Quality evaluation of pineapple fruit during drying process

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ABSTRACT

Pineapple (*Anana comosus*) slices were dried by hot-air convective drying technique at fixed temperature (45, 60 and 75 °C) and constant air velocity of 1.5 m/s. The effect of drying conditions (drying time and air temperature) on the pineapple quality was evaluated. The quality of dehydrated pineapple was analyzed by color and texture changes, L-ascorbic acid loss and the ability of water uptake during rehydration procedure. Water uptake during rehydration was described by Page model. Statistical analysis of data revealed not significant difference ($p > 0.05$) among color and mechanical characteristics of pineapple samples dried at different drying temperatures to preset moisture content. Pineapple samples dried at 45 °C had better rehydration ability and more L-ascorbic acid retention than those obtained by air drying 75 °C. Hence, 45 °C drying temperature was best condition for pineapple quality preservation.

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1. Introduction

Pineapple (*Anana comosus*) is a tropical fruit with attractive sensorial (mechanical properties, flavour, acidity/sweetness ratio, color) and nutritional (ascorbic acid, minerals, fibres, antioxidants, etc.) characteristics. Nevertheless, drying process can induce numerous physical and chemical changes in plant tissues, which have a high impact on its overall quality. So, a loss of rehydration ability, ascorbic acid degradation, color changes, shrinkage, etc., can take place during drying of pineapple.

The deterioration of the color attributes with drying conditions has been widely studied in a large number of vegetables, mainly in apple (Mandala et al., 2005); banana, carrot and potato (Krokida et al., 1998); kiwi fruit (Maskan, 2001); cherries (Ohaco et al., 2001); quince, prune and strawberry (Tsami and Katsioti, 2000), among others. Pineapple color is a decisive factor in the judging of product acceptability since a pale yellow is associated with ripening and development of the flavour characteristic of the fruit (Bartolome et al., 1996).

Shape distortion and mechanical property changes are evident negative effects of drying process (Lewicki, 2006). In order to reduce these disadvantageous effects of drying on the food quality, process conditions must be carefully designed. Same textural attributes of apple rings were greatly influenced by air temperature of drying (Farris et al., 2008); Leite et al. (2007) showed that softer texture was presented by the product generated at the lower temperature during drying of banana. Nevertheless, the effect of the drying temperature on the compression characteristics of durian chips was found insignificant (Jamradloedluk et al., 2007).

Degradation rate of ascorbic acid is affected by several factors such as temperature, water activity, pH, storage time and metal ions (Fennema, 1993; Pardio Sedas et al., 1994). The retention of ascorbic acid during vegetable drying is a function of process conditions. Zanoni et al. (1999) studied the loss of vitamin C during tomatoes drying at 80 and 100 °C, determining that nutrient degradation is affected by the temperature of the process. Similar results were published by Orikasa et al. (2008) in a study of kiwi drying. Santos and Silva (2009) studied the effect of ethanolic atmosphere on the degradation kinetics of ascorbic acid and the drying behavior of pineapple. Pardio Sedas et al. (1994) studied ascorbic acid loss in pineapple during storage under fixed conditions of temperature and relative humidity.

The largest part of the dehydrated products must be rehydrated during their final use. Rehydration is a process performed in order to obtain an adequate restitution of raw material properties when dried material is in contact with water (Taiwo et al., 2002). In some foods, as dry fruits for breakfast, the rehydration velocity is very important in the judgment of its quality. Some authors modeled the rehy-

Nomenclature

AA	ascorbic acid
a, b, L	coordinates of the Hunter color scale
A_o	contact area (m²)
C	L-ascorbic acid content (mg/g of dry matter)
COR	coefficient of rehydration, dimensionless
E	elasticity or deformability modulus
Epp	average relative error
$F(t)$	force (N)
$H(t)$	height (m)
K, N	Page model parameters
m_{dh}	mass of dehydrated sample, before rehydration (kg)
m_{rh}	mass of rehydrated sample (kg)
MR	moisture ratio, dimensionless
n	number of observations used in calculation
RR	rehydration ratio, dimensionless
t	time (min)
W	moisture content at time t (kg water/100 kg dry matter)
W_{dh}	moisture content, after drying (kg water/100 kg dry matter)
W_e	equilibrium moisture content (kg water/100 kg dry matter)
W_f	moisture content at the end of rehydration (kg water/100 kg dry matter)
X_0	moisture content of fresh fruit (kg water/100 kg solid)
X_{dh}	moisture content, after drying (kg water/100 kg solid)
X_{rh}	moisture content of rehydrated sample (kg water/100 kg solid)
σ_H, ε_H	Hencky parameters

dration process as a diffusive phenomenon described by second Fick's Law (Sanjuán et al., 1999). Krokida and Marinos-Kouris (2003) studied the rehydration kinetics of various dehydrated fruits and vegetables, in which the water gain follows a first order kinetics. Other authors have applied empirical models to describe the process (García-Pascual et al., 2006).

