −20 °C until further analysis. These samples were considered to be raw carrots for our studies.

Blanching Process. Carrot slices were blanched in boiling water for 1 min (sample:water ratio was 1:30), cooled immediately in cold water, drained properly and spread in the convective air-dryer tray or in the ultrasound plate as a single layer. Some blanched carrots were freeze-dried and kept as previously described until further analysis.

Convective Air-Drying Process. Dehydration by convective hot air was carried out using a computer controlled air tray dryer (SBANC, Edibon Technical Teaching Units, Spain). The experimental dryer basically consisted of an air oven provided with an electrical heater, a shielded propeller fan to distribute the hot air and a squared plate parallel drying chamber with the sample tray directly exposed to the continuous hot air. A weight system was directly connected to the sample tray and recorded the changes in weight of the carrots due to the evaporation of moisture during dehydration. Carrot slices were dehydrated for 6 h at different temperatures, and air-drying flow rates were established by a central composite face-centered design (CCD) (**Table 1**) (*35*). Response surface methodology (RSM) was used for optimizing the convective air drying method according to the effect of the two independent variables (temperatures and air-drying flow rates) on the two dependent response variables (vitamin C and β-carotene). The air dryer was preheated for 30 min at the temperature established for each experiment. The trays were loaded with the blanched carrots as a single layer and inserted into the heated chamber. The internal temperature and sample weight were monitored throughout the drying period. Each drying experimental condition was performed in duplicate. Air-dried carrots were freeze-dried and kept as previously described until further analysis.

Ultrasound-Dehydration Process. Power ultrasound dehydration was carried out in unblanched and blanched carrot slices using a prototype of ultrasonic power generator constituted by a transducer with a rectangular flexural-vibrating plate and an electronic unit for driving the transducer (*18*). This preliminary study was carried out using the ultrasonic parameters previously applied by Soria et al. (*20*) for the dehydration of carrots: ultrasonic frequency = 20 kHz; power level = 100 W cm/s; air speed = 1.2 m/s; suction pump = 120 mba; contact pressure = 1.6 kg/cm; air temperature (20, 40, and 60 °C); and drying time (75, 90, and 120 min). Each drying experiment was performed in duplicate. Ultrasound-dehydrated carrots were freeze-dried and kept as previously described until further analysis.

Determination of Vitamin C. The quantification of vitamin C content in dehydrated carrots was carried out by capillary electrophoresis using a fused silica capillary TSP075375 (47 cm × 75 μm) purchased from Composite Metal Services LTD (The Chase, Hallow, Worcester, U.K.). A P/ACE system 2050 (Beckman Instruments, Fullerton, CA) and UV detection at 254 nm were used for the analysis, according to Frias et al. (*36*). Briefly, 0.5 g of freeze-dried carrots was extracted with 20 mL of 3% metaphosphoric acid (Sigma-Aldrich, Steinheim, Germany), and after homogenization for 2 min using a Ultraturrax homogenizer T25 Digital (Ika Werke GMBH & Co. KG, Staufen, Germany), the volume was adjusted to 25 mL with 3% metaphosphoric acid. The resulting slurry was filtered through a Whatman No. 1 filter paper. 1.5 mL of the filtrate was added to 100 μL of isoascorbic acid (Fluka, Steinheim, Germany) as an internal standard (0.6 mg/mL) in aqueous 0.2% D,L-dithiothreitol (Sigma-Aldrich, Steinheim, Germany), made up to 2 mL with aqueous 0.2% D,L-dithiothreitol, mixed thoroughly and filtered through a 0.45 μm membrane. D,L-Dithiothreitol is a reducing agent added to prevent the oxidation of the ascorbic acid to the corresponding dehydroascorbic. Vitamin C was quantified from a calibration curve built with pure ascorbic acid standard (Fluka) and with the response factor relative to the internal standard. Results were expressed as mg/100 g of dry weight basis (dm).

