Quality assessment of dried eggplant using different drying methods: hot air drying, vacuum freeze drying and atmospheric freeze drying.

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ABSTRACT

Dehydration constitutes a traditional preservation method for fruits and vegetables and it represents a very important operation in food processing. The way how water is removed from food affects the final product quality, thus the characteristics of dried products are dependent on the drying technique used.

The main objective of the present study was to evaluate the effect of different drying techniques on the quality of dried eggplant.

For this purpose, cubic samples (10 mm side) were obtained from the flesh of Spanish origin eggplants (Solanum melongena var. Black Enorma). Three different drying techniques were applied: hot air drying (HAD, 50 ºC and 2 m/s), atmospheric freeze drying (AFD, -14 ºC and 2 m/s) and vacuum freeze drying (VFD). The drying kinetics of HAD and AFD were determined by weighing the samples at preset times during the process. To evaluate the influence of drying method on the final quality of the product, rehydration kinetics of HAD, AFD and VFD samples were monitored. Moreover, textural profile analyses (TPA) were carried out to characterize the hardness of the rehydrated samples. A diffusion model was used to mathematically describe drying and rehydration kinetics.

Drying method influenced significantly (p<0.05) in both rehydration behaviour and textural properties. AFD samples showed intermediate properties between VFD and HAD samples. AFD samples showed a faster and higher rehydration capacity than HAD and a hardness slightly higher than VFD samples. Therefore, AFD could represent an interesting alternative to HAD and VFD to achieve high quality dried products at lower cost than VFD. Its application at industrial scale needs a thorough study on the influence of different variables in both, the kinetics of drying process and the final quality of the product.

Keywords: dehydration; rehydration; diffusion; hardness.

INTRODUCTION

Drying is a classical method to preserve foods, which provides longer shelf life, lighter weight for transport and smaller space for storage [1] than fresh products. However, drying prompts a loss of quality properties due to a structural collapse and biochemical changes. Obviously, the quality degradation depends on the drying technique used. Hot air drying (HAD) is the most common dehydration technology in the food industry because the operation is easy to carry out and requires a small investment. However, HAD affects the final quality of dried products, mainly in the case of heat sensitive products. Vacuum freeze drying (VFD) uses low drying temperatures and oxygen processing environment, that may help to improve the quality and nutritive value of dried products [2], but it is an expensive operation. Atmospheric freeze drying (AFD) could represent an intermediate technique that could provide higher quality products than HAD being a cheaper operation than vacuum freeze drying [3].

Eggplant is an important vegetable in Asian and Mediterranean markets and has a very limited shelf life for fresh use. Dehydration constitutes an alternative to provide higher stability eggplant products, which may be shipped to external markets or used along the whole year [4]. Dried eggplant could be used as a new ingredient in foodstuffs, like soups and sauces. Most of dried products should be rehydrated before consumption. Therefore, it is necessary to know the behavior of the product when it is soaked in water. On the other hand, softening and loss of texture is a problem of dried/rehydrated products, thus texture profile analysis is frequently used to evaluate the textural properties of rehydrated products this being an indication of the tissue damage suffered during the operation.

The main objective of the present study was to evaluate the effect of different drying techniques on the quality of dried eggplant.
MATERIALS & METHODS

Drying experiments
Drying experiments were conducted by three different methods: hot air drying (HAD), atmospheric freeze drying (AFD) and vacuum freeze drying (VFD).

Hot air drying kinetics were carried out in a convective drier, which has already been described in the literature [5]. The drier operates completely automatic, air temperature and velocity are controlled using a PID algorithm and samples are weighed at preset times by combining two pneumatic systems and a PLC (CQM41, Omron, Japan). Hot air drying experiments of eggplant cubes were conducted at constant air velocity (2 m/s) and temperature (50 ºC).

Atmospheric freeze drying experiments were conducted in a convective drier with air recirculation, which was placed inside a freezing chamber to keep the sample at low temperature. Kinetics were carried out at constant air velocity (2 m/s), temperature (-14±1 ºC) and relative humidity of the air (10±1 %). The samples were weighed manually at preset times.

Vacuum freeze drying cubes were obtained using a vacuum freeze drier (Telstar, Lioalfa-6, Germany) that worked at 10⁻³ mbar and -45 ºC. Due to the VFD equipment operates in vacuum and discontinuous way, drying kinetics were not monitored for VFD samples.

In all the cases, HAD, AFD and VFD experiments were carried out, at least, in triplicate and extended until samples lost 90 % of the initial weight.

