Contents lists available at ScienceDirect

Food and Bioproducts Processing

journal homepage: www.elsevier.com/locate/fbp

# Effect of temperature on structural properties of *Aloe vera* (*Aloe barbadensis* Miller) gel and Weibull distribution for modelling drying process

*Margarita Miranda*[a], *Antonio Vega-Gálvez*[a,*], *Purificación García*[b], *Karina Di Scala*[d,e], *John Shi*[c], *Sophia Xue*[c], *Elsa Uribe*[a]

[a] *Department of Food Engineering, Universidad de La Serena, Avenida Raúl, Bitrán s/n, 599, La Serena, Chile*
[b] *Department of Food Technology, Universidad Politécnica de Valencia, Camino de Vera s/n, 46022, Valencia, Spain*
[c] *Guelph Food Research Center, Agriculture and Agri-Food Canada, Guelph, Ontario, Canada*
[d] *Food Engineering Research Group, Facultad de Ingeniería, Universidad Nacional de Mar del Plata, Juan B. Justo 4302, Mar del Plata, Argentina*
[e] *CONICET (Consejo Nacional de Investigaciones Científicas y Técnicas), Argentina*

A B S T R A C T

*Aloe vera* (*Aloe barbadensis* Miller) gel was dried at five inlet temperatures 50, 60, 70, 80 and 90 °C, in a convective dryer with a constant air flow of 2.0 ± 0.2 m/s. Rehydration ratio, water holding capacity, texture, microstructure and total polysaccharide content were evaluated. Drying kinetics was estimated using the Weibull distribution ($r^2 > 0.97$ and Chi-square < 0.0009). Values of scale and shape parameters ranged from 90.94 to 341.06 (min) and 1.43 to 1.49, respectively. Furthermore, the influence of temperature on the model parameters as well as on the quality attributes was analysed using a least significant difference test ($p$-value < 0.05). These effects were more evident for the long drying period (e.g. 810 min at 50 °C). However, minor alterations in the structural properties and total polysaccharide content were produced at drying temperatures of 60–70 °C, resulting in a high quality gel.

© 2009 The Institution of Chemical Engineers. Published by Elsevier B.V. All rights reserved.

*Keywords:* *Aloe vera*; Microstructure; Texture; Drying; Rehydration; Weibull distribution

## 1. Introduction

*Aloe vera* (*Aloe barbadensis* Miller), which is grown as an industrial plant, is a member of the family Liliaceae. A thick epidermis (skin) that surrounds the mesophyll constitutes the leaves of Aloe. These can be differentiated in collenchyma cells and thin wall cells that form the parenchyma (gel). Parenchyma cells contain mucilaginous transparent gel, which is referred to as *A. vera* gel. The presence of polysaccharides accounts for most of the dry matter of parenchymal tissue of *A. vera*, with two main types of polymers: acemannans (reserve polysaccharides rich in mannose), which are found inside cell protoplasts; and a wide variety of polysaccharides that form the net of the cell wall, which is mainly constituted of pectic substances, cellulose, and also hemicellulose (Femenia et al., 1999, 2003; Chang et al., 2006).

Although *A. vera* gel is best known for its therapeutic effect, the product is nowadays introduced as an additive to our fruits and vegetables products (ingredient, coatings, etc.). Thus, the choice of a preservation method is a relevant task. Hot-air drying is defined as a process of moisture loss as a result of the simultaneous occurrence of mass and energy transfer phenomena, representing a traditional method for food conservation, which extends the shelf life of the product. In fact, low moisture content products can be stored at ambient temperatures for long periods of time (Vega et al., 2007). Besides, drying provides the advantage of reducing the packaging as well as the storage and transport costs, due to a lower size and weight of the dried product. Despite these benefits, the drying process causes evident physical and structural changes on fruit and vegetable tissues (Vega-Gálvez et al., 2008). These changes are mainly related to the loss of water from the inner

* *Corresponding author*. Tel.: +56 51 204305; fax: +56 51 204305.
E-mail address: avegag@userena.cl (A. Vega-Gálvez).
Received 30 January 2009; Received in revised form 1 June 2009; Accepted 22 June 2009
0960-3085/$ – see front matter © 2009 The Institution of Chemical Engineers. Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.fbp.2009.06.001

**Nomenclature**

| | |
|---|---|
| $X_{wo}$ | initial moisture content (g water/g d.m.) |
| $X_{wt}$ | moisture content at a time t (g water/g d.m.) |
| $X_{we}$ | equilibrium moisture content (g water/g d.m.) |
| t | time (min) |
| $\alpha$ | shape parameter (dimensionlees) of Weibull model |
| $\beta$ | scale parameter (min) of Weibull model |
| $MR_{ei}$ | experimental moisture ratio (dimensionless) |
| $MR_{ci}$ | calculated moisture ratio (dimensionless) |
| N | number of data |
| z | number of constants |
| $W_{reh}$ | weight of the sample after the rehydration process |
| $W_{dried}$ | weight of the sample after the drying process |
| $W_l$ | weight of the drained liquid after centrifugation |
| $X_{reh}$ | moisture content of the sample after the rehydration process on a wet matter |
| $X_{dried}$ | moisture content of the sample after the drying process on a wet matter |