Drying processes induce many changes in the structure and composition of plant tissue which result in damaged reconstitution properties as rehydration degree (Lewicki, 1998). Degree and velocity of rehydration are dependent as much of the nature and composition of the vegetable as of conditions of dehydration and rehydration processes (McMinn and Magee, 1997; Krokida and Marinos-Kouris, 2003; Khraisheh et al., 2004).

The objective of the present work was to determine the effect of drying conditions (drying time and air temperature) on the pineapple quality. The quality of dehydrated pineapple was evaluated by color and texture changes, L-ascorbic acid loss and the ability of water uptake during rehydration procedure.

2. Materials and methods

2.1. Sample preparation

Pineapple Fruits (*A. comosus*) of the Smooth Cayenne variety were purchased from the local market. Fruits, in the range 11.2–12.8° Brix, were manually peeled, cored and cut into half rings (slices) of 6.0 ± 0.5 mm thick and 115 ± 5 mm in diameter. Because there is a great variation in the nutrients content between the base and the top of the fruit (Miller and Hall, 1953; Ramallo and Mascheroni, 2004), only the central zone of each pineapple fruit was used in experiments.

2.2. Drying process

Drying experiments were performed in a convective cross flow pilot dryer at 45, 60 and 75 °C, by triplicate. Air velocity was fixed at 1.5 m/s. The pineapple slices were put in an aluminum basket avoiding the contact between fruit pieces. At pre-established times, three samples were removed (at random) from the dryer; in order to measure the color and determine moisture and ascorbic acid content.

Moisture content was determined gravimetrically by oven drying at 75 °C until constant weight (48 h approximately).

2.3. L-Ascorbic acid determination

2.3.1. Extraction process
All analyses were carried out by duplicate on vegetable tissue. Each sample (7–9 g) was weighed and crushed in porcelain mortar for 5 min, with gradual addition of 50 mL of buffer solution (pH 2.5). Buffer solution used in this step is the same of mobile phase. This mixture was transferred to a dark flask, sonicated for 10 min and then filtered though filter paper. Portions of the extract (10 μL) were injected into the HPLC chromatograph. All procedures were carried out carefully without much exposure to light.

2.3.2. Quantitative determination
L-Ascorbic acid was determined by high performance liquid chromatography (HPLC), in isocratic conditions with an All-tima C-18 column (250 mm × 4.6 mm, 5 mm particle size). A mobile phase of buffer (potassium phosphate 0.02 M, pH = 2.5 by phosphoric acid):acetonitrile (98:2, v/v) was used at a flow rate of 1.0 mL/min. Detection of L-ascorbic acid was carried out at $\lambda = 254$ nm. Identification and quantification were carried out by comparison of the retention time and the peak area of the sample with those of a standard reference. Standard solution of L-ascorbic acid was prepared by diluting 100 mg L-ascorbic acid (A-0278, Sigma) in 100 mL buffer; then this solution was diluted (1/10, 1/50 and 1/100). The reference peak area was obtained by injecting 10 μL of solution with standard concentration of 0.02 mg/mL (external standard procedure). During the assay, the reference chromatogram was done every 2 h.

2.3.3. L-Ascorbic acid variation in fresh fruit
Variation of L-ascorbic acid content in fresh fruit as a function of position from the bottom towards the top was studied. Fruits were peeled, cored and cut into slices of 13 ± 1 mm thickness; these slices were classified according to the position (number 1 is the top); 8–9 slices of each fruit were obtained. The L-ascorbic acid content in each piece was evaluated. This experiment was carried out by triplicate.

2.4. Color

The color of pineapple was measured before drying and at different time intervals during drying by a HunterLab® D25A-9 colorimeter (HunterLab, Reston, VA), with a measuring area of

50 mm diameter. Before the color measurements, the instrument was calibrated using a standard white plate ($x = 82.43$, $y = 84.55$, $z = 99.39$) and a standard black plate ($x = 0$, $y = 0$, $z = 0$).

Pineapple samples were placed within a glass Petri dish of 60 mm-diameter and 10 mm-depth. Slices were superposed so as to cover completely the surface. During the measuring, the Petri dish with samples was covered by a black cylindrical box. The illumination was done from the bottom side of the glass Petri.

Each measurement was registered as the average of four readings on a same sample, rotating the container (Petri dish) 90° between each reading. In fresh fruit, color measurements were done by triplicate taking samples from different zones of the fruit. Pineapple color was measured in CIE and Hunter scale in which $+a$, $-a$, $+b$, $-b$ represent red, green, yellow and blue respectively; L characterizes lightness with a range from 0 (black) to 100 (white). From those values, *Hue* angle and *Chroma* parameters were calculated through Eqs. (1) and (2):

$$Hue\ \text{angle} = \tan^{-1}\left(\frac{b}{a}\right), \quad (\text{when } a > 0) \tag{1a}$$

$$Hue\ \text{angle} = 180 + \tan^{-1}\left(\frac{b}{a}\right), \quad (\text{when } a < 0) \tag{1b}$$

$$Chroma = (a^2 + b^2)^{1/2} \tag{2}$$

Hue parameter describes what people think when they describe the color (i.e. green, red, yellow, etc.), while the *Chroma* represents the intensity or purity of the *Hue*.

