The spatial distribution of β -carotene impregnated in apple slices determined using image and fractal analysis

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Abstract Changes in the concentration profiles of β -carotene caused by diffusion through parenchymatic dried apple tissue were characterized by image and fractal analysis. Apple slices were dried by convection, and then impregnated with an aqueous β -carotene solution. Scanning electron microscopy images of dried apple slices were captured and the fractal dimension (FD) values of the textures of the images were obtained (FD_{SEM}). It was observed that the microstructure of the foodstuff being impregnated have an important effect on the impregnation phenomenon, generating irregular concentration profiles of β -carotene, which are numerically described by the fractal dimension FD_{PROFILES} and are related to the diffusion process during impregnation in dried edible tissue.

Keywords Diffusion profiles · Image analysis · Fractal analysis · Impregnation · Air drying

Introduction

Functional foods include any food or food component that provides human health benefits beyond basic nutrition. Recently, consumers have shown a great deal of interest in the inclusion of natural bioactive compounds as functional ingredients in their diets, given the various associated health benefits. Many foods and beverages are now enriched with vitamins (including folic acid and vitamin E), provitamins (such as carotenoids), pigments, and nutraceuticals. Nonetheless, the poor water-solubility, high melting point, chemical instability, and low bioavailability of certain hydrophobic vitamins has limited their use in the fortification of food products.

Impregnation of foodstuffs with nutrients by soaking them in solutions of physiologically active components can effectively incorporate nutrients into the edible parts of fruits and vegetables (Santacruz-Vázquez et al. 2008). This edible part is usually a parenchymatous tissue that provides a matrix structure. During impregnation, the rates of diffusion of water and active components depend on factors such as the temperature and concentration of the solution, and the moisture content, geometry, and size of the material being impregnated (Hawkes and Flink 1978; Kaymak and Cakaloğlu 1996).

Impregnation of dry or partially dry material involves both capillary action and diffusion. Whenever capillary forces govern the migration of water, variations in the sizes of the pores within the substrate complicate prediction of the efficiency of mass transfer. Diffusion is also altered by the tortuosity of the material, which further restricts mass transfer when the tissue shrinks during drying.

Understanding the mechanisms responsible for impregnation and diffusion of solution in dried matrix two main approaches used to describe such phenomena are (i) empirical or semi-empirical models, such as the Peleg or the Weibull equations (Hsu 1983; Peleg 1988; Peppas 1994; Machado et al. 1998, 1999; Weerts et al. 2003); and (ii) diffusive models based on Fick's second law (Khraisheh et al. 1997; Yildirim et al. 2011). In many studies that use Fick's law, movement of liquid water cannot be modeled simply as a diffusion process (Mayor and Sereno 2004). Profile analysis obtained from microscopic observations allows the application of novel kinetic models, which may be able to overcome some of the restrictions associated with the currently used Fickian models as complex and anisotropic cellular structure of vegetable tissues and the effects of mass transfer mechanisms. A distinctive feature of non-steady-state diffusion processes is the presence of non-linear concentration gradients for the species that is diffusing. Accordingly, image analysis and fractal geometry can describe processes associated with irregularly shaped structures, and thereby explain phenomena associated

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with the drying and impregnation of biological tissues with solutes (Quevedo et al. 2002).

The concept of fractal dimension (FD) was introduced to describe rough or irregular patterns in images. According to Quevedo et al. (2008), the texture of images usually called the texture feature (TF) provides an important means for pattern recognition to characterize the arrangement of basic constituents of a surface material. The TF is useful for the analysis and description of natural scenes and environments and for the classification or categorization of pictorial data (Quevedo et al. 2002; Santacruz-Vázquez et al. 2007; Valous et al. 2009). The TF can be determined by analyzing the surface intensity (SI), which is in turn obtained by plotting the pixel coordinates (x and y axes) against the gray level of each pixel (z axis) (Valous et al. 2009). When SI is characterized using FD, the TF is called the fractal texture of the image (Amadasun and King 1989; Quevedo et al. 2009). Furthermore, Pedreschi et al. (2000) showed that the FD of a surface dictates the fractal of the image intensity surface, which could be similar to the FD of the physical surface. Fractal texture has been reported to be sufficiently sensitive to detect the surface ruggedness of several products, including chocolate, bread, and potatoes (Kerdpiroon et al. 2007). The microstructure of materials has substantial effects on the physical properties of foodstuffs. Some examples include the deformation and shrinkage that occurs during drying, which is governed by the effects of the microstructural characteristics of materials on diffusion mechanisms and other parameters associated with moisture transfer (Dávila and Parés 2007).