parts towards the surface and the surrounding air, possibly causing stiffness, spoilage, and disruption of the cell walls, and even a collapse of the cell tissues (Maltini et al., 2003; Troncoso and Pedreschi, 2007). Several studies have tried to characterize these physical and structural changes in terms of parameters such as changes in volume, surface, size, and shape (Kerdpiboon et al., 2007; Panyawong and Devahastin, 2007; Troncoso and Pedreschi, 2007). Structural properties of the product depend on the type of drying, the operative variables and the food microstructure formed during the process (Aguilera, 2005). Most fruits and vegetables are particularly difficult to dehydrate by hot-air drying, because they have an initial high water content, which implies long drying times, causing serious structural changes (Moreira et al., 2008). Some authors have studied the correspondence between loss of water and loss of internal pressure, shrinkage, and softening of the cell tissues (Troncoso and Pedreschi, 2007; Blahovec, 2007). This pressure is known as turgidity and it plays a significant role in rheological and textural properties of vegetable tissues (Aguilera, 2005)

There are several empirical equations used for the modelling of mass transfer kinetics during the dehydration process, which are useful for the optimization of the process itself. An equation widely used in food engineering is the probabilistic model of Weibull, due to its simplicity and flexibility in the estimation of its two parameters. In addition, this model has been used to the kinetics of chemical, enzymatic or microbiological degradation processes and to describe the behaviour of rehydration kinetics (Marabi et al., 2003; García-Pascual et al., 2006; Marfil et al., 2008). However, in the published scientific literature, there is scarcity of information available about using the Weibull model for the air-drying of vegetable products (Corzo et al., 2008).

The aim of this research was to study the applicability of the Weibull distribution model to predict the moisture content of *A. vera* gel dried by hot-air and to evaluate the effects of temperature on the kinetic parameters, structural properties (texture and microstructure), and total polysaccharide content.

## 2. Materials and methods

### 2.1. Sample preparation

*A. vera* leaves were provided by the INIA-Intihuasi, Coquimbo, Chile. Homogenous leaves were selected according to size, ripeness, colour, and freshness according to visual analysis. Acibar (a yellow-coloured liquid) was extracted by cutting the base of the leaves and allowing them to drain vertically for 1 h. The epidermis was then separated from the gel, which was manually cut into slabs of $10 \pm 1$ mm in thickness. The samples were maintained at $4 \pm 1$ °C in a refrigerator (Samsung, model SR-34RMB, Seoul, South Korea) up prior to use which did not exceed 1 day of storage.

### 2.2. Physical–chemical characterization of fresh *A. vera* gel

The crude protein content was determined using the Kjeldahl method with a conversion factor of 6.25 (A.O.A.C. no. 960.52). The lipid content was analysed gravimetrically following Soxhlet extraction (A.O.A.C. no. 960.39). The crude fibre was estimated by acid/alkaline hydrolysis of insoluble residues (A.O.A.C. no. 962.09). The crude ash content was estimated by incineration in a muffle furnace at 550 °C (A.O.A.C. no. 923.03). All methodologies followed the recommendations of the Official Method of Analysis (A.O.A.C., 1990). The available carbohydrate content was estimated by difference. The moisture level was determined by means of A.O.A.C. method no. 934.06 (A.O.A.C., 1990). All measurements were done in triplicate.

### 2.3. Modelling of drying process

Drying was done at five temperatures (50, 60, 70, 80, and 90 °C). A convective tray dryer was used with temperature and air flow control (Vega et al., 2007). The drying air flow velocity was held constant at $2.0 \pm 0.2$ m/s (perpendicular direction to sample) and measured with an omnidirectional anemometer (Extech Instrument Inc., 451112, Waltham, USA). The inlet relative humidity was $64.0 \pm 4.5$%, measured by an ambient digital hygro-thermometer (Extech Instrument Inc., 445703, Waltham, USA). All the drying experiments were carried out in triplicate, with a load density of $10.0 \pm 0.5$ kg/m$^2$. The samples are arranged in a thin layer within a stainless steel basket, which is suspended from a digital balance (model SP402, Ohaus, NJ, USA) accurate to $\pm 0.01$ g and connected to a personal computer using an electronic interfacing device (model RS232, Ohaus, NJ, USA). The computer records and stores all data from the balance in real time until the sample reaches a constant weight (equilibrium condition), using the Microsoft Hyperterminal software (Microsoft, Redmond, WA, USA). By the end of the drying process, the samples were removed and vacuum-sealed in polyethylene bags for storage.

The moisture ratio (MR) was employed as dependent variable (Eq. (1)), which relates the sample moisture content in real time with the initial moisture content and the equilibrium moisture contents (Akpinar et al., 2003; Babalis and Belessiotis, 2004; Simal et al., 2005; Vega et al., 2007; Hacıhafızoğlu et al., 2008). The model used to simulate the drying kinetics was the empirical equation proposed by Weibull (Eq. (2); Corzo et al.,

2008).

$$MR = \frac{X_{wt} - X_{we}}{X_{wo} - X_{we}} \quad (1)$$

$$MR = \exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] \quad (2)$$

### 2.4. Rehydration process

The rehydration process was done in triplicate using approximately 5.00 ± 0.05 g of dried samples of *A. vera* at 50, 60, 70, 80, and 90 °C. Each sample was placed in a glass beaker filled with 200 mL of distilled water (1:40 solid to liquid) at 20 °C for 10 h. The excess water was then allowed to drain for several minutes. Finally, the samples were weighed, packed and stored at 4 ± 1 °C in a refrigerator (Samsung, model SR-34RMB, Seoul, South Korea) up prior to use which did not exceed 4 h. The moisture level was determined by means of A.O.A.C. (1990) method no. 934.06.