Cubic particles (10 mm side) were obtained from the flesh of Spanish origin eggplants (Solanum melongena var. Black Enorma) using a houseware tool. In the case of HAD samples, they were processed just after preparation. While in AFD and VFD, samples were sealed, frozen and stored at -18 ºC during 24 hours until drying. Initial moisture content was measured placing samples at 70 ºC and 200 mmHg until constant weight according to AOAC standards [6].

Rehydration experiments
The rehydration experiments were carried out, at least three replicates, in distilled water at 25 ºC using a thermostatic bath. The dried cubes (HAD, AFD and VFD) were rehydrated until constant weight.

Texture
Textural properties of dried/rehydrated and fresh eggplant cubes were measured with a TA-XT2 texturometer (SMS, Godalming, UK) with a load cell of 25 kg. Texture profile analysis (TPA) was carried out by two compression cycles between parallel plates performed in the eggplant cubes, at 25 % strain, using a flat 75 mm diameter aluminum plunger (SMS P/75) and with a 5 s set period of time between cycles. Hardness was calculated from force/deformation profiles. At least, 10 measurements were performed for each set of samples (HAD, AFD, VFD rehydrated and fresh eggplant cubes).

Analysis of variance (ANOVA) (p<0.05) and the LSD (Least Significant Difference) intervals were carried out using the statistical package of Statgraphics Plus 5.1. (Statistical Graphics Corp., Warrenton, USA) in order to estimate if the drying method had a significant influence on the hardness of the rehydrated samples.

Modelling drying kinetics
A diffusion model based on the Fick’s law was used to mathematically describe the drying kinetics (HAD and AFD) of eggplant cubes. The differential equation of diffusion can be obtained combining Fick’s law and the microscopic mass balance. For cubic geometry the diffusion equation was written (Eq. 1) considering constant effective moisture diffusivity and isotropic solid.

\[
\frac{\partial W_p(x,y,z,t)}{\partial t} = D_e \left( \frac{\partial^2 W_p(x,y,z,t)}{\partial x^2} + \frac{\partial^2 W_p(x,y,z,t)}{\partial y^2} + \frac{\partial^2 W_p(x,y,z,t)}{\partial z^2} \right)
\]

(1)

Where \( W_p \) is the local moisture (kg w/kg d.m.), \( t \) is the time (s), \( D_e \) is the effective moisture diffusivity (m²/s) and \( x, y \) and \( z \) represent the characteristic coordinates in cubic geometry (m).

In order to solve Eq. 1, some assumptions were considered: the solid symmetry, uniform initial moisture content and temperature, a constant shape during drying and a negligible external resistance to water transfer. Taking into account these assumptions, the analytical solution of the diffusion equation is expressed in terms of the dimensionless moisture content in Eq. 2 [7].
\[
\psi(t) = \frac{W(t) - W_e}{W_0 - W_e} = \left[ \sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} e^{-\frac{D_e (2n+1)^2 \pi^2}{4L^2}} \pi \right]^{3/2}
\]

Where \( W \) is the average moisture content (kg w/kg d.m.), \( L \) the half-length of the cube side (m) and subscripts 0 and e represent the initial and equilibrium state, respectively.

**Modelling rehydration kinetics**

Rehydration kinetics of the HAD, AFD and VFD eggplant cubes were also modelled considering the diffusion theory (Eq. 3) and assuming the same hypothesis than in Eq. 2.

\[
\psi(t) = \frac{W_e - W(t)}{W_e - W_0} = \left[ \sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} e^{-\frac{D_e (2n+1)^2 \pi^2}{4L^2}} \pi \right]^{3/2}
\]

**Model fitting**

For drying kinetics, the effective moisture diffusivity was identified by minimizing the sum of the squared difference between experimental and calculated average moisture content of samples. Using the same objective function, the effective moisture diffusivity and the equilibrium moisture were identified for rehydration kinetics. In both cases, identification was carried out by using the Generalized Reduced Gradient (GRG) method, available in Microsoft Excel spreadsheet (Microsoft Corporation, Seattle, WA, USA). The goodness of the fit was determined by calculating the percentage of explained variance (%VAR, Eq. 4) [8].

\[
\%VAR = \left[ 1 - \frac{S_{xy}^2}{S_y^2} \right] \cdot 100
\]

Where \( S_{xy} \) and \( S_y \) are the standard deviation of the estimation and the sample, respectively.

**RESULTS & DISCUSSION**

**Drying kinetics**

Hot air drying kinetics of eggplant cubes carried out at 50 °C and 2 m/s are shown in Figure 1A. It can be observed that the time that samples need to reach an average moisture content of 0.5 kg w/kg d.m. was around 2 hours. The results of the drying kinetics modelling are shown in Table 1. The value of the effective moisture diffusivity \( D_e \) for hot air drying experiments was \( 7.64 \cdot 10^{-10} \) m²/s and the percentage of explained variance of the model 89.30%. The low value of the explained variance could mean that assumptions considered in the model formulation were not properly chosen. This fact is also observed in Figure 1A, where the diffusion model results are plotted along the experimental data.