β-Carotene Analysis. The content of β-carotene in carrots under analysis was determined following the extraction procedure described by Lavelli et al. (*37*). Briefly, 0.2 g of freeze-dried carrots was added to 10 mL

Table 2. Effect of Dehydration by Ultrasonic System on the Content of Vitamin C and β-Carotene of Carrots[a]

	ultrasonic process conditns					
carrots	temp (°C)	drying time (min)	vitamin C (mg/100 g dm)	retention of vitamin C (%)	β-carotene (mg/100 g dm)	retention of β-carotene (%)
raw			44.96 ± 0.82 e		48.57 ± 1.19 e	
raw	20	120	41.56 ± 1.70 d	92	47.77 ± 0.70 de	98
raw	40	90	39.27 ± 0.92 c	87	47.29 ± 0.10 cd	97
raw	60	75	36.87 ± 1.74b	82	46.48 ± 1.16 c	96
blanched			37.01 ± 0.70 b	82	45.25 ± 1.25 b	93
blanched	20	120	24.81 ± 1.09 a	55	42.59 ± 1.08 a	88
blanched	40	90	24.90 ± 0.65 a	55	42.64 ± 0.99 a	88
blanched	60	75	24.93 ± 0.67 a	55	42.23 ± 0.49 a	87

[a] Mean value ± SD of 6 determinations. The same letters in the same column mean no significant differences ($P \leq 0.05$).

of tetrahydrofuran (THF) and stabilized by the addition of 0.1% butylated hydroxytoluene (BHT). The mixture was kept refrigerated in an ice bath and mixed by an Ultra-Turrax homogenizer (T-25 Janke & Kunkel IKA Labortechechnik) under nitrogen at moderate speed for 2 min. The extract was centrifuged (12000*g* at 5 °C for 10 min), and the residue was re-extracted with 10 mL of stabilized THF and centrifuged as above. The clarified THF extracts were quantitatively transferred into a volumetric flask and brought up to 25 mL with stabilized THF. Extractions were carried out in duplicate per set of drying process. β-Carotene content was quantified by HPLC using a Vydac 201TP54 C18 reverse column (250 × 4.6 mm), equipped with a C18 precolumn (100 × 4.6 mm). The chromatographic system consisted of an Alliance separation module 2695 (Waters), a photodiode array detector (Waters) set at 450 nm, and a personal computer running the Empower II for Windows chromatographic software (Waters). Chromatographic separation was performed with methanol/stabilized THF (95:5) as the eluent under isocratic conditions, at 1.0 mL/min flow rate and at room temperature. Quantitation was carried out by the external standard method, using a commercial standard of β-carotene (Sigma Chemical Co., St. Louis, MO). The purity of β-carotene was measured spectrophotometrically at 453 nm (*38*), and concentrations of standard solutions were corrected accordingly. Results were expressed as mg/100 g on a dry weight basis (dm).

Statistical Analysis. Data provided are the mean of three determinations of each experimental replicate and were subjected to multifactor ANOVA using the least-squared difference test (LSD) with the Statgraphic 5.0 Program (Statistical Graphics Corporation, Rockville, MD) for Windows. Central composite face-centered design (CCD) and response surface methodology (RSM) were performed using Statgraphics Centurion XV (Statistical Graphics Corporation, Rockville, MD) for Windows.

RESULTS AND DISCUSSION

Among the processes used to preserve vegetables, air-drying is the most industrially used. However, the operating conditions which are usually employed in convective drying (40−80 °C air temperature, 0.1−5 m/s air velocity and long drying times) may produce important chemical changes in the heat-sensitive carrot constituents. Therefore, in order to optimize experimental conditions, response surface methodology (RSM) using a central composite face-centered design (CDD) was carried out in the convective air-drying process, in which not only extreme points but also midpoints were selected for the study. The drying time of the process was kept constant, and the temperature (°C) and air flow rate (10^{-1} m/s) were considered independent variables. Temperatures ranging from 40 to 65 °C, and air velocities from 2 to 6 × 10^{-1} m/s were selected for a constant drying time of 6 h. The use of RSM is suitable for studying the main and interactive effects of the factors on the response variables. The response surface model has also been applied to investigate the changes occurring with the vitamin C and β-carotene during air-drying.

Power ultrasonic drying is a promising low-temperature dehydration process which is under development; therefore, as a preliminary study, different times (30, 60, and 120 min) and temperatures (20, 40, and 60 °C) have been chosen, as previously described in Soria et al. (*20*). Additionally, the effects of blanching before ultrasonic drying and only ultrasonic drying on vitamin C and β-carotene contents were studied.