## 3. Evaluation of quality parameters

### 3.1. Rehydration indices

To study the effect of temperature on the rehydration phenomenon, two typical rehydration indices were evaluated for dehydrated foods (García-Pascual et al., 2006; Moreira et al., 2008; Vega-Gálvez et al., 2008). The first index was the rehydration ratio (RR), which was calculated by Eq. (3) and is expressed as g adsorbed water/g d.m. The second index was water holding capacity (WHC), which was determined by centrifuging the rehydrated samples at 4000 × *g* for 10 min at 5 °C in tubes fitted with a centrally placed plastic mesh which allowed water to drain freely from the sample during centrifugation. The water holding capacity was calculated from the amount of water removed according to Eq. (4), and is expressed as g retained water/100 g water. All measures were done in triplicate and means were calculated for each sample.

$$RR = \frac{W_{reh} \cdot X_{reh} - W_{dried} \cdot X_{dried}}{W_{dried} \cdot (1 - X_{dried})} \quad (3)$$

$$WHC = \frac{W_{reh} \cdot X_{reh} - W_{l}}{W_{reh} \cdot X_{reh}} \times 100 \quad (4)$$

### 3.2. Determination of total polysaccharide content

Polysaccharide content was estimated by a colorimetric analysis. One gram of both fresh and rehydrated *A. vera* gel was extracted with 80 mL of water in bath at 100 °C for 2 h, with constant agitation and the samples were vacuum filtered. The filtrate was diluted to 100 mL in a beaker according to the methodology suggested by Hu et al. (2003). Two milliliters of the solution and 10 mL of absolute ethanol were added in plastic tubes; samples were centrifuged at 2500 × *g* for 30 min, and the supernatant was removed; the precipitate was dissolved in a final volume of 50 mL water. One milliliter of the filtered solution, 1 mL of phenol at 5 g/100 mL, and 5 mL of concentrated sulphuric acid were added to the tops of the tubes. It was allowed to settle for 30 min. Sample absorbance was determined at 490 nm (Spectronic® 20 Genesys™, IL, USA). Total polysaccharide content was estimated by comparison with a standard curve generated from D-+-glucose analysis. All solvents and reagents were purchased from Sigma (Sigma Chemical Co., St. Louis, MO, USA) (Hu et al., 2003).

### 3.3. Maximum puncture force

Texture was measured as the maximum puncture force of the *A. vera* rehydrated samples, used a texture analyzer TA-XT (Stable Mycro Systems, Texture Technologies Corp., Scardale, NY, USA) fitted with a 25 kg load cell. Test run speed was 1 mm/s. This assay used a 2 mm diameter cylinder probe. For each measurement 10 replications were collected to estimate the mean values. The maximum force value was expressed in Newtons (N).

### 3.4. Cryo-SEM observations

Sample microstructure was observed by Cryo-SEM in a JEOL JSM-5410 microscope (Jeol, Tokyo, Japan). Dried *A. vera* samples were rehydrated for 10 h at room temperature. Square rehydrated samples of more or less 4 mm × 1.5 mm × 5 mm, were cryo-fixed by immersion in slush nitrogen (−210 °C), fractured, etched (at −90 °C, $10^{-5}$ Torr for 15 min), gold coated, and viewed on the SEM cold-stage. The fractured surface was viewed directly while it was maintained at −150 °C or lower. The micrographs were taken at 500× magnification to observe changes in cell structure.

### 3.5. Statistical analysis

The goodness of fit of the proposed models for the drying kinetics data was estimated by means of the determination coefficient ($r^2$) and the Chi-squared parameter ($\chi^2$) (Eq. (5)):

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{ei} - MR_{ci})^2}{N - z} \quad (5)$$

The effect of temperature on the kinetic parameters of the Weibull model ($\alpha$ and $\beta$) and the quality parameters was estimated using Statgraphics® Plus 5.0 (Statistical Graphics Corp., Herndon, VA, USA). The results were analysed by means of an analysis of variance (ANOVA). Differences between the means were analysed using the Fisher's least significant difference (LSD) test with a significance level of $\alpha = 0.05$ and a confidence interval of 95% ($p$-value < 0.05). The multiple range test (MRT) included in the statistical program was used to demonstrate the existence of homogeneous groups within each of the parameters.

## 4. Results and discussion

### 4.1. Physicochemical analyses and modelling of drying kinetics

Proximate analysis of *A. vera* gel presented an initial moisture content of 55.68 ± 1.09 g/100 g d.m.; crude protein (nitrogen × 6.25) of 3.62 ± 0.34 g/100 g d.m.; total lipids of 4.61 ± 1.10 g/100 g d.m.; crude fibre of 12.85 ± 1.66 g/100 g d.m.; crude ash of 17.62 ± 0.43 g/100 g d.m.; and available carbohydrates (by difference) of 1.08 ± 0.22 g/100 g d.m. Fig. 1 shows the drying kinetics characteristics of *A. vera* gel at the five working temperatures. In this figure, where MR was plotted as a function of time, there was also a clear effect of temperature on the drying kinetics. Thus, as the process temperature increased the drying time decreased (Fig. 1). In addition, as the tem-

