Modeling of drying kinetics of ripe plantain (*Musa paradisiaca*) chips in a forced convection tunnel

Modelización de la cinética de secado de astillas de plátano maduro (Musa paradisiaca) en un túnel de convección forzada

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ABSTRACT

In this work the mathematical modeling of the drying process of plantain (*Musa paradisiaca),* with hot air in a tunnel under forced flow conditions is presented. The temperature of air was 60 °C at a velocity of 3.0 m/s. The geometric form of the product cuts was considered: round slices of 4.0 cm of diameter and 1.5 mm of thickness. The drying time for the slices was 300 min. The numerical model obtained for the kinetics of drying was the logarithmic one. Organoleptic properties were used to evaluate the quality of the productor final.

Keywords: Plantain, *Musa paradisiaca*, forced convection, numerical model.

RESUMEN

En este trabajo se presenta la modelación matemática del proceso de secado de plátano (Musa paradisiaca), con aire caliente en un túnel bajo condiciones de flujo forzado. La temperatura del aire fue de 60 °C a una velocidad de 3,0 m/s. Se consideró la forma geométrica de los cortes del producto: rodajas redondas de 4,0 cm de diámetro y 1,5 mm de espesor. El tiempo de secado de las lonchas fue de 300 min. El modelo numérico obtenido para la cinética de secado fue el logarítmico. Las propiedades organolépticas se utilizaron para evaluar la calidad del producto final.

Palabras clave: Plátano, Musa paradisiaca, convección forzada, modelo numérico.

1 INTRODUCTION

The annual production of bananas in Mexico is 2 460 000 ton and includes all the existent varieties, 445 000 ton of which correspond to plantain (*Musa paradisiaca)* (SIAP, 2021). Approximately, 30 % (134 000 ton) of this production is not commercialized for several reasons, specifically outstanding, the fact that the fruit reaches its maturity state in the commerce spots, eventually the color of its peel becomes black and the fruit rotes.

Plantain is used in Mexico in a wide variety of dishes, which comprise part of the Mexican gastronomy since pre-Hispanic times (Delgado Calderón *et al.*, 2011). Recently it has been used in its dry form as a snack, in different presentations and with condiments such as sugar, ground hot pepper, and salt. The drying process commonly takes place in the open air; the fruit is cut into 1.0-cm slices and set in trays which are covered at night to prevent the absorption of the humidity that has been previously lost during the day. This process lasts from 6 to 7 days.

There have been several studies concerning the drying of bananas. Garcia *et al.* (1988) reported drying data for a particular geometry of sliced banana, but their fitted equations do not facilitate the calculation of the moisture diffusivity, which is a geometry-independent property. Nogueira and Park (1992) presented values of the moisture diffusivity as a function of temperature and air velocity for the drying of whole, peeled banana to obtain the dried product, referred to in Brazil as "banana-passa". They fitted the diffusivity values to the Arrhenius equation, quantifying the temperature effect and determining the activation energy. Demirel and Turhan (2003), Karim and Hawlader (2005), and Nguyen and Price (2007), have studied the drying of banana slices using hot air, but up to date there are no reports concerning the drying of plantain. Famurewa and Adejumo (2015) used a coal stove to dehydrate unripe 5 mm-thick plantain slices at 70 °C, the time used was 240 min and the model of the process obtained was that of Henderson. Méndez *et al.* (2015) dried the banana and other fruits with the use of the ultrasound method, used approximately 350 min in the process and the model obtained was the logarithm. Campo-Vera et al. (2020) also obtained similar results with the same ultrasound technique.

The objective of this work was to study the kinetics of the drying of the plantain with hot air in a tunnel under forced flow conditions. The temperature of air was 60 °C at a velocity of 3.0 m/s. The geometric form of the product cut was studied, using round slices of 1.5 mm thickness and 4.0 cm diameter.

