FLUIDIZED BED DRYING PROCESS OF MINIFLAKES BANANA
(Musa acuminata)

PROCESO DE SECADO EN LECHO FLUIDIZADO DE MINIHOJUELAS DE PLATANO (Musa acuminata)

Calderón-Santoyo M1, López-Hurtado JA2, Luna-Solano G2, Bautista-Rosales PU1 and Ragazzo-Sánchez JA1


ABSTRACT
The influence of pre-treatment and drying conditions on physical characteristics (moisture content, water activity, net colour difference, shrinking and effective diffusivity) of banana miniflakes during fluidized bed drying was investigated. Banana miniflakes in physiological state (diameters 1.0 - 2.0 cm) were pre-treated with citric acid solution (0-1 % w/w) before to be submitted to the drying process. Drying process (air temperature 50-70 °C) timed 90 min and was monitored every 5 min. A surface response model was used in order to analyse the effect of factors. Citric acid solution (1 % w/w) decrease colour difference since a minor difference of 2.72 was obtained. Banana miniflakes showed aw<0.2 after 60 min treatment, supposing a microbiological stable product. Miniflakes shrinking turned out to be independent of diameter, then, values from 20-25 % were achieved for the whole samples. It was found an inverse function between diffusivity coefficient (E) and diameter sample. Drying of banana miniflakes was influenced by pre-treatment, drying temperature and miniflakes diameter.

Keywords: Banana miniflakes, fluidized drying, response surface.

INTRODUCTION
Banana is considered one of the most important fruits worldwide because of its high content of vitamins (B, C and K) and minerals (iron, phosphorus and calcium). Da Mota et al. (2000) and Langkilde et al. (2002), pointed out the convenience of processing banana fruits in physiological state because of the fruits presented a more adequate texture to be dried. In Mexico, banana culture is highly extended but there is a lack of adequate strategies of commercialization and industrialization. Banana is sensitive to chemical and microbial deterioration during postharvest storage and handling; therefore, it has a limited shelf life in a fresh form, causing economic losses. Development of a shelf-stable product from fresh banana is an important consideration to reduce these losses. Rapid expansion of the fast-food industry shows the potential of quick-cooking dehydrated vegetable products to use as rehydrated products or as ingredients in vegetable and soup mixes (Ravindra and Chattopadhyay, 2000). Although the banana is known in the international markets, it is necessary to obtain a processed product with a longer shelf life and consumption diversity to increase its commercialization.

Drying is one of the oldest, most popular and most efficient natural methods for food preservation. In this context it is essential to determine the coefficients for the models used in this process in order to predict the behavior of the drying operation (Baini and Langrish, 2007). The basic aim of the drying process is the removal of water from the food products up to a level, at which microbial spoilage and deterioration are minimal (Cohen and Yang, 1995). In the cases of fruits, dehydration is generally carried out by convective drying. Many studies have been carried out for various types of vegetables like carrots, pepper, corn, tomatoes, mushrooms, garlic, onions, potato, spinach, pumpkin and banana (Krokida et al., 2003; Sukhchan et al., 2006; Dorota, 2006; Reyes et al., 2007; Demirel and Turhan, 2003). Using...
convencional air-drying dried products with acceptable physicals and organoleptic characteristics can be obtained (Torregiani and Bertolo, 1998).

The major disadvantage of some drying process of foods is their low energy efficiency and long drying time required for the falling rate period. Among the convective dryers with particle-air contact, the fluidized bed drying offers the advantages of good mixing; high heat and mass transfer coefficients and hence increased drying rate. This drying process involves the fluidizing of particles in a flowing gas stream, typically heated air. Fluidized bed drying offers a tight control of process and product temperature necessary for processing heat sensitive plant and food products (Chua and Chou, 2005).

Response surface methodology (RSM) is a compilation of mathematical and statistical techniques used to model and analyze problems where a variable is affected by some factors. The aim of this statistical tool is to optimize the variable, finding the optimal conditions for the operation of the system (Montgomery, 2005). The objective of this study was to determine the optimal operation condition by RSM of banana cv. Roatan (M. acuminata) miniflakes manufacturing by fluidized bed drying.