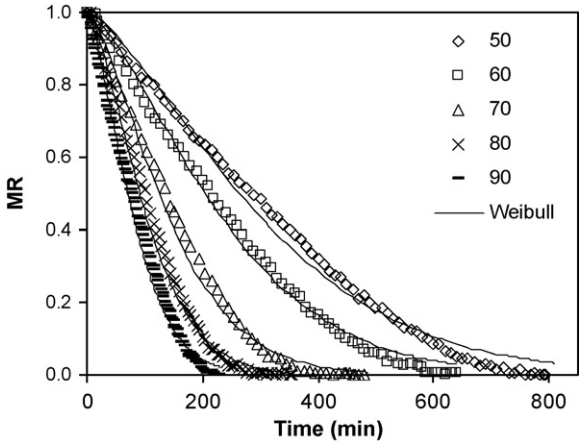


**Fig. 1 – Drying curves corresponding to the dehydration of *A. vera* parenchyma at different temperature (°C).**

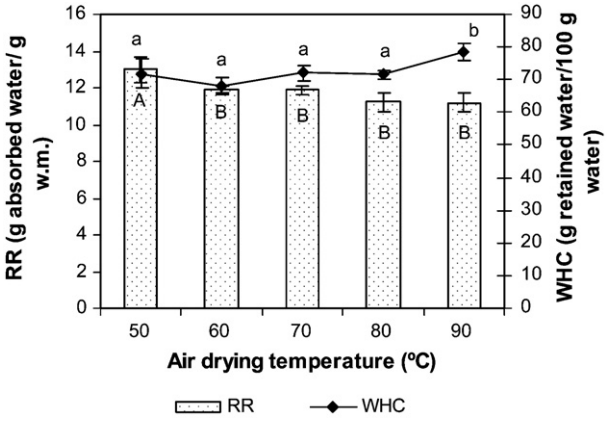


**Fig. 2 – Interaction between rehydration ratio (RR) and water holding capacity (WHC) for rehydrated aloe slabs dried at different air-drying temperatures. Different letters above the bars indicate significant differences ($p$-value < 0.05).**

perature increased, there was an increase in the rate of mass transfer (water) to achieve a similar equilibrium moisture content of approximately 1.0 g water/100 g d.m. (Simal et al., 2000; Femenia et al., 2003; Vega et al., 2007). Furthermore, this figure showed an exponential tendency in the drying curves, which was validated using the Weibull distribution model to simulate the drying of the product.

Table 1 shows the results of the nonlinear regression to fit a fractional amount of moisture content according to the Weibull distribution model. The determination coefficients ($r^2$) presented values higher than 0.97 for all drying temperatures and the Chi-square ($\chi^2$) values for the modelling were low (<0.0009). The $r^2$ and $\chi^2$ values indicate a good fit to the experimental data. This suggests that the Weibull distribution model is suitable for predicting the moisture content of *A. vera* gel and it is an excellent tool to estimate the drying time for this product. Similar behaviour has been reported for coroba slices (Corzo et al., 2008) and for osmotically dehydrated sardine sheets (Corzo and Bracho, 2008). The values of shape ($\alpha$) and scale ($\beta$) parameters of the Weibull distribution model at different drying air temperatures are shown in Table 1. In general, the shape parameter increased with a decrease of temperature. The shape parameter is related to the speed of the mass transfer at the beginning, e.g., the lower the $\alpha$ value, the faster the drying rate at the beginning (Corzo et al., 2008). The scale parameter decreased as air temperature increased. The reciprocal of $\beta$ could be compared to the effective diffusion coefficient of the diffusion model, since those two parameters are the kinetic constants for each model (García-Pascual et al., 2006; Corzo et al., 2008). ANOVA indicated that both $\alpha$ and $\beta$ are dependent on the drying air temperature ($p$-value < 0.05). Similar results were obtained working with coroba slices (Corzo et al., 2008), sardine sheets (Corzo and Bracho, 2008) and mushrooms (García-Pascual et al., 2006).

### 4.2. *Measurement of rehydration indices*

Fig. 2 shows the behaviour of the properties related to the rehydration of *A. vera* gel such as rehydration ratio (RR) and water holding capacity (WHC). It can be observed that both parameters are function of drying temperature. When analysing RR, an increase in temperature leads to low RR values. RR measures the ability of the dried product to rehydrate, and it might show the damage of the tissue due to drying or rehydration processes. This behaviour could be due to irreversible cellular damage and rupture due to thermal process (Moreira et al., 2008). In fact, loss of tissue integrity and a dense structure of collapsed, greatly shrunken capillaries with reduced hydrophilic properties, especially at high temperatures (e.g. 80 and 90 °C), are the structural modifications associated with the food damage (Jayaraman et al., 1990; Krokida et al., 1999). A maximum value of 13.00 ± 0.70 g adsorbed water/g d.m. was reported at 50 °C. From ANOVA, least significant differences were obtained ($p$-value < 0.05) among the samples, and according to MRT, two homogenous groups at 50 °C and 60–70–80–90 °C were presented. The same figure shows the WHC index behaviour that estimates the ability of the food matrix to absorb water with respect to the water loss during drying (Moreira et al., 2008). It can be seen that WHC values increased as temperature increased. According to ANOVA, there is a least significant difference ($p$-value < 0.05) among the samples, and according to MRT, two homogenous groups were shown: 90 °C and 50–60–70–80 °C with an interval of confidence of 95%. WHC behaviour is influenced by physicochemical