2.5. Rehydration

2.5.1. Experimental methodology

Samples for the rehydration tests were obtained at the end of drying process. Rehydration experiments were performed by immersing each sample (a slice of dehydrated pineapple) in a glass beaker containing 150 mL of deionised water at temperature of the test (25 or 40 °C); then, the glass container was placed onto the thermostatic hot-plate provided with a magnetic stirrer and was covered with aluminum film; the system was agitated at constant speed (70 rpm) throughout the test. Samples were weighed before rehydration procedure (m_{dh}).

Pineapple slabs were removed at predetermined time intervals; the adhering water was carefully blotted with filter paper, weighed (m_{rh}) and immediately returned to the same soaking water. This procedure was repeated until constant weight during an immersion period of 15 min. All the experiments were performed in triplicate.

From moisture content data previous to rehydration (after of drying) and the increase of sample weight, the water content in the fruit during rehydration, in grams of water per 100 g of dry matter, was evaluated.

Low temperatures were chosen to study the fruit rehydration because a probable application of the pineapple dehydrated in breakfasts, added to milk or yogurt, and in the dessert elaboration is expected, where the rehydration process takes place at low temperatures and short times.

There are numerous works in which researches measure the ability of the dried material to rehydrate; nevertheless there is no consistency in the experimental procedures applied nor in the nomenclature used (Lewicki, 1998).

In order to quantify the capacity of dehydrated pineapple to rehydrate two coefficients were used: the rehydration ratio (RR) and the coefficient of rehydration (COR).

The rehydration ratio (RR) is defined as the mass ratio of rehydrated sample to that of dry sample (Cunningham et al., 2008).

$$RR = \frac{m_{rh}}{m_{dh}} \tag{3}$$

The coefficient of rehydration, which indicates the degree of weight recovery with respect to the fresh product, is calculated according to the following expression (Prabhanjan et al., 1995; Khraisheh et al., 2004):

$$COR = \frac{m_{rh}(100 - X_0)}{m_{dh}(100 - X_{dh})}, \tag{4}$$

where m_{rh} is the mass of rehydrated sample (g); m_{dh} is the mass of dehydrated sample (before rehydration); X_{dh} is the moisture content (% wet basis: g water per 100 g of matter) of sample after drying; X_{rh} is the moisture content (% wet basis) of the rehydrated sample (during rehydration process); X_0 is the moisture content (% wet basis) of fresh fruit, previous to drying.

2.5.2. Mathematical modeling of rehydration

The Page model was used to describe the water uptake kinetic of dehydrated pineapple during the rehydration process at constant temperature. This empirical model is based on the following assumptions: water temperature is constant during rehydration and initial moisture content is uniform.

With the aim of explaining the water loss during single-layer drying Eq. (5) was developed (Page, 1949):

$$MR = \frac{W - W_e}{W_{dh} - W_e} = \exp(-K\,t^N) \tag{5}$$

The equilibrium moisture content, W_e, can be approximated by the moisture content at the end of the process (W_f). This modification was applied for rice drying by Ramesh and Rao (1996), obtaining the following equation:

$$MR = \frac{W - W_f}{W_{dh} - W_f} = \exp(-K\,t^N) \tag{6}$$

It was considered appropriate to apply Eq. (6) for the analysis and description of the rehydration kinetic of pineapple slices. In this equation W_{dh} represents the fruit moisture content (kg water per 100 kg of dry matter) at the beginning of the rehydration process and W is the moisture content (kg water per 100 kg of dry matter) at time t (min).

Plots of $\ln(MR)$ vs. immersion time t were constructed from experimental data and K and N values were estimated by lineal regression analysis of Eq. (7).

$$\ln(MR) = -K\,t^N \tag{7}$$

In order to evaluate the goodness of fit, the average relative error (Epp) criterion (Eq. (8)), was applied, where n is the number of experimental data, W_{exp} and W_{calc} are experimental and calculated values of average moisture content, respectively.

$$Epp = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{W_{exp} - W_{calc}}{W_{exp}} \right| \times 100 \tag{8}$$

2.6. Evaluation of mechanical properties

Mechanical properties of fresh and dehydrated samples were analyzed through uniaxial compression test (TA-XT2i Texture Analyzer with a 60 mm acrylic plate).

Pineapple slices were cut out into 25 mm-diameter discs. The applied compression rate was 0.5 mm/s, until 50% sample deformation of the original height. These assays were performed on five samples from different processed slices; then these five measures were averaged.