The content of vitamin C of raw carrots was ∼40−45 mg/100 g dm (**Tables 1** and **2**), amounts that are within the range found in the literature (*26*, *30*, *39*).

When the carrot slices were subjected to blanching for 1 min, a significant ($P \leq 0.05$) decrease (∼20%) in vitamin C content was found, probably due to the instability of this vitamin to high temperatures and oxidation conditions. Ascorbic acid is a very labile molecule that can be easily degraded through chemical and enzymatic oxidation, and the extent of vitamin C loss during thermal processing is influenced by temperature, presence of oxygen, pH and metal ions (*40*). In addition, matrix disruption during sample preparation (peeling, slicing) can bring ascorbic acid into contact with enzymes such as ascorbic acid oxidase and ascorbic acid peroxidase, hence facilitating ascorbic acid oxidation (*41*) and the cleavage of the lactone ring which originates the irreversible formation of 2,3-diketogulonic acid, a compound devoid of vitamin C activity (*40*, *41*). Furthermore, due to the water solubility of ascorbic acid, this vitamin can leach into the blanching water that has been removed during the process. Blanching is an important operation before processing vegetables for freezing, canning or dehydration. Shivhare et al. (*42*) found variations of vitamin C in blanched carrots at different conditions, and maximum vitamin C retention was obtained after blanching in either water or a 0.05N acetic acid solution at 95 °C. Similar results have been reported by Howard et al. (*30*) for ascorbic acid reductions after blanching carrots in hot water.

The temperature and air flow rate used during air-drying of carrots brought about further degradation on vitamin C, and retentions ranged from 32% in carrots dried at 65 °C and 4 × 10^{-1} m/s to ∼50% in carrots dehydrated at 40 and 43.6 °C, irrespective of the air velocity (**Table 1**); this indicates that hotter drying temperatures led to lower vitamin C retentions. A similar observation was reported by Silva et al. (2005) (*43*) in their study on ascorbic acid degradation of camu camu (*Myrciaria dubia*) slices at different temperatures.

Figure 1A shows the three-dimensional surface plot illustrating the effect of temperature and air flow rate on the vitamin C content during convective air drying of carrots. The predictive regression model for the dehydrated carrots was considered adequate because the value of the determination coefficient ($R^2 = 0.9854$) ensured a satisfactory adjustment of the quadratic model to the experimental data. The value of R^2 indicated that the model could explain about 98.5% of the vitamin C variations and only 1.5% of the variation was due to other factors not included in the model. The regression equation fitted to the model was

$$\text{vitamin C (mg/100gdm)} = -5.64853 + 0.851949T + 4.41074V - 0.00755517T^2 - 0.0841819TV - 0.0483764V^2$$

where T is temperature (°C) and V is the air flow rate (10^{-1} m/s).

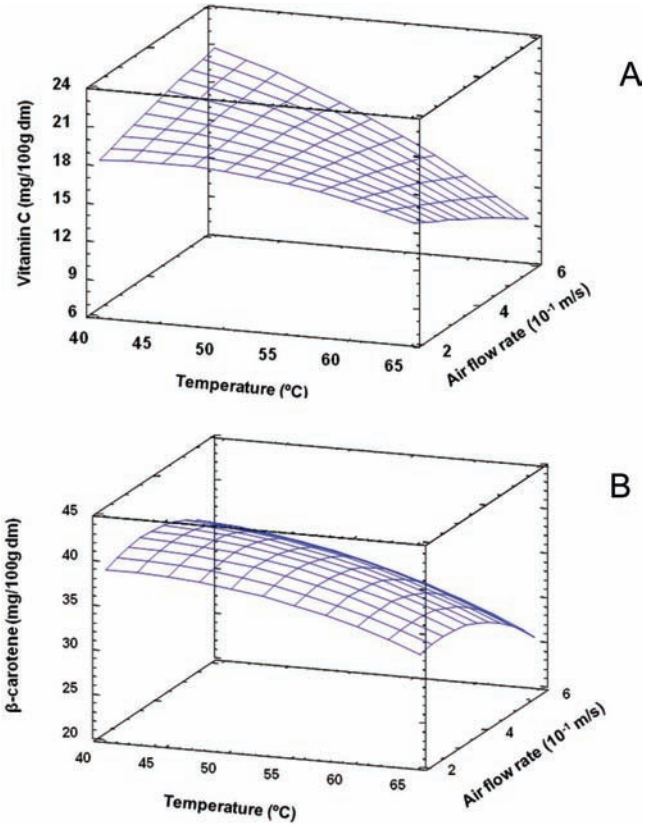

Figure 1. Response surface plot of the vitamin C (**A**) and β-carotene (**B**) contents as a function of temperature and air flow rate in carrots dehydrated by convective air dryer.