In Figure 1B, the AFD kinetics of eggplant cubes may be observed. In these experiments, the drying times were considerably longer than in HAD experiments due to the low temperature used (-14±1 °C). In this case, the time that samples needed to reach an average moisture content of 0.5 kg w/kg d.m. was between 25 and 30 hours. Thus, the value of effective moisture diffusivity for the atmospheric freeze drying experiments was almost one order of magnitude lower \( (5.28 \cdot 10^{-11} \) m²/s) than in HAD (Table 1). The percentage of explained variance was 92.07%, showing that the diffusion model fitted to the AFD experimental data slightly better than to HAD data.
Figure 1. Hot air (50 °C and 2 m/s, A) and atmospheric freeze drying kinetics (-14 °C and 2 m/s, B).

Rehydration kinetics

The rehydration kinetics of the HAD and AFD eggplant cubes are shown in Figure 2, where it can be observed that AFD samples rehydrated faster than hot air dried cubes and reached higher values of equilibrium moisture (W_{eq}). Vacuum freeze dried cubes reached the equilibrium moisture immediately after their immersion in distilled water (in less than 2 seconds), as is observed in Figure 2. This fact may be explained due to the high porosity of vacuum freeze dried samples. The equilibrium moisture reached by the AFD and the VFD samples was similar and close to the fresh eggplant (12.285±0.925 kg w/kg d.m.).

Figure 2. Rehydration kinetics (25 ºC) of hot air dried (HAD), vacuum freeze dried (VFD) and atmospheric freeze dried (AFD) eggplant cubes.

Table 1 also shows the results of the rehydration kinetics modelling, that is the effective moisture diffusivity, the equilibrium moisture content and the percentage of explained variance. As can be observed in Table 1, the diffusion model fitted to the HAD rehydration kinetics better than to the AFD ones. Moreover, the effective moisture diffusivity for the AFD rehydration experiments was almost one order of magnitude higher than in HAD experiments due to the high porosity of the AFD cubes. Hot air drying reduces the intercellular spaces and creates a compact tissue, partially losing the spongy structure of the eggplant and decreasing the porosity [9]. In AFD samples, the shrinkage was almost negligible due to drying being conducted at a temperature lower than sample thawing point, thus a very low cellular stress is produced.

Table 1. Results of drying and rehydration kinetics modelling.

<table>
<thead>
<tr>
<th></th>
<th>D_{e} (m²/s)</th>
<th>W_{eq} (kg w/kg d.m.)</th>
<th>VAR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Drying</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HAD</td>
<td>7.64·10^{-10}</td>
<td>-</td>
<td>89.30</td>
</tr>
<tr>
<td>AFD</td>
<td>5.15·10^{-11}</td>
<td>-</td>
<td>90.37</td>
</tr>
<tr>
<td><strong>Rehydration</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HAD</td>
<td>4.43·10^{-7}</td>
<td>6.496</td>
<td>96.56</td>
</tr>
<tr>
<td>AFD</td>
<td>2.56·10^{-8}</td>
<td>9.653</td>
<td>88.58</td>
</tr>
</tbody>
</table>
Texture

Hardness was determined from force/deformation profiles obtained by texture profile analysis of the rehydrated samples. The average values of the hardness for the rehydrated eggplant cubes are plotted in Figure 3. The value for the fresh cubes (9.9±4.7 N) is not plotted because its magnitude was one order of magnitude higher than dried samples. Dehydration involves a high degradation of eggplant structure [9], thus rehydrated samples don’t recover the initial texture. Regardless the drying method, dried/rehydrated samples were much softer than fresh eggplant. Significant differences (p<0.05) between the texture of dried samples were also observed. VFD samples showed the lowest and HAD the highest hardness after rehydration. AFD samples showed intermediate textural properties.

![Figure 3](image_url)

**Figure 3.** Hardness of rehydrated eggplant cubes: atmospheric freeze dried (AFD), vacuum freeze dried (VFD) and hot air dried (HAD). Average values and LSD intervals.

CONCLUSION

Drying method prompted changes in textural properties, as well as, rehydration pattern of eggplant samples. AFD samples showed an intermediate rehydration rate and hardness between HAD and VFD samples. Therefore, AFD could represent an interesting alternative to HAD and VFD to achieve high quality dried products with lower cost than VFD. Its application at industrial scale needs a thorough study on the influence of different variables in both, the kinetics of drying process and the final quality of the dried product.

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