Also, force $F(t)$(N) and height $H(t)$(m) data were recorded. These data were turned into Hencky parameters: stress (σ_H) and strain (ε_H), by assuming constancy of sample volume during compression test (Rodrigues et al., 2003; Chiralt et al., 2001), according to Eqs. (9) and (10).

$$\sigma_H = \frac{F(t)H(t)}{H_0 A_0} \qquad (9)$$

$$\varepsilon_H = -\ln\left(\frac{H(t)}{H_0}\right) \qquad (10)$$

where A_o (m^2) is the initial contact area, H_o (m) is the sample height at beginning of compression test and $H(t)$ is the height after a deformation time t. Stress (σ_{HF}) and strain (ε_{HF}) at fracture were determined at the maximum point of stress–strain curve. The elasticity or deformability modulus (E) was calculated from the slope of the initial linear portion of the stress–strain curve when sample deformation (small-strain) was not higher than 6% (Ribeiro et al., 2003; Renkema et al., 2001):

$$E = \left(\frac{d\sigma}{d\varepsilon}\right)_{\varepsilon \to 0} \qquad (11)$$

3. Results and discussions

Drying tests of half pineapple slices at 45, 60 and 75 °C were carried out. Values of the moisture content between 720 ± 60 g of water by 100 g of product (in fresh fruit) and 43 ± 18 g of water by 100 g of product (in dry fruit), and drying times between 150 and 430 min, were found. Dimensionless moisture content (W/W_0) during pineapple drying is shown in Fig. 1a (W_0 is the moisture content of fresh fruit and W is the moisture content at time t). The temperature effect on the behavior of dehydration rate (water extracted in a time interval divided this time interval [g water/100 g dry matter / min]) as a function of drying time can be observed in Fig. 1b. As it can be seen, the constant rate drying period was absent in the dehydration of pineapple slices under these experimental conditions.

3.1. Color

3.1.1. Color parameters a, b and L
The increase of a and b parameters was independent of the drying temperature (Fig. 2). The relative visual yellow color (b value) was slightly increased during drying at 45 and 60 °C, and practically remained without changes during the drying at 75 °C. Similar results for the variation of values of parameter a were found by Chutintrasri and Noomhorm (2007) in pineapple puree during thermal processing at 70–110 °C. These authors found that values of parameter b remained constant during thermal processing at 70 °C.
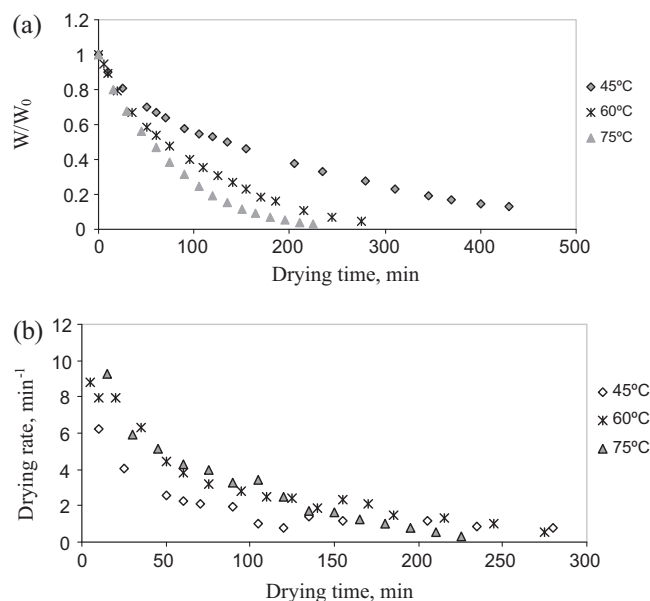

Fig. 1 – Effect of drying air temperature on (a) moisture ratio and (b) drying rate of pineapple slices.

During drying at 75 °C the only observed variation was the increase in parameter a (from -12.41 ± 1.73 to -7.02 ± 0.4), which would mean that the system lowered green pigmentation without increases in the yellow color.