The linear and quadratic factors of temperature and air flow rate, as well as interaction term between these independent variables, had significant ($P \leq 0.05$) influence on vitamin C degradation. The model (**Figure 1A**) also illustrates that, at lower temperatures (< 50 °C), larger vitamin C contents were achieved when air-drying rate increased, but at higher temperatures (>50 °C), the increase of air velocity had a negative effect on vitamin C content. According to the model, air dryer conditions should be set at 40 °C and 6×10^{-1} m/s to maximize the retention of vitamin C in dried carrots. No information has been found on the degradation of vitamin C during convective air drying of carrots.

The β-carotene content of raw carrots was ~44−49 mg/100 g dm (**Table 1** and **2**), values that are in accordance with those found in the literature for this vegetable root (*26*, *42*, *44*).

After blanching treatment, the content of β-carotene underwent a significant ($P \leq 0.05$) decrease and ~8% loss was observed (**Table 1**). Blanching is a critical step in the drying of vegetables and usually leads to a degradation of β-carotene due to its relative heat instability. In addition, it might be argued that blanching causes physical damage to tissues by which β-carotene becomes highly prone to oxidation (*45*). Alternatively, it has been suggested that substances which are responsible for stabilizing the carotenoids (such as vitamin C) are either degraded or leached during blanching thereby making β-carotene more susceptible to oxidation (*46*). Our results agree with those reported by Negi and Roi (*26*), who found a decrease in β-carotene content of 12% in carrots blanched in water for 90 s.

Air-drying following blanching led to larger β-carotene degradation, and the extent of the losses depended on the process conditions (**Table 1**). The lowest β-carotene retentions (73−74%) were obtained when carrot slices were dried at 52.5 °C and 6×10^{-1} m/s, and at 65 °C and 4×10^{-1} m/s, followed by conditions of 61.4 °C and 2.6×10^{-1} m/s (78% retention). The rest of the experimental conditions caused rather similar β-carotene retention, that is, between 85% and 90%, and only slight significant ($P \leq 0.05$) differences among them were found (**Table 1**). These results show that not only the temperature but also the air flow rate influenced β-carotene retention and the stability of carrots during convective air drying.

Figure 1B shows the response surface plot for β-carotene in convective air dehydrated carrots for 6 h as a function of temperature and air flow rate. The predictive regression model was considered adequate because it was significant with a relationship between the variables at a 98.6% confidence level ($R^2 = 0.9857$). The model was fit to the following regression equation:

$$\beta\text{-carotene (mg/100 g dm)} = 118.256 + 9.7393T + 53.3397V - 0.110974T^2 - 0.306057TV - 6.25353V^2$$

where T is temperature (°C) and V is the air flow rate (10^{-1} m/s).

The model shows the reduction of β-carotene in carrots during convective air-drying. The linear and quadratic factors of temperature and air flow rate, as well as the interaction term between both of these independent variables, had a significant ($P \leq 0.05$) influence on β-carotene degradation, and the model indicated that the effect of temperature and air-drying flow could explain about 98.6% of β-carotene losses and only 1.4% of the variation was due to other factors not included in the model.

Table 1 and **Figure 1B** show that both air velocity and temperature affect the β-carotene content of carrots. The model showed that the optimal conditions to maximize the β-carotene content in air-dried carrots were 40 °C and an air velocity of 3.3×10^{-1} m/s.

Dehydration increases the vegetable surface area and leads to susceptibility of β-carotene to oxidation when exposed to light and oxygen unless the products are protected from air and light (*47*). In the present work, carrot slices were not protected from the daylight and they were exposed directly to the oxygen of the air during drying process. Therefore, higher losses of β-carotene were obtained when stronger air flows were used during dehydration, at a high drying temperature. Our results are quite similar to those reported by Negi and Roy (*26*), who found a β-carotene loss of 22% when carrots were dehydrated with a cabinet drying.