Kerdpiroon et al. (2007) used fractal and image analysis to demonstrate a relationship between microstructural changes in carrot cubes and physical alteration of the cubes during air drying. Alamilla et al. (2005) evaluated the microstructure of dehydrated surfaces and observed changes that were proposed to be correlated with shrinkage of model food spheres. Aguilera and Lillford (1996) correlated the roundness, diameters, and orientations of pores, with the spatial distribution, density, and concentration of a particular component, as well as the extent of water diffusion during drying.

This study aimed to describe the diffusion profiles of β -carotene solution in parenchymatic apple slices using image and fractal analysis when air drying and impregnating process are combined to obtain a β -carotene enriched product.

Materials and methods

Raw materials

Apples (*Malus domestica*, Red delicious) were obtained at a local market in Puebla, Mexico. Apples were cut into slices (5.0 cm $\times$ 5.0 cm $\times$ 0.3 cm) parallel to the longitudinal axis of the fruit. The thicknesses of the slices were measured using a

micrometer (No. 39652-20, Mitutoyo, Japan). A dipping treatment to avoid browning was performed by immersing the slices in a 1,000 mg L⁻¹ solution of sodium bisulfite for 5 min.

Air-drying process

Apple slices were air-dried using a experimental laboratory-scale forced-air drier (Puebla, México) with air-flow parallel to the slice. Temperature and air-flow velocity were measured using a thermo-anemometer (LCA 6000, Air Flow Developments, Buckinghamshire, England), and air humidity was measured using a digital humidity meter (Testo 610, Shanghai, China). Samples were placed on a metal mesh. Variable drying air conditions were studied following a 2² complete factorial design, performing each experiment in triplicate: the air-drying temperature was set to either 60 °C $\pm$ 2 °C or 70 °C $\pm$ 2 °C, and the flow velocities were set at either 2 or 3 m s⁻¹. The final moisture content of the samples was 0.2 $\pm$ 0.05 g water g⁻¹ dry mass. Treatments applied to dry apple slices were named according to the temperatures and air-flow velocities used: DC60-2, 60 °C $\pm$ 2 °C and 2 m s⁻¹; DC60-3, 60 °C $\pm$ 2 °C and 3 m s⁻¹; DC70-2, 70 °C $\pm$ 2 °C and 2 m s⁻¹; and DC70-3, 70 °C $\pm$ 2 °C and 3 m s⁻¹.

Characterization of the roughness and irregularity of slice surfaces

The microstructures of dried samples were observed using a Scanning Electron Microscope (JEOL JSM-5900LV, magnification 300X). The images obtained were stored as bit maps in gray scale (255 Gy levels). The scanning differential box counting method was used to evaluate the FD of sample micrographs (FD_{SEM}) by using ImageJ 1.34 s software (National Institute of Health, NIH, USA), specifically the code proposed by Per Henden (Version 1.0, 2006).

Impregnation process

Dried apple slices were impregnated with β -carotene by immersing them in a β -carotene-water solution (0.1 g mL⁻¹) at 25 °C. The β -carotene used in the experiment, Lucarotin 1 CWD (CWD, cold-water dispersible), is a powder that consists of a dispersion of stabilized β -carotene in medium-chain triglycerides, which is embedded in the form of very fine droplets in a matrix of modified food starch (E 1450) and glucose syrup. Lucarotin 1 CWD, which contains DL- β -tocopherol (E 307) and sodium ascorbate (E 301) as antioxidants, and tricalcium phosphate (E 341) as an anti-caking agent, was acquired from the BASF Division of Nutrition and Human Health (Prod: 20177402, Ludwigshafen, Germany).

Dried apple slices were impregnated with the β -carotene solution in a polystyrene container filled with the liquid and a

plastic support that kept the sample completely submerged during treatment. The sample:liquid ratio was maintained at 1:10 to avoid significant changes in the composition of the medium. Samples were removed from the container after 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, and 120 min. Immediately after being removed, samples were blotted with tissue paper for 30 s to eliminate excess liquid.

Weight gain at any given time was calculated as the difference between the weight measured at that time and the initial weight.

Fractional impregnation (M_t/M_l) of β -carotene solution in dried apple slice under different conditions was determined as:

$$\text{Fractional impregnation} = M_t/M_l, \quad (1)$$

where M_t is the weight of the slices at impregnation time t (g), and M_l is the weight of the slices at equilibrium after impregnation (g).