Variations of L values were not significant during pineapple drying; this parameter was not affected by process temperature. In addition, an important dispersion of measured L values was observed. Similar observations about of L values (notable dispersion of measured values; without tendency to change during the process; independence of the drying temperature) were reported by Krokida et al. (1998) during apple, banana, carrot and potato drying and by Tsami and Katsioti (2000) during the drying of strawberries.
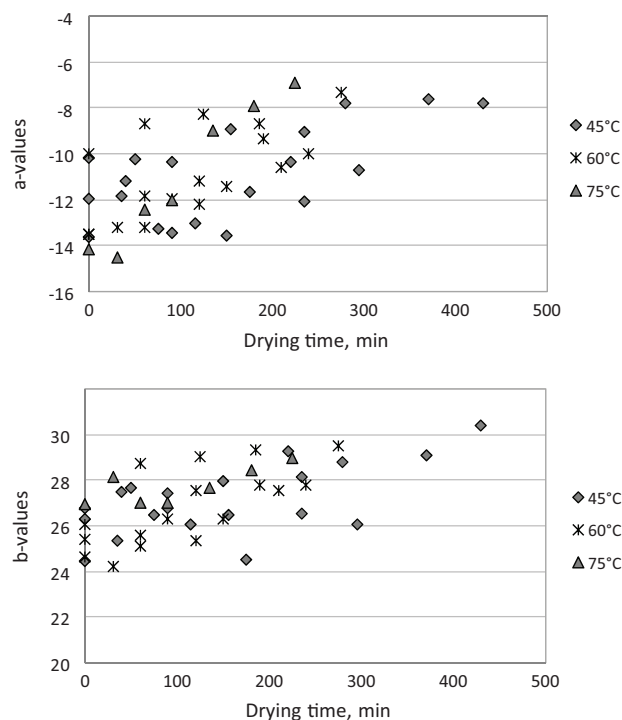

Fig. 2 – Variation of a and b values during pineapple drying at 45, 60 and 75 °C.
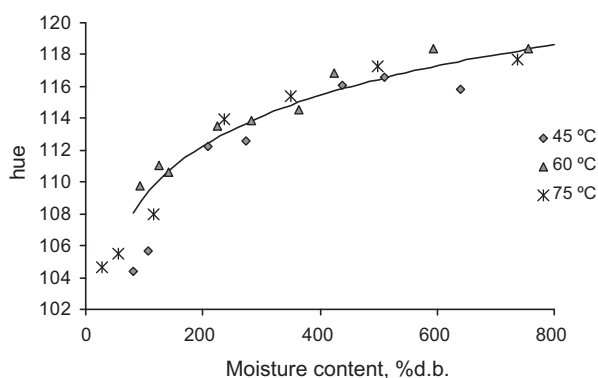
Fig. 3 – Relationship between *hue* parameter and moisture content during pineapple drying at 45, 60 and 75 °C. Full line: values estimated with Eq. (12).

Pineapple slices tend to get darker ("more red") as drying proceeds (as a result of non-enzymatic browning reactions) as indicated by the progressive increasing of *a* values, without change of *L* values.

The average *L*-, *a*- and *b*-values of fresh pineapple were 68.77 ± 2.63, -12.41 ± 1.73 and 28.23 ± 1.67, and of dried pineapple were 69.26 ± 2.92, -8.62 ± 0.85 and 29.11 ± 1.58, respectively.

3.1.2. Hue and Chroma parameters

The overall appearance of any product is a combination of its chromatics attributes (color) and its geometric attributes. Chromatic attributes are those attributes associated with color. They are: Lightness (*L*), *Hue* and *Chroma*. *Hue* is widely used as analytical tool for describe the color, since it is the attribute by means of which a color is perceived to be red, yellow, green, blue, etc. The *hue* angle values vary from 0 (pure red color), 90 (pure yellow color), 180 (pure green color) to 270 (pure blue color).

In all measurements on fresh fruit the *hue* value was higher than 100; this value lowered as the dehydration progressed, although smaller values to 90° never were registered. This fact indicates reduction of green color (when *hue* > 90) but without reaching the orange-red color (when *hue* <90).

Hue was the color parameter that showed more significant and regular changes during the process. It was found that the variation of *hue* with drying time had a linear behavior and its change rate increased with the process temperature, denoting an increase in yellowness.

The statistical analysis of experimental data indicated that *hue* parameter has a semi-logarithmic variation with moisture content and the consequent empirical model, Eq. (12), is independent of drying temperature. The curve predicted for this equation is shown in Fig. 3 as a full line. The squared correlation coefficient between observed and predicted values (r^2) was 0.9065.

$$hue = 4.8843 \ln(W) + 86.03 \tag{12}$$

Chroma or saturation represents the degree of departure from gray, it is the purity of color. A greater *chroma* value represents a more pure and intense color. *Chroma* had a slight increase during drying at 45 and 60 °C and very little (or no) variation at 75 °C (not shown here). This indicates stability of color during drying of pineapple fruit. *Chroma* values ranged between 28 and 32. Maskan (2001) has reported similar behavior of *chroma* values during drying of kiwifruits.
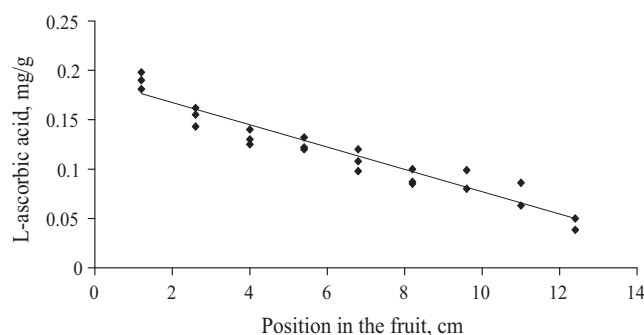

Fig. 4 – L-Ascorbic acid content in function of slice position into a fresh fruit (distance from the top).