Nomenclature

\[
\begin{align*}
\Delta E & : \text{Net colour difference} \\
\Delta L & : \text{Luminosity difference} \\
\Delta a & : \text{Green-red difference} \\
\Delta b & : \text{Blue-yellow difference} \\
X & : \text{Humidity (kg water/kg d.s.)} \\
a_w & : \text{Water activity} \\
t & : \text{Time (s)} \\
X_e & : \text{Equilibrium humidity (kg water/kg d.s.)} \\
X_0 & : \text{Initial humidity (kg water/kg d.s.)} \\
L & : \text{Distance (m)} \\
Def & : \text{Effective diffusivity (m}^2/\text{h)} \\
A & : \text{Constant} \\
K & : \text{Drying constant (m}^{-1}) \\
Do & : \text{Initial diffusivity} \\
R & : \text{Ideal gases constant} \\
(8.3144\times10^{-3} \text{ kJ mol}^{-1} \text{ K}^{-1}) \\
T & : \text{Temperature (°K)} \\
Ea & : \text{Activation energy (kJ/mol K)}
\end{align*}
\]

**MATERIALS AND METHODS**

**Materials**

Banana variety Roatan (M. acuminata) in physiological state was obtained in a local market in Tepic, Nayarit, Mexico. Banana fruits were washed with tap water. Banana miniflakes with diameters of 1.0, 1.5 and 2.0 cm and thickness were obtained by using a cutting device designed for this purpose. Banana miniflakes were dipped into solutions containing citric acid (0, 0.5, 1 % w/w) prior to drying process during 15 minute. Then the miniflakes were dried into a fluidized bed dryer operated at different temperatures (50, 60, 70 °C) during 90 min with an air rate of 7 m/s.

**Drying Equipment**

Fluidized bed and tray type pilot plant dryers were used to carry out the drying experiments. Fluidized bed dryer (FBD) with an inner diameter of 0.15 m (cross sectional area = 0.018 m²) and a height of 0.85 m was used. It had several supporting features such as air flow meter, temperature controller, heaters and pressure manometers. The vertical tray dryer (VTD) used in this study, consisted of a steel drying chamber connected to an electric heater of 4.5 kW capacity. The heater increases the temperature of air to the desired drying temperature and can be electronically controlled within an error limit of ± 1 °C. The drying chamber contains ten perforated trays (0.50 m wide and 0.75 m long) through which the drying air flows vertically. The air velocity in both FBD and VTD dryers was measured with an anemometer at the outlet of the dryer.

**Experimental Design**

A 2³ rotatable central composite design with three factors (independent variables) was performed for dehydration of banana miniflakes tests. The experiment was performed three times. The factors investigated were temperature (40-60 °C), concentration of citric acid (0-1 % w/w) and miniflakes diameter (1.0 – 2.0 cm). Three levels of each variable (Table 1) were chosen for this study, including central values.

**Response Variables**

Moisture content, water activity, net colour difference, effective diffusivity and shrinking were the response variables evaluated. These variables were monitored every 5 min during the first hour and every 10 min after this period and until 90 min.

Moisture content was determined by a thermodalance (Sartorius MA 35) at 70 °C. The results were expressed as percentage in dry basis (g water/g d.b).

Water activity was determined with an Aqualab Mod. CX2 (DECAGON Devices, Pullman, Washington) at 25 °C.

Net colour difference (ΔE): was measured by a colorimeter Hunter Lab (Model MiniScan XE Plus). The equipment was calibrated with White and Black standards. The colour

<table>
<thead>
<tr>
<th>Table 1. Codified independent variables used for response surface analysis.</th>
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<tr>
<td><strong>Independent Variables</strong></td>
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<tr>
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<tr>
<td>Temperature (°C)</td>
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<tr>
<td>Citric acid (% w/w)</td>
</tr>
<tr>
<td>Miniflakes diameter (cm)</td>
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</table>
was determined by reflectance mode and expressed as L* (Luminosity), a (green-red) and b (blue-yellow) parameters. Net colour difference between the dried and fresh samples was calculated using the equation 1 proposed by Chen and Ramaswamy (2002).

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2}$$  \hspace{1cm} (1)

It was used a second degree polynomial model (equation 2) to describe the response variables:

$$Y_k = b_0 + \sum_{i=1}^{3} b_{i0} X_i + \sum_{i=1}^{3} \sum_{j=1}^{3} b_{ij} X_i X_j$$  \hspace{1cm} (2)

Where $b_{i0}$, $b_{ij}$ represent regression coefficients (lineal, cross product and quadratic), and $X_i$'s are the codified independent variables ($X_1$, $X_2$ and $X_3$).