**Table 1 – Parameters and statistical test for Weibull model proposed of drying curves at different temperatures.**

| Temperature (°C) | Parameters | | Statistical tests | |
|---|---|---|---|---|
| | $\alpha$ (dimensionless) | $\beta$ (min) | $r^2$ | $\chi^2$ ($\times 10^{-4}$) |
| 50 | 1.4339 ± 0.0187[a] | 341.0604 ± 4.7760[a] | 0.985 | 9.59 |
| 60 | 1.4420 ± 0.0103[a,b] | 264.4262 ± 16.4866[b] | 0.987 | 8.91 |
| 70 | 1.4516 ± 0.0202[a,b] | 160.7847 ± 2.8667[c] | 0.984 | 9.19 |
| 80 | 1.4960 ± 0.0043[c] | 116.9382 ± 5.7441[d] | 0.985 | 8.03 |
| 90 | 1.4632 ± 0.0056[b] | 90.9391 ± 4.0231[e] | 0.976 | 6.43 |

Similar letters in the exponential in the same column show there are no significant differences ($p$-value < 0.05).

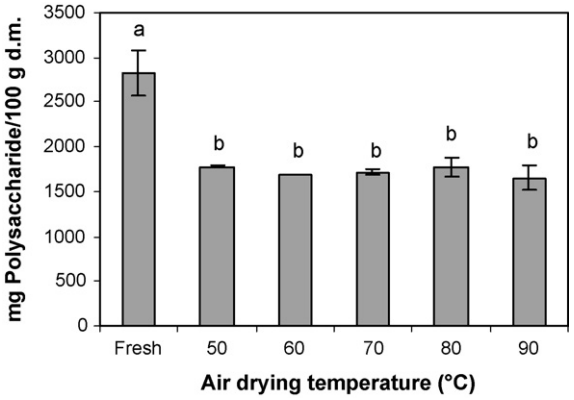


**Fig. 3 – Total polysaccharide content from *A. vera* parenchyma dried at different temperatures. Different letters above the bars indicate significant differences ($p$-value < 0.05).**

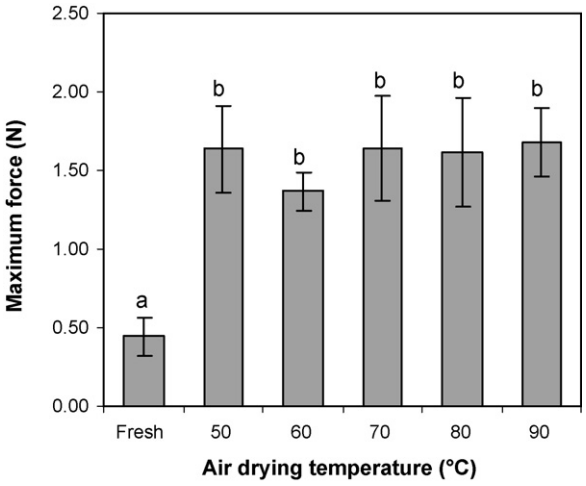


**Fig. 4 – Maximum force of rehydrated *A. vera* slabs dried at different air-drying temperatures. Different letters above the bars indicate significant differences ($p$-value < 0.05).**

interactions (e.g. wetting) and on the setting of the product on a dense microstructure as occurs at lower temperatures where drying times necessary to decrease moisture content were considerably higher (Aguilera and Stanley, 1999). This fact could explain the low WRC exhibited by samples dehydrated at 50 and 60 °C. On the other hand, from 70 to 90 °C, the effect of temperature on this rehydration parameter seemed to be the most important factor. This latter could be probably related to entrapment of moisture or "case hardening" implying that interior moisture can not be easily removed (Fernando et al., 2008; Simal et al., 2000), specially at high temperatures (e.g. 70, 80 and 90 °C). In fact, the maximum value for WHC is shown at 90 °C (78.76 ± 2.52 g retained water/100 g water). The results from this research are not correlated to those reported by other authors working with mushrooms, apples, chestnuts and pepper. Those researches suggested that the higher the drying temperature, the lower the rehydration capacity, due to collapse and damages on vegetable tissues, which is not the case for WHC that shows an inverse behaviour with temperature (Askari et al., 2006; García-Pascual et al., 2006; Moreira et al., 2008).

In summary, precise numerical data of shape changes (shrinkage) as well as case hardening during drying is still a challenge to assist in correlating them with process conditions and rehydration properties (Fernando et al., 2008; Aguilera, 2005).

### 4.3. *Polysaccharide content*

Fig. 3 shows the total polysaccharide content of the parenchymal tissue of fresh and dehydrated *A. vera* gel at different temperatures. All the dehydrated samples show significant changes in the total polysaccharide content in comparison to the fresh *A. vera* gel sample ($p$-value < 0.05), presenting two homogenous groups clearly defined by the dehydrated samples between 50 and 90 °C and the fresh gel. In general, the loss of total polysaccharide content remained in a constant value of 39.08 ± 1.83% for dried sample with respect to fresh gel. Similar results were reported by other authors working with *A. vera* (Femenia et al., 1999; Femenia et al., 2003; Chang et al., 2006). The decrease of the content for these constituents might be due to thermal degradation during the hot-air drying process. This degradation leads to the disruption of the polysaccharides network of the cell wall (Cohen and Yang, 1995; Femenia et al., 1999; Chang et al., 2006). Femenia et al. (2003) working with *A. vera* suggested that pectic substances were the type of polysaccharides that caused the highest degree of degradation during the dehydration process, which was mainly due to the reaction of $\beta$-disposal provoked by heating, although temperatures over 50 °C could also increase degradation of the enzymes of pectic polysaccharides. However, Chang et al. (2006), working with *A. vera* gel juice, reported that a decrease of the polysaccharide content was observed at lower temperatures during the process, mainly due to the enzymatic action that results in hydrolysis of long-chain polysaccharide molecules to others of smaller size.