After all these observations, we can suppose that changes in the color are due to pigments concentration during the drying.

3.2. L-*Ascorbic acid content*

3.2.1. L-*Ascorbic acid variation in fresh fruit*
L-Ascorbic acid content results show a linear variation with the distance from the top. Eq. (13) gives an adequate fit ($r^2 = 0.922$)

$$C_{AA} = C_{max} - 0.00113y, \tag{13}$$

where C_{AA} = average L-ascorbic acid content in the slice, mg/g of fruit; C_{max} = maximum value of L-ascorbic acid content in the fruit, mg/g of fruit; y = slice position in the fruit, distance from the top, mm.

Experimental results of L-ascorbic acid content distribution in the fresh fruit are shown in Fig. 4. Tissue heterogeneity of pineapple fruit indicates the need for caution in the determination of the initial content of vitamin C and explains the variability of results obtained during the study. Similar situation was observed in green vegetables (Giannakourou and Taoukis, 2003).

3.2.2. Degradation of L-ascorbic acid during the drying process
Variation of L-ascorbic acid content during pineapple drying at 45, 60 and 75 °C is shown in Fig. 5. The vitamin C retention is expressed as C/C_0, where C = mg of L-ascorbic acid per g of dry solid (mg/g of dry matter) and C_0 = mg of L-ascorbic acid per g of dry solid prior to drying (mg/g of dry matter).

The maximum vitamin C retention was observed during drying at 45 °C. Difference in C_0 values did not affect the deterioration kinetics, since the global behavior was similar
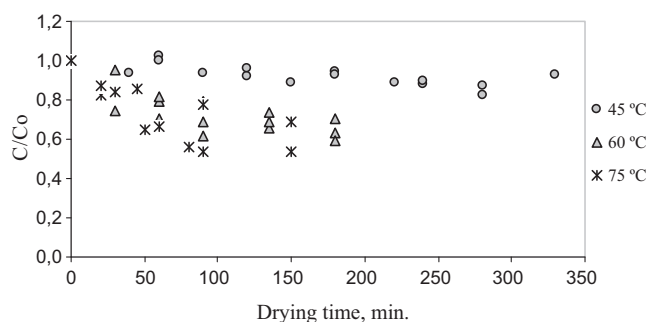

Fig. 5 – L-Ascorbic acid content during pineapple drying at 45, 60 and 75 °C.

in three independent drying tests at every temperature. The nutrient degradation was increased with air temperature. At 75 °C the dispersion of results was the most important (Fig. 5). However, similar situation of variability was observed in fresh fruit of pineapple (Santos and Silva, 2009), in green vegetables (Giannakourou and Taoukis, 2003) and during persimmons drying (Nicoleti et al., 2004), among others.

An increment of the drying temperature increases the dehydration rate, but also increases the rate of ascorbic acid degradation. When the moisture content descends next to 50% and 30% of initial moisture, the ʟ-ascorbic acid retention and the required drying time, at every drying temperature, are presented in Table 1. The ʟ-ascorbic acid retention is expressed as a percentage of its content in the fresh fruit. Standard deviation is a widely used measure of the variability or dispersion; obtained values in this work are shown in Table 1. The time needed to reach a certain value of W/W_0 is smaller at 75 °C than at 45 °C, nevertheless greater ascorbic acid retention was observed at 45 °C than at 75 °C. This fact is showing that the temperature effect was more important than the time effect on the ʟ-ascorbic acid degradation during drying process. These observations are in agreement with that expressed by Santos and Silva (2009). They studied kinetics of ʟ-ascorbic acid degradation during pineapple drying at 40 and 60 °C and two air velocities: 0.42 or 0.84 m/s. In those conditions, the ʟ-ascorbic acid retention was smaller than which was found in our present study. These discrepancies can be due to the difference in air velocity values that causes, consequently, a remarkable difference in drying time.

For a given value of moisture content, similar AA content was measured at 60 and 75 °C; but at 45 °C the AA retention was higher.

3.3. Rehydration

Experimental measures of the water content in pineapple fresh fruit displayed a high variability, ranged between 6 kg water/kg d.m. and 9 kg water/kg d.m. In the experimental conditions of the present study, samples did not reach moisture values higher than 4.5 kg water/kg d.m., if the moisture was calculated with the assumption that the dry matter remains constant during the rehydration process.