Quantification of β -carotene by analysis of impregnated apple slices using high-performance liquid chromatography (HPLC)

The β -carotene contents of apple slices collected after different impregnation times were quantified using HPLC as described by Mercadante and Rodriguez-Amaya (1990). HPLC analyses were obtained of whole slices (5.0 cm $\times$ 5.0 cm $\times$ 0.3 cm) at different impregnation times (5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, and 120 min). Impregnated apple slices (approximately 3 g) were weighed on an Ohaus explorer balance (Zurich, Switzerland), ground using a pestle and mortar, and the homogenate was resuspended in 100 mL of cold HPLC-grade acetone (Merck, Darmstadt, Germany) at 5 °C. The mixture was then filtered, and several extractions were carried out until a clear extract was obtained. All HPLC analyses were performed using a Beckman System Gold High Performance Liquid Chromatograph instrument (Minnesota, USA) equipped with a UV–VIS detector and a Gold Nouveau™ 1.72 system for analysis of chromatographic data. A Prodigy™ 5 m ODS-2 chromatographic column (25 cm length and a 4.6 mm internal diameter) was used. The elution system involved a mix of HPLC-grade solvents (acetonitrile:methanol:tetrahydrofuran (65:25:10); Merck, Darmstadt, Germany) at a flow rate of 1 mL min⁻¹ (Bushway 1985). The β -carotene content was evaluated by means of a mass balance relationship:

$$CG = \frac{W_t X_{c_{ct}}}{W_o}, \quad (2)$$

where CG is the β -carotene gain, W_o is the initial weight of the sample (g), W_t is the weight of the sample after impregnation treatment at time t (g), and $X_{c_{ct}}$ is the β -carotene concentration at time t (mg g⁻¹ dry mass) obtained by HPLC analysis.

Diffusion coefficients in the impregnation process

The kinetics of the impregnation of dried apple slices was analyzed according to the unsteady-state Fick's diffusion law (Crank 1975; Kaymak and Cakaloz 1996; Rastogi and Raghavarao 2004). A simplified solution of Fickian equation was used to determine the diffusion coefficient. Fick's second law solution for β -carotene diffusion on an infinite slice can be written as follows (Crank 1975):

$$\frac{(c-c_0)}{(c_1-c_0)} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left[-(2n+1)^2 \pi^2 \frac{t}{l^2} D \right] \quad (3)$$

where c is the concentration of the diffusing component (mg/g), c_0 is the initial concentration of the diffusing component (mg/g), c_1 is the saturation concentration of the diffusing component (mg/g), t is the time of impregnation (s), l is the distance of diffusion (m), and D is the diffusion coefficient for the impregnating component (m² s⁻¹). The diffusion coefficients for β -carotene solution were determined from the slope of a logarithmic plot of $\frac{(c-c_0)}{(c_1-c_0)}$ against time.

Description of the spatial distribution of carotene by digital imaging and FD analysis

Concentration profiles of impregnated solution were observed by making a transverse cut through the center of the impregnated slice. The spatial distribution of the β -carotene introduced by impregnation was observed using a tri-ocular light microscope (American Optical Series 10 Trinocular Microscope, NY, USA) coupled to a Nikon SMZ-2T camera (Nikon Japan), and was used to generate images at intervals along the distance of diffusion after 30, 60, 90, and 120 min of impregnation. Observations were made using light source (6 V, 15 W incandescent bulbs) with an illumination angle of 60° with respect to the horizontal surface (Quevedo et al. 2002). The objects being observed were magnified 4X, and the exploration area was 5 $\times$ 0.3 mm. The plot profile was obtained by image analysis of light micrographs, and was defined as the dimensionless gray scale Y_s :

$$Y_s = \frac{(G_s - G_{s0})}{(G_{s1} - G_{s0})} \quad (4)$$

where Y_s is the dimensionless gray scale at impregnation time t , G_s is the gray scale at impregnation time t , G_{s0} is the gray level at time $t=0$, and G_{s1} is the saturation gray level. The FD_{PROFILES} was calculated using the box counting algorithm via the use of ImageJ software (version 1.42q, National Institutes of Health, Bethesda, MD) as described by Sansiribhan et al. (2012) (Fig. 1).

Statistical analysis

The experimental data were analyzed by determining the analysis of variance (ANOVA) using SPSS® software (version 13; SPSS, Inc., Chicago, IL). The results are presented as mean values with standard deviations. Duncan's multiple range test was employed to establish differences between mean values at a confidence level of 95 %. All experiments were performed in triplicate.