### 4.4. *Puncture force*

Fig. 4 shows the changes in the texture of the dry–rehydrated sample, processed at different hot-air temperatures and compared to fresh A. vera gel. ANOVA results showed that there are least significant differences ($p$-value < 0.05) between fresh and all the dry–rehydrated samples for different drying temperatures, but there are not any significant differences between dry–rehydrated samples, showing two homogenous groups: fresh and dry–rehydrated samples. These forces values varied from 0.4 ± 0.1 to 1.7 ± 0.2 N. When the puncture test was applied, it was noticed that the necessary maximum force was significantly greater for all dry–rehydrated samples compared to the fresh ones, independent of the drying air temperature used. This might be due to the development of a compressed structure in the parenchymal tissue mainly formed by structural polysaccharides located within the cell wall such as pectins, cellulose, and hemicellulose, which provide stiffness to the cell wall after drying (Femenia et al., 2003; Askari et al., 2006). In addition, the presence of case-hardening phenomenon, in particular at high drying temperatures, could contribute to enhance the puncture force (Simal et al., 2000). Moreover, since *A. vera* gel contains calcium, calcium pectate three-dimensional networks might have been formed with the pectins, which provide firmness to the parenchymal tissue after the drying treatment (Femenia et al., 1999; Femenia et al., 2003; Miranda et al., 2009). Similar behaviour was reported by Askari et al. (2006) when dehydrating apples in slices. Although there is a large collection of data on puncture force of foods in many books and publications, its relation to microstructure is minimal and still qualitative (Aguilera, 2005).

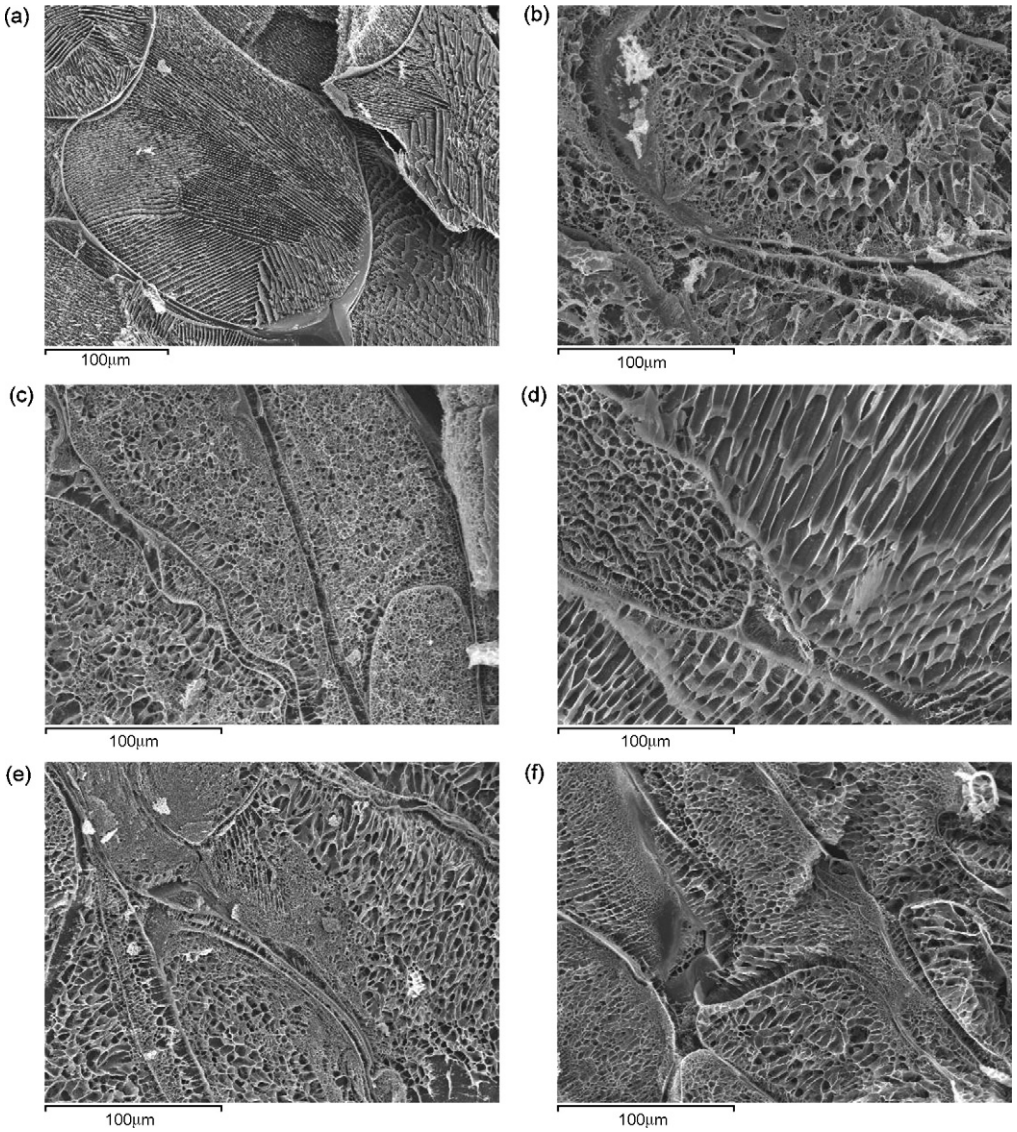


**Fig. 5 – Cryo-SEM micrographs of *A. vera* fresh and rehydrated-dried at different air-drying temperatures (×500): (a) fresh, (b) 50 °C, (c) 60 °C, (d) 70 °C, (e) 80 °C and (f) 90 °C.**