With the aim to evaluate how much water could be absorbed (saturation moisture), pineapple samples pre-dried with air at 75 °C were rehydrated through 10 h. The moisture content reached only 52% of the moisture value in fresh fruit used in this assay. It was observed that 60% of the water gain took place in the first hour of immersion. As the saturation moisture is smaller than fresh fruit moisture, we can infer that irreversible structural damages have taken place in vegetal tissue during drying, resulting in a loss of rehydration ability. This effect was observed by other researchers (Krokida and Philippopoulos, 2005; Krokida and Marinos-Kouris, 2003) during the rehydration of pre-dried fruits and vegetables.

The Page model was fitted to the experimental data of moisture content during rehydration at 25 and 40 °C; the results of parameter estimation (K and N parameters) as well as the corresponding values of the average relative error (Epp) are summarized in Table 2. All r^2 values were higher than 0.92, showing that the Page model is appropriate to describe the water uptake in pineapple during rehydration. There was little difference among predicted and experimental values, as it manifests in relative error values (Epp) of the estimation, equal to or lower than 4.13%, as can be seen in Table 2. The parameter

N did not exhibit dependence on the previous drying process conditions, being considered as an average constant value ($N = 0.93$).

Model parameters (K and N) have no physical meaning. However, K parameter can be considered as an estimation of the water gain rate when N values are constant, since N determines the scale of abscissa axis (t^N). Thus, it was observed that K value increases with the rehydration temperature and it reduces when the drying temperature is increased, indicating a greater rehydration rate in pineapple pre-dried at 45 °C than in pineapple dried at 75 °C, as is shown in Table 2.

This result could be due to the fact that a higher temperature of drying creates a more rigid structure and, in consequence, produces the collapse of channels for water uptake. As a result, a smaller rehydration rate could happen.

The capacity of water uptake during rehydration can be quantified by RR and COR indexes. Values of COR and RR for pineapple samples with 2 h of rehydration are detailed in Table 3. These coefficients are expressed as the average of results of three independent drying-rehydration tests.

The rehydration ratio (RR) increases with the rehydration time, is independent of the rehydration process temperature and the drying pre-processing temperature, even though the average values indicate a tendency. So, the statistical analysis (ANOVA) explains that there are not significant differences ($p > 0.05$) between values of RR parameter for samples dried at different temperatures and between samples with the same drying temperature and different rehydration temperatures.

Similar results were obtained from the statistical analysis of COR index values obtained in rehydration individual tests. There were no statistical differences ($p > 0.05$) among COR values. However, average values of this coefficient would be indicating a greater ability of water absorption in pineapple samples pre-treated at 45 °C. This result is concordant with values of K coefficient obtained from fitting of the Page model (Table 2) to the rehydration data.

Other researchers have reported that rehydration characteristics are dependent on the physical properties of the dried product and the drying conditions (Khraisheh et al., 2004; Krokida and Marinos-Kouris, 2003).

3.4. Mechanical properties

Compression or elasticity modulus, failure or fracture stress and strain are mechanical properties usually associated to elasticity, strength and firmness, respectively (Torres et al., 2006). Table 4 shows that the drying process causes an increment in the fracture strain (ε_{HF}) as well as in the values of failure stress (σ_{HF}), evidencing greater hardness in dehydrated fruit. Also, the dehydration provoked a drastic decrease in the compression modulus (E) of pineapple, perhaps owing to the loss of turgor and firmness in the vegetable tissue.

The statistical analysis (ANOVA) indicated the insignificant effect of the drying temperature on σ_{HF} values, when the fruit was dried at different air temperatures until the final moisture content was reached. So, there are not differences among the means of σ_{HF} values ($p > 0.05$) in samples with approximately 80% moisture content, obtained by drying at 45, 60 and 75 °C (Table 4). Prachayawarakorn et al. (2008) also noted the insignificant effect of the drying temperature on the maximum compression force of dried banana slices.

The σ_{HF} value was increased between 1.3 and 1.6 times in the first hour of drying. As the water content of these samples decreases during drying, we would expect to observe greater

Table 1 – Ascorbic acid retention in dried pineapple slices, when the moisture content reaches 50% and 30% of its initial value.

Drying temperature (°C)	50% of the initial moisture		30% of the initial moisture	
	Time (min) ± sd	AA retention (%) ± sd	Time (min) ± sd	AA retention (%) ± sd
45	115.0 ± 18.02	93.9 ± 1.01	231.7 ± 27.54	88.7 ± 0.58
60	71.0 ± 3.60	79.7 ± 5.13	133.3 ± 7.64	71.3 ± 8.08
75	45.0 ± 5.00	73.3 ± 11.37	80.0 ± 10.00	63.0 ± 19.67

sd = standard deviation.

Table 2 – Parameters of Page equation and *Epp* of estimations for the rehydration process.