Results and discussion

Effect of the initial microstructure of apple on the impregnation process

Prior to impregnation with β -carotene solution, apple slices were dried by convection under different drying conditions to obtain a moisture content of $0.2 \text{ g water g}^{-1}$ dry mass.

Scanning electron micrographs of dried apple slices at different conditions are shown in Fig. 2. The dried apple microstructure showed extensively wrinkled cells, with damaged and disrupted walls caused by the dehydration process. It was possible to obtain microscopically dense products as a

result of compact folds of the cell wall in samples dried using the conditions DC70-2 and DC70-3, whereas samples prepared using the conditions DC60-2 and DC60-3 showed an increase in the irregularity of the folds of the cell wall, resulting in less dense products that are more porous and rough. Similar results were obtained by Ramos et al. (2004) and Askari et al. (2009). Changes in the microstructure of apple slices during convective drying were described by FD_{SEM} .

Analysis of the FD_{SEM} values (Fig. 2) indicated that convective drying of apple slices at 70°C with an air-flow velocity of 3 m s^{-1} produced a less rougher tissue microstructure than the other conditions tested, most likely as a consequence of ordered rapid water loss during drying (Witrowa-Rajchert and Rzaca 2009). The highest FD_{SEM} value was obtained for samples dried at 60°C with an air-flow velocity of 2 m s^{-1} (DC60-2). This suggests that the roughest microstructure of apple slices might result from the rapid escape of water and vapor, which breaks tissues and causes the formation of large pores or tunnels, resulting in substantial structural damage. Tissues dried at 70°C and air-flow velocity of 3 m s^{-1} (DC70-3) had a more homogenous cellular structure than those dried at 60°C – 2 m s^{-1} (DC60-2) as a result of slower, more orderly dehydration (Fig. 2).

Fig. 1 Diagram of experimental procedure

Fig. 2 SEM photomicrographs of dried apple tissue at different conditions and their corresponding FD_{SEM} values

Samples dried at 70 °C and air-flow velocity of 2 m s⁻¹ (DC70-2) and at 60 °C and air-flow velocity of 3 m s⁻¹ (DC60-3) had intermediate levels of homogeneity, with the former being more homogenous than the latter.

The micrographs shown in Fig. 2 reveal that the microstructure of foodstuffs plays an important role in the impregnation phenomenon, generating irregular concentration profiles of β -carotene. These concentration profiles are numerically described by the fractal dimension $FD_{PROFILES}$, which is related to the diffusion process during impregnation of dried food tissue.

Impregnation process

The fractional impregnation (M_t/M_1) of dried apple slices with β -carotene solution is shown in Fig. 3. Loss of solids during soaking was minimal (2.6 % $\pm$ 0.3 % of the original total solids content).

Graphical representation of changes in (M_t/M_1) over the course of impregnation revealed two stages (Fig. 3). During the first stage, the impregnation of β -carotene solution in the tissue was fast ($t < 15$ min), with a higher diffusion rate than during the second stage ($t > 60$ min). The impregnation rate was low during the second stage and saturation was achieved after 120 min of impregnation.

The maximum concentrations of β -carotene in dried apple slices were 4.1, 3.2, 3.6, and 2.8 mg g s.s⁻¹ for the samples subjected to conditions DC60-2, DC60-3, DC70-2, and DC70-3, respectively.

An overall increase in fractional impregnation (M_t/M_1) of β -carotene solution from 0 to 1 was observed in apple slices. In apple slices dried using the DC70-2 condition, the level of solution of impregnated β -carotene during the first 60 min of impregnation was 9.4 %, 3.5 %, and 3.8 % higher than for those dried using the DC60-2, DC60-3, and DC70-3 conditions, respectively. However, during the second stage, the samples dried using condition DC60-2 displayed higher values of fractional impregnation (M_t/M_1) than in any of the three other conditions tested. These results can probably be attributed to the large pores in the apple slices used, which increased the rates of impregnation during the second stage of impregnation. Statistical analysis by multiple comparisons revealed significant differences in values of fractional impregnation (M_t/M_1 ; $P \leq 0.05$) during impregnation of apple slices with β -carotene under different conditions.