Different authors have also studied the effect of the moisture content and slice thickness of carrots during a drying process. Likewise, they have described the degradation kinetics of β-carotene during air-drying (*34*, *37*). The moisture loss of dehydrated carrots by convective air-dryer system carried out in the present work ranged from 81% for carrots dried at 43.4 °C and 2.6×10^{-1} m/s to 86% for those dried at 61.4 °C and 2.6×10^{-1} m/s (*35*), and among these samples significant ($P \leq 0.05$) differences in β-carotene content were found (**Table 1**).

Table 2 collects the content of vitamin C and β-carotene after the ultrasound drying process in different experimental conditions, both with and without a blanching pretreatment. The ultrasound treatment significantly affected ($P \leq 0.05$) the content of vitamin C in all the studied conditions (**Table 2**), and both low temperature and high drying time (20 °C, 120 min) led to the maximum vitamin retention (92%), while high temperature and short drying time (60 °C, 75 min) brought about larger losses of vitamin C, and a retention of 82% was obtained.

When carrot slices were submitted to blanching, a reduction of 18% in the vitamin C amount was observed (**Table 2**). Blanched carrot submitted to dehydration by means of ultrasound technology

led to a 45% reduction of vitamin C content compared to raw carrots, but no significant ($P \leq 0.05$) differences between temperature and drying time were found (**Table 2**). Following blanching, quite possibly the carrot tissue integrity may have been damaged and effects such as microagitation, creation of microscopic channels and cavitation of water molecules created during the ultrasound treatment led to further vitamin degradation, irrespectively of the temperature and drying time applied. No previous studies have been performed on the effect of ultrasound drying on the vitamin C content of carrots.

Table 2 also collects the changes which occurred in β-carotene during the dehydration of carrots with and without blanching pretreatment. Raw carrot slices submitted directly to ultrasound drying experienced a very low decrease in the content of β-carotene (2−4%) that, compared to the content in raw carrots, was only significantly ($P \leq 0.05$) different for the drying performed at 40 °C for 90 min and 60 °C for 90−75 min. This indicates a relative stability of β-carotene to the ultrasound drying conditions. However, blanching produced a slight but significant ($P \leq 0.05$) reduction of β-carotene (7%) (**Table 2**). Blanching pretreatment and subsequent ultrasonic drying led to further β-carotene reductions of 12−13% compared to the raw carrots. No significant ($P \leq 0.05$) differences among ultrasound conditions were found. No information has been found related to the effect of ultrasound drying in the content of β-carotene, and our results indicate that this mild dehydration procedure has a slight effect on the content of this provitamin A. Moreover, ultrasound dried unblanched carrots presented higher β-carotene content than those submitted previously to blanching. These results could indicate that, during blanching, the integrity of some carrot cells is disrupted, the tissues are heat-humidified and ultrasound waves can affect β-carotene stability, irrespectively of ultrasound conditions.

One of the main reasons for the use of ultrasonic energy in many applications of food technology is the high amplitude vibrations that are capable of increasing heat and mass transfer processes in materials by producing changes in concentration gradients, diffusion coefficients and boundary layer; this leads to the removal of moisture without significantly heating the product (*22*, *48*). The synergic effect of ultrasound and temperature increases the dehydration rate of carrots (*18*), and in the experimental conditions used in the present work, the moisture loss of ultrasound treated carrots was always superior to 85% (*20*), which is particularly useful for preserving the bioactivity of heat-sensitive carrot constituents, as has been shown for vitamin C and β-carotene. Sensitive indicators such as Amadori compounds formed in the early stages of the Maillard reaction are used to assess the quality of the heat dried carrots (*33*). The ultrasound dried carrots show that 2-furomethyl-amino acids were significantly ($P \leq 0.05$) lower than those of dehydrated commercial carrots whereas those samples subjected to blanching before ultrasonic drying presented higher Amadori compounds (*20*). This evidence calls attention to the strong effect of this thermal pretreatment of drying on quality parameters. Therefore, power ultrasound should be applied without blanching to obtain dehydrated products of good nutritional quality.

In conclusion, power ultrasound is an emerging technology to ensure good quality dehydrated carrots from the point of view of vitamin C and β-carotene content.

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