Drying temperature	Rehydration at 25 °C				Rehydration at 40 °C			
	K	N	r^2	Epp	K	N	r^2	Epp
45 °C	0.0286 ± 0.0041	0.93	0.985	2.65	0.0374 ± 0.0042	0.93	0.980	2.95
60 °C	0.0237 ± 0.0021	0.93	0.968	4.08	0.0276 ± 0.0039	0.93	0.925	3.67
75 °C	0.0173 ± 0.0009	0.93	0.987	4.13	0.0206 ± 0.0033	0.93	0.992	3.11

Table 3 – Rehydration characteristics of pineapple pre-dried in hot air. These values were calculated with experimental data obtained towards the end of 2 h of rehydration.

Drying temperature	Rehydration at 25 °C		Rehydration at 40 °C	
	COR	RR	COR	RR
45 °C	0.515 ± 0.078	2.051 ± 0.237	0.604 ± 0.112	1.992 ± 0.170
60 °C	0.493 ± 0.102	2.582 ± 0.441	0.544 ± 0.095	2.757 ± 0.612
75 °C	0.492 ± 0.064	2.938 ± 0.183	0.498 ± 0.011	2.863 ± 0.373

Average values and LSD ranges of the rehydration ratio (RR) and the coefficient of rehydration (COR).

Table 4 – Stress (σ_{HF}) and strain (ε_{HF}) at failure and deformability modulus (E) of pineapple slices, fresh and dehydrated through different periods.

Dehydration time (min)	Water content (g/100 g of product)	σ_{HF} ± sd (kPa)	ε_{HF} ± sd	E ± sd (kPa)
Air dehydration at 45 °C				
0	87.3	49.42 ± 9.65	0.32 ± 0.045	69.54 ± 8.31
90	80.4	62.76 ± 6.61a	0.53 ± 0.036a	26.98 ± 2.80a
180	75.2	68.26 ± 10.11	0.72 ± 0.043	14.76 ± 4.38
360	55.5	82.46 ± 18.84	1,00 ± 0.12	9.44 ± 3.52
Air dehydration at 60 °C				
0	85.2	48.42 ± 4.87	0.32 ± 0.045	69.54 ± 8.31
60	80.7	67.34 ± 8.56a	0.49 ± 0.024b	20.91 ± 5.36a
120	73.1	71.62 ± 11.58	0.66 ± 0.078	18.35 ± 5.17
180	65.3	64.63 ± 7.68	0.74 ± 0.078	10.91 ± 3.32
240	56.9	75.03 ± 4.93	0.81 ± 0.095	10.00 ± 2.70
Air dehydration at 75 °C				
0	85.5	48.42 ± 4.87	0.32 ± 0.045	69.54 ± 8.31
45	79.7	75.27 ± 10.33a	0.44 ± 0.049c	29.76 ± 9.89a
90	69.8	84.61 ± 16.99	0.63 ± 0.054	22.42 ± 8.90
155	49.0	86.21 ± 18.48	0.78 ± 0.12	13.07 ± 4.05

Samples, with approximately 80% moisture content, in same column with different letters differ significantly at $p < 0.05$.

values of failure stress; however the failure stress had only slight changes during all process.

Statistical analysis (ANOVA) showed the E variation was independent of drying temperature, even though changes of the attribute are smaller at high temperature. The E value decreased 2.4–3.4 times in the first hour of drying; afterward, the change of this parameter was smaller but proportional to water loss. In brief, pineapple dried at 75 °C appeared as more rigid (greater E) than the samples of pineapple dried at 45 °C, but much less rigid than fresh fruit.

In contrast, the failure strain ε_{HF} of dried pineapple was lower when the process temperature was higher. This mechanical attribute was influenced by drying temperature

($p < 0.05$). Failure strain of dried pineapple was higher than the one in fresh pineapple, because dehydration process increased the hardness of fruit tissue. This attribute (ε_{HF}) showed systematic increase with the progress of drying. These observations are in agreement with those reported for kiwifruit during osmotic dehydrated in different conditions (Talens et al., 2002).

4. Conclusions

Hue values changed with pineapple moisture content in independent way of the process temperature. More expressly, the color preservation during pineapple drying may be measured

by the invariability of *L* and *chroma* parameter (both almost constant in the present study). For a given value of moisture content in pineapple dehydrated at different temperatures, similar ʟ-ascorbic acid content was found at 60 and 75 °C; however, at 45 °C and the same moisture content, ʟ-ascorbic acid content was higher. The rehydration rate of dried pineapple increases with the rehydration temperature and it reduces when the drying pre-processing was carried at higher temperature, indicating a greater rehydration rate in pineapple dried at 45 °C that in pineapple dried at 75 °C. The Page equation gave a good statistical fit to rehydration experimental data, with low values of mean percentage error, 2.6–4.1%. Changes in mechanical properties are little affected by the drying temperature. Nevertheless, results would indicate that the fruit tissue dried at high temperature has a greater firmness.

In brief, ascorbic acid content was more adversely affected by high drying temperature than textural attributes and rehydration ability, while color was not affected by drying conditions. Hence, 45 °C drying temperature was best condition for ascorbic acid retention, while color and mechanical properties remained almost independent of temperature.

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