Mathematical Considerations

The mathematical study was supported in terms that mass transfer during the drying process is performed from the fruit inner to the outer. Fruit is considered as a thin slide. The Fick’s law of diffusion has been applied before to explain the drying process during the final stage were the drying velocity decrease. The diffusion coefficient $D$ is estimated by the equation:

$$D = \frac{4L^2m}{p^2}$$  \hspace{1cm} (3)

The diffusivity dependence on the temperature was calculated with the aid of Arrhenius’ equation as follows:

$$D = D_0 \exp \left( -\frac{E_a}{RT} \right)$$  \hspace{1cm} (4)

Where, $D$ = Diffusivity; $D_0$ = Initial diffusivity; $R$ = Ideal gases constant ($8,3144 \times 10^{-3}$ kJ mol⁻¹K⁻¹), and $T$ = Temperature (°K). $E_a$ was obtained from the slope resulted from the graphic $1/T$ vs $\ln(D)$.

RESULTS AND DISCUSSIONS

The miniflakes drying kinetics performed at 50, 60 y 70 °C are showed in Figure 1. A dependence of temperature to reach the equilibrium moisture was demonstrated, this profile has been demonstrated before (Villegas-Santiago, 2011).

The exponential regression used to fit the drying kinetics showed a $R^2 > 0.95$ for the whole treatments. The response surface analysis was conducted by StatGraphics software and the optimal values for the factors were found. This analysis indicated that 70 °C was the optimal temperature to obtain miniflakes with a moisture content significantly lower as the content showed by the samples treated at 50 y 60 °C.

The surface response plot (Fig. 2) showed the effect of the drying temperature on the moisture content, this effect was more significant than the others because a minimal effect was observed during variation of citric acid concentration and miniflakes diameter.

A food is considered as microbiologically stable when water activity ($a_w$) is lower than 0.5 (Beuchat, 1981). One of the objectives in this study was to optimize the values for the tested factors to obtain miniflakes with a low $a_w$ in order to produce a microbiologically stable product. The surface response plot for $a_w$ showed a clear effect of the temperature on this parameter. As observed in the moisture content profile, there was not a significant effect of the other factors analysed (Fig. 3). According to the surface response analysis,
the optimal value for the temperature was 70 °C. This temperature enables the process to obtain a product with a lower than 0.5.

The food colour is highly important to have the preference from consumers (Dorota, 2006; Pérez et al., 2006; Chen and Ramaswamy, 2002). Thus, it is important to take care of the drying process in order to preserve the characteristics of the fresh product as possible. Two pathways realize the colour changes in oxidation sensible fruits: the enzymatic (PPO) and the chemical (Maillard reaction). The last one is mainly affected by the temperature. Treatments showing a greater net colour change were those in which 0.5 % citric acid was used (Fig. 4). Even if miniflakes in those treatments were treated with the antioxidant, this used concentration was not enough to avoid the oxygen action and to observe a preserving effect on the colour miniflakes.

The citric acid concentration that minimized the net colour difference was 1 % (Fig. 5). Some reports have demonstrated that citric acid is the best antioxidant among other compounds because of the inactivation of poliphenoloxidase, the enzyme responsible of fruits oxidation (Mancini et al., 2009; Limbo and Piergiovanni, 2006; Sammel and Claus, 2006; Villegas-Santiago, 2011). In this case, temperature did not have a significant effect on net colour difference, showing that Maillard reaction does not take place in the process.

Some methods have been reported for obtaining correlations between size reduction and moisture loss throughout the drying process (Nguyen and Price, 2007; Hatamipour and Mowla, 2005; Corzo et al., 2008). Figure 6 shows the procedure proposed by Hatamipour and Mowla (2005) to obtain the correlation between the diameter diminution and the moisture loss at the three temperatures tested. In this study, miniflakes shrinking rate was calculated using the correlations showed in the figure 6. In fact, this value corresponds to the slope of the lineal regression used to fit the diameters data plotted as a function of time. Surface response analyses indicate that miniflakes shrinking was only affected by temperature. Then 70 °C was the temperature that had the greatest effect on size reduction.