Analysis of the effect of microstructure on the kinetics of sample impregnation revealed that the diffusivity of β -carotene solution in apple slices was strongly affected by the formation of a crust on the slice surface, which hardened during drying. Diffusion coefficients for the impregnated β -carotene solution are listed in Table 1. The adequacy of the Fick's law model for fitting the β -carotene concentration data and to obtain diffusional coefficient during impregnation of dried apple slices was evaluated by determining the correlation value R^2 . The kinetic data and diffusional coefficient determined during the impregnation of dried apple slices with β -carotene solution are functions of the microstructure of the slices and the convective drying conditions used, which also

Fig. 3 Fractional impregnation (M_t/M_i) of β -carotene solution in dried apple slices

affected the overall quality of the final product. Statistical analysis showed that microstructure significantly affected the diffusional coefficient (D) ($P < 0.05$; Table 1).

Description of experimental diffusion profiles by image analysis

Parenchymatous tissue provides channels for the movement of fluids (Figs. 4a, 5a, 6a and 7a), and thus permits rapid penetration of exogenous β -carotene solution into the tissue in apple fruits during impregnation.

Figures 4a, 5a, 6a and 7a show impregnated apple viewed under light microscopy (4X). Diffusion of the β -carotene solution depends on the topography of the solid surface,

which makes contact with the liquid phase, resulting in heterogeneous diffusion fronts with a possible resistance to the solution of β -carotene.

The profiles obtained by image analysis for the impregnated apple slices are shown in Figs. 4b, 5b, 6b and 7b. Irregularities on the topography of the apple microstructure in the impregnation process are reflected by the irregular profiles observed. The distribution of β -carotene throughout the sample was analyzed using image analysis, and expressed as reduced driving force values (Y_s from Eq. 3).

Values of Y_s were obtained as a function of the dimensionless thickness X/L , representing the saturation degree and distribution caused by the diffusion of β -carotene along the impregnation distance (Figs. 4c, 5c, 6c and 7c). The tissue closest to the interface with β -carotene solution (X/L close to 1) was characterized by zones with higher β -carotene levels than the innermost areas. The outermost areas of tissue were darker than the innermost areas. The tissue located far from the interface (X/L close to 0, at the center of slice) appeared a lighter gray, which was associated with lower concentrations of β -carotene solution than tissue near the sliced surface.

The values of Y_s reported in Figs. 4c, 5c, 6c and 7c show the effect of impregnation time on the samples. For all processing conditions, the profile at 30 min shows a higher concentration gradient of the β -carotene solution along the impregnation distance, as opposed to the results at impregnation times of 60, 90, and 120 min. At $X/L = 0$ (center of the slice), values of Y_s for samples subjected to the DC60-2

Table 1 Values of the diffusional coefficient (D) of β -carotene solution in apple slices dried under different drying condition during impregnation at 25 °C

Convective drying air temperature T (°C)	Convective drying airflow v (m/s)	β -carotene diffusion coefficient D ($\text{m}^2/\text{s} \times 10^{11}$)	Correlation value R^2
60	2	1.88 a	0.92
60	3	2.89 a	0.95
70	2	3.94 a	0.98
70	3	4.74 a	0.96

Values in the same column with the same letters are significantly different ($P > 0.05$)

Fig. 4 Light microscopy images (4X) (a) and gray scale profiles of impregnated apple tissue dried at 60 °C with an air-flow velocity of 2 m s⁻¹ (b, c)

condition (Fig. 4c) are 0.70 for impregnation times of either 30 or 60 min, and 0.82 and 0.9 for impregnation times of 90 and 120 min, respectively. The decrease in concentration gradients with impregnation time results from saturation of the matrix.

It was evident that rates of impregnation with β -carotene under condition DC60-2 probably exceeded those under any of the three other conditions tested as a result of the porous apple microstructure. This is reflected by a rapid uptake of

Fig. 5 Light microscopy images (4X) (a) and gray scale profiles of impregnated apple tissue dried at 60 °C with an air-flow velocity of 3 m s⁻¹ (b, c)

β -carotene solution into the solid matrix until the structure becomes saturated. These results agree with the kinetics of impregnation shown in Fig. 3.

Figure 5c shows that the values of Y_s at the center of a slice subjected to the DC60-3 condition for either 30 or 60 min is 0.75, and is 0.82 after either 90 or 120 min. This indicates that

at any given impregnation time, peripheral parts of the slice take up the β -carotene solution more rapidly than the center of the slice showing a resistance to the movement of β -carotene solution to innermost areas. Values of Y_s higher than 0.9 are obtained when uniform and complete impregnation occurred after the treatment of apple slices for 120 min.