### 4.5. *Microstructural changes*

Structural changes of the *A. vera* gel were observed by Cryo-SEM. Fig. 5a shows the cell structure of fresh *A. vera* gel and Fig. 5b–f shows morphological and microstructure changes observed in dry–rehydrated samples. Fig. 5a shows an *A. vera* gel structure with the parenchymal cells intact, of well-rounded shape with characteristic diameter, whose dimensions are in the range of 300–400 μm. Similarly, close contact among the cell walls of adjacent cells can be observed. The cellulose of the cell wall gives stiffness and strength to the structure, whereas pectin and hemicelluloses of the middle lamella give plasticity and dictate the degree to which the cells can be pulled apart during deformations (Lewicki and Porzecka-Palak, 2005). The effect of drying temperature on the tissue structure of rehydrated *A. vera* gel is shown in Fig. 5b–f, where it is seen that after the rehydration of the samples, the cell structure presented an irregular form, with a decrease in the intracellular integrity. A tendency of the cell walls to separate from each other leading to lose contact has been observed, especially at high drying temperatures (e.g. 70–80–90 °C). Intercellular spaces are filled by exudate resulting from the loss of cell content as a result of cellular stress produced during the drying stage and after rehydration. In addition, it also shows a clear turgor loss, presenting degradation and causing a probable shrinkage in the contours of the cell wall (Aguilera and Stanley, 1999). The cellular shrinkage during dehydration has been observed during convective drying of grapes (Ramos et al., 2004). These microstructural changes (shrinkage, case hardening, etc.), which affect all the properties of aloe, are related to very complex mechanisms and they are still under investigation. Important advances in food science during the last decades have emanated from the understanding of the food structure, its relation to properties (so-called structure–property relationships), and how to engineer and control them (Aguilera, 2005).

## 5. Conclusions

The equation proposed by Weibull accurately modelled the drying of *A. vera* (*A. barbadensis* Miller) gel. Thus, it represents an excellent tool for estimating the drying time for this particular vegetable. Both distribution parameters (shape parameter and scale parameter) were affected by temperature. The shape parameter increased with the decrease of air temperature and the scale parameter decreased with an increase in air

temperature. It was found that conventional hot-air drying modifies the structural components of dry–rehydrated *A. vera* gel. A decrease in the rehydration ratio and an increase in water holding capacity occurs with an increase in air drying temperature, which implies diminishment in the rehydration ability of this vegetable at lower temperatures, was reported. Temperature had a clear effect on the reduction of the total polysaccharide content, mainly due to their solubilisation and degradation. The necessary maximum force was significantly greater for all dry–rehydrated samples, independently of drying air. Moreover, dry–rehydrated *A. vera* gel presented an irregular cellular structure, degradation and shrinkage in the contours of the cell wall at high drying temperatures, which is a common result in the convective drying of vegetables.

## Acknowledgements

The authors gratefully acknowledge the Research Department of the Universidad de La Serena (project DIULS 220-2-06), Chile, for providing financial support for the publication of this research; as well as the National Institute for Agricultural Research Intihuasi. In addition, we thank the microscopy service of Universidad Politécnica de Valencia, Spain; for assistance in relation to the Cryo-SEM micrographs.

## References

Aguilera, J.M., 2005, Why food microstructure? J Food Eng, 67: 3–11.

Aguilera, J.M. and Stanley, D.W., (1999). Simultaneous heat and mass transfer: dehydration. In *Microstructural Principles of Food Processing & Engineering* (2nd edition). (Aspen Publishers, Inc, Gaithersburg, MA, USA).

Akpinar, E.K., Bicer, Y. and Yildiz, C., 2003, Thin layer drying of red pepper. J Food Eng, 59(1): 99–104.

A.O.A.C., Association of Official Analytical Chemists., (1990). *Official Method of Analysis* (15th ed.). (Association of Official Analytical Chemists, Washington, DC, USA).

Askari, G.R., Emam-Djomeh, Z. and Mousavi, S.M., 2006, Effects of combined coating and microwave assisted hot-air drying on the texture, microstructure and rehydration characteristics of apple slices. Food Sci Technol Int, 12(1): 39–46.

Babalis, S.J. and Belessiotis, V.G., 2004, Influence of the drying conditions on the drying constants and moisture diffusivity during the thin-layer drying of figs. J Food Eng, 65(3): 449–458.

Blahovec, J., 2007, Role of water content in food and product textura. Int Agrophys, 21: 209–215.

Chang, X.L., Wang, Ch., Feng, Y. and Liu, Z., 2006, Effects of heat treatments on the stabilities of polysaccharides substances and barbaloin in gel juice from *Aloe vera* Miller. J Food Eng, 15: 245–251.