The effective diffusivity coefficient could be affected by factors others than temperature. In this study a clear effect of citric acid addition was observed (Fig. 7). This could be due to the formation of weak bonds with water bonded before to banana components. This water could be considered as free water and be eliminated easier than bonded water in the product. The drying temperature also had influence on the effective diffusivity coefficient, showed a type Arrhenius behaviour. Applying the equation 4, a value of 34,5588036 kJ/mol K for Ea was determined. The model coefficients obtained by regression for the second order polynomials of responses surface of $Y_k$ to $Y_5$ are shown in table II.
The analysis of variance (ANOVA) performed with the NCSS 2004 software showed that there is a direct relation between temperature and the moisture content, water activity, net colour difference and the effective diffusivity coefficient. The antioxidant (citric acid) concentration affected the net colour difference as well as the effective diffusivity coefficient. Concerning the miniflakes final diameter, it was observed that the factor affecting the most was the antioxidant concentration.

**Table 2.** Regression coefficients obtained for the response surface models

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Y1</th>
<th>Y2</th>
<th>Y3</th>
<th>Y4</th>
<th>Y5</th>
</tr>
</thead>
<tbody>
<tr>
<td>b_{k0}</td>
<td>0.0238258</td>
<td>0.256759</td>
<td>33.804</td>
<td>1.215</td>
<td>3.12532E-8</td>
</tr>
<tr>
<td>b_{k1}</td>
<td>-0.0299762</td>
<td>-0.0870833</td>
<td>-0.839189</td>
<td>-0.0358333</td>
<td>7.15164E-9</td>
</tr>
<tr>
<td>b_{k2}</td>
<td>-0.00881226</td>
<td>0.0136667</td>
<td>-7.95237</td>
<td>-0.00111111</td>
<td>5.01052E-9</td>
</tr>
<tr>
<td>b_{k3}</td>
<td>0.00888257</td>
<td>0.023333</td>
<td>3.10585</td>
<td>0.431111</td>
<td>-4.328E-10</td>
</tr>
<tr>
<td>b_{k12}</td>
<td>0.0133696</td>
<td>0.027638</td>
<td>2.57441</td>
<td>0.0341667</td>
<td>3.40852E-9</td>
</tr>
<tr>
<td>b_{k13}</td>
<td>0.00860605</td>
<td>0.0035</td>
<td>0.148792</td>
<td>0.00833333</td>
<td>1.17103E-9</td>
</tr>
<tr>
<td>b_{k23}</td>
<td>-0.00656386</td>
<td>0.00345833</td>
<td>-1.66825</td>
<td>-0.01625</td>
<td>1.17283E-10</td>
</tr>
<tr>
<td>b_{k11}</td>
<td>0.00789693</td>
<td>-0.0299444</td>
<td>-19.2165</td>
<td>0.0</td>
<td>-4.39358E-9</td>
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<tr>
<td>b_{k22}</td>
<td>-0.00791278</td>
<td>-0.0221667</td>
<td>-1.59505</td>
<td>0.00833333</td>
<td>-9.95567E-10</td>
</tr>
<tr>
<td>b_{k33}</td>
<td>-0.0107351</td>
<td>0.0130556</td>
<td>-1.54185</td>
<td>-0.0783333</td>
<td>-2.55933E-10</td>
</tr>
</tbody>
</table>

**Figure 6.** Miniflakes shrinking rate determination during dehydration process (♦ 50 ºC, ■ 60 ºC and ▲ 70 ºC).

**Figure 7.** Surface response plot for effective diffusivity coefficient as a function of temperature, % citric acid and miniflakes diameter.

**Figura 6.** Velocidad de deformación de mini-hojuelas durante el proceso de secado (♦ 50 ºC, ■ 60 ºC and ▲ 70 ºC).

**Figura 7.** Gráfico de superficie de respuesta del coeficiente de difusividad efectiva en función de la temperatura, % ácido cítrico y diámetro de mini-hojuelas.
CONCLUSIONS

The drying kinetics were efficiently adjusted by the exponential regression ($R^2 > 0.95$) indicating that data are correctly recovered. Optimal conditions calculated by response surface methodology turned out to be perfectly comparable to results obtained by statistical analysis. The optimized factors to obtain the best characteristics for banana miniflakes were temperature of 70 °C, 1% citric acid concentration and size of 1 cm. The miniflakes drying kinetics for the whole assayed temperatures could be described in terms of the Fick’s second law, using the first term. The values for the effective diffusivity coefficient are comparable with those reported for other fruits. Arrhenius behaviour was observed for the temperatures used.

References