Fig. 6 Light microscopy images (4X) (a) and gray scale profiles of impregnated apple tissue dried at 70 °C with an air-flow velocity of 2 m s⁻¹ (b, c)

Fig. 7 Light microscopy images (4X) (a) and gray scale profiles of impregnated apple tissue dried at 70 °C with an air-flow velocity of 3 m s⁻¹ (b, c)

The effects of the dry air temperature on the microstructures of the samples and their impregnation profiles are shown in Figs. 6c and 7c. It was observed that after 30, 60, 90, and 120 min of impregnation, the values of Y_s ($X/L = 0$)

were lower for samples subjected to the DC70-2 condition than for samples subjected to the DC60-2 condition. Therefore, at the same zone of the sample (close to the center of the slice), the degree of penetration of the solution was

Table 2 FD_{PROFILES} values recorded during the impregnation of dried apple slices with β -carotene solution for different impregnation times

Treatments	30 min	60 min	90 min	120 min
DC60-2	1.021 a	1.031 b	1.036 c	1.095
DC60-3	1.019 a	1.062 b	1.132 c	1.145 d
DC70-2	1.051 a	1.082 b	1.133 c	1.172 d
DC70-3	1.095 a	1.145 b	1.172 c	1.095

Values in the same column with the same letters are significantly different ($P>0.05$)

lower for samples subjected to the DC70-2 condition than for samples subjected to the DC60-2 condition. This behavior may result from cellular collapse of the tissue, which has been reported during drying at high temperatures (Ramos et al. 2004; Sansiribhan et al. 2010). Collapse of the tissue prevents the generation of a homogeneous impregnation profile. Consequently, the extrinsic aspects of the drying treatment (e.g., the air drying temperature and air-flow velocity) affect the mechanical conditions of the matrix that is being impregnated (through shrinkage and cellular collapse), and thereby affect the entire impregnation process. The impregnation profiles of samples subjected to the DC60-3 and D70-3 conditions (Figs. 5c and 7c) were significantly different ($P<0.05$).

Characterization of the irregularity of profiles

As a consequence of the irregular microstructure of dried apple tissue, an irregular impregnation profile (values of Y_s) was obtained. The irregular distribution of β -carotene solution in apple slices, represented by jagged profiles, was evaluated as a gray-scale distribution and then characterized by FD analysis of the gray scale profile (FD_{PROFILES}). Given that the FD_{PROFILES} values were higher than 1.0 (Table 2), this process is irregular and has a fractal nature. Peleg and Barbosa (1993) reported that jagged lines must have a FD between 1.0 (Euclidian) and 2.0, and that the greater the line tortuosity, the higher the FD. Therefore, FD_{PROFILES} is useful as a measure of the degree of jaggedness of impregnation profiles in apple slices.

The FD_{PROFILES} values are quantitative indicators of the roughness of the diffusion process in the matrix. Given that the diffusion process is non-uniform, the media may be regulated by non-linear dynamics and produce concentration profiles with fronts that have fractal morphologies (Peleg and Barbosa 1993).

The FD_{PROFILES} values (Table 2) indicated that tissues dried at 70 °C with an air-flow velocity of 3 m s⁻¹ had a more homogenous cellular structure than did tissues subjected to any of the other conditions tested. This was the result of an ordered dehydration process, which is reflected in the

diffusion of β -carotene solution into the tissue during impregnation. Values of FD_{PROFILES} for samples dried at 70 °C (DC70-2 and DC70-3) were lower than those obtained at 60 °C (DC60-2 and DC60-3). Analysis of the FD_{SEM} values for the dried apple slices revealed a similar tendency. The impregnation rate of dried apple slices with β -carotene is a function of both the microstructure of the tissue and the convective drying conditions, which also affected the overall quality of the final product. Statistical analysis (Table 2) showed that FD_{PROFILES} was significantly affected by the microstructure of the sample ($P<0.05$).

Conclusions

The combination of convective drying and impregnation provides an alternative to current approaches used for the nutritional fortification of apples with β -carotene.

The FD, topography, and electronic micrographs of food-stuffs are tools that demonstrate the complexity of diffusion mechanisms, given that convective microstructural changes of the product are intimately bound to the spatial distribution of the β -carotene solution in a solid food matrix.

The diffusion process associated with the impregnation of fresh, dried, or partially dried foods with nutritional supplements is affected by a range of complex microscopic mechanisms. Fractal geometry can be used to correlate the selected quantitative microstructural changes caused by characteristic physical changes, such as shrinkage and changes in hardness during convective drying and impregnation process.

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