Cohen, J.S. and Yang, T.C.S., 1995, Progress in food dehydration. Trends Food Sc Technol, 6: 20–26.

Corzo, O., Bracho, N., Pereira, A. and Vásquez, A., 2008, Weibull distribution for modeling air drying of coroba slices. Lebensm Wiss Technol, 41(10): 2023–2028.

Corzo, O. and Bracho, N., 2008, Application of Weibull distribution model to describe the vacuum pulse osmotic dehydration of sardine sheets. Lebensm Wiss Technol, 41: 1108–1115.

Femenia, A., García-Pascual, P., Simal, S. and Rosselló, C., 2003, Effects of heat treatment and dehydration on bioactive polysaccharide acemannan and cell wall polymers from *Aloe barbadensis* Miller. Carbohydr Polym, 51: 397–405.

Femenia, A., Sánchez, E.S., Simal, S. and Rosselló, C., 1999, Compositional features of polysaccharides from *Aloe vera* (*Aloe barbadensis* Miller) plant tissues. Carbohydr Polym, 39: 109–117.

Fernando, W.J.N., Ahmad, A.L., Shukor, S.R. Abd. and Lok, Y.H., 2008, A model for constant temperature drying rates of case hardened slices of papaya and garlic. J Food Eng, 88: 229–238.

García-Pascual, P., Sanjuán, N., Melis, R. and Mulet, A., 2006, *Morchella esculenta* (morel) rehydration process modelling. J Food Eng, 72: 346–353.

Hacıhafızoğlu, O., Cihan, A. and Kahveci, K., 2008, Mathematical modelling of drying of thin layer rough rice. Food Bioprod Process, 86(4): 268–275.

Hu, Y., Xu, J. and Hu, Q., 2003, Evaluation of antioxidant potencial of *Aloe vera* (*Aloe barbadensis* Miller) extracts. J Agric Food Chem, 51: 7788–7791.

Jayaraman, K.S., Grupta, D.K. and Babu Rao, N., 1990, Effect of pretreatment with salt and sucrose on the quality and stability of dehydrated cauliflower. Int J Food Sci Technol, 25(1): 47–60.

Kerdpiboon, S., Devahastin, S. and Kerr, W.L., 2007, Comparative fractal characterization of physical changes of different food producta during drying. J Food Eng, 83: 570–580.

Krokida, M.K., Kiranoudis, C.T. and Maroulis, Z.B., 1999, Viscoelastic behaviour of dehydrated products during rehydration. J Food Eng, 40: 269–277.

Lewicki, P.P. and Porzecka-Palak, R., 2005, Effect of osmotic dewatering on apple tissue structure. J Food Eng, 66: 43–50.

Maltini, E., Torreggiani, D., Venira, E. and Bertolo, G., 2003, Water activity and the preservation of plant foods. Food Chem, 82(1): 79–86.

Marabi, A., Livings, S., Jacobson, M. and Saguy, I.S., 2003, Normalized Weibull distribution for modeling rehydration of food particulates. Eur Food Res Technol, 217(4): 311–318.

Marfil, P.H.M., Santos, E.M. and Telis, V.R.N., 2008, Ascorbic acid degradation kinetics in tomatoes at different drying conditions. Lebensm Wiss Technol, 41(9): 1642–1647.

Miranda, M., Maureira, H., Rodríguez, K. and Vega-Gálvez, A., 2009, Influence of temperature on the drying kinetics, physicochenical properties, and antioxidant capacity of *Aloe vera* (*Aloe barbadensis* Miller) gel. J Food Eng, 91(1): 297–304.

Moreira, R., Chenlo, F., Chaguri, L. and Fernandes, C., 2008, Water absorption, texture, and color kinetics of air-dried chestnut during rehydration. J Food Eng, 86: 584–594.

Panyawong, S. and Devahastin, S., 2007, Determination of deformation of a food product undergoing different drying methods and conditions via evolution of a shape factor, 2007. J Food Eng, 78: 151–161.

Ramos, I.N., Silva, C.L.M., Sereno, A.M. and Aguilera, J.M., 2004, Quantification of microstructural changes during first stage air drying of grape tissue. J Food Eng, 62: 159–164.

Simal, S., Femenia, A., Garau, M.C. and Roselló, C., 2005, Use of exponential, Page's and diffusional models to simulate the drying kinetics of kiwi fruit. J Food Eng, 66(3): 323–328.

Simal, S., Femenia, A., Llull, P. and Roselló, C., 2000, Dehydration of *Aloe vera*: simulation of drying curves and evaluation of functional properties. J Food Eng, 43: 109–114.

Troncoso, E. and Pedreschi, F., 2007, Modeling of textural changes during drying of potato slices. J Food Eng, 82: 577–584.

Vega, A., Uribe, E., Lemus, R. and Miranda, M., 2007, Hot-air drying characteristics of *Aloe vera* (*Aloe barbadensis* Miller) and influence of temperature on kinetic parameters. Lebensm Wiss Technol, 40: 1698–1707.

Vega-Gálvez, A., Lemus-Mondaca, R., Bilbao-Sáinz, C., Fito, P. and Andrés, A., 2008, Effect of air drying temperature on the quality of rehydrated dried red bell pepper (*capsicum annuum* L.). J Food Eng, 85(1): 42–50.