2 MATHEMATICAL MODELING

The moisture ratio was calculated using $MR = (M_t - M_e)/(M_0 - M_e)$, which has been simplified to M_t/M_0 by some researchers, such as Kaymak-Ertekin (2002), and Akpinar *et al.* (2003), because of the continuous fluctuation of the relative humidity of the drying air during the processes. For mathematical modeling, the thin layer drying equations in Table 1 were tested to select the best model to describe the drying curve equation of plantain using hot air.

The higher values of the correlation coefficient R, and the lower values of χ^2, were the primary criteria for selecting the best equation to describe the drying curve. These were calculated as

$$R^2 = \frac{\sum_{i=1}^{n}(MR_i - MR_{pre,i}) \cdot \sum_{i=1}^{n}(MR_i - MR_{exp,i})}{\sqrt{\left[\sum_{i=i}^{n}(MR_i - MR_{pre,i})^2\right] \cdot \left[\sum_{i=1}^{n}(MR_i - MR_{exp,i})^2\right]}} \quad (1)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(\mathrm{MR}_{\mathrm{exp,i}} - \mathrm{MR}_{\mathrm{pre,i}}\right)^2}{\mathrm{N-n}} \quad (2)$$

where $MR_{exp,i}$ stands for the experimental moisture ratio found in any measurement, $MR_{pre,i}$ is the predicted moisture ratio for this measurement and n are the number of observations and the number of constants respectively (Yaldis and Ertekin, 2001).

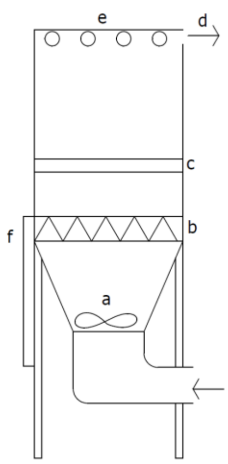
Table 1. Mathematical models applied to the moisture ratio values

Model	Model name	References
MR = exp(-kt)	Newton	Jayas *et al.* (1991)
MR = exp(- kt^n)	Page	Page, 1949
MR = exp[- $(kt)^n$]	Modified Page	Overhults *et al.* (1973)
MR = a exp(- kt)	Henderson and Pabis	Henderson and Pabis (1961)
MR = a exp(- kt)+c	Logarithmic	Togrul and Pehlivan (2002)
MR = a exp(-kt)+b exp(-k_1t)	Two Terms	Henderson (1974)

3 EXPERIMENTAL APPARATUS

The scheme of the drying tunnel used in this study is presented in figure 1. Air is conducted by means of an axial-flow fan, (a). The velocity of air can be varied between 1.0 and 4.0 m/s; in this study the velocity applied was 3.0 m/s. There is a panel of two electrical resistances of 1750 W each, they are operated independently, which allows the selection of the energy to be supplied, (b). The test chamber is 20-cm width and 20-cm length (c), it has an air outlet designed as a vertical vent (d), and a control system (e).

Figure 1. Drying tunnel, a) fan; b) electrical resistances; c) testing chamber; d) air vent; e) infrared lamp and f) control panel.



INSTRUMENTATION AND MEASUREMENT

Air and product-surface temperatures were measured using calibrated K-type thermocouples (0.5 °C exactitude); the relative humidity of the environment was determined using a model EA25 EXTECH digital hygro-thermometer, with 0.1 % resolution. A model 451112 EXTECH anemometer (0.1 m/s resolution) was used to measure the velocity of air. Mass was quantified using a model BL1505 SARTORIUS scale, with a 0.001 g span. Data acquisition was programmed using LABVIEW software.

EXPERIMENTAL PROCEDURE

Plantain fruits were bought from a local market in Mexico. The product cut was studied, round slices of 1.5 mm thickness and 4.0 cm diameter. Temperature of air was 60 °C at a velocity of 3.0 m/s. This temperature was chosen because in preliminary essays, at higher values, such as those used by Famurewa and Adejumo (2015), the product darkened excessively. Tests were done in a continuous drying process, to guarantee that no perturbation could hinder the course of the experiment (Simal *et al.*, 1997).

The electrical resistances were operated to raise the surface temperature of the probes up to 60 °C. Mass, air temperature, probe-surface temperature and relative humidity were automatically monitored and registered in a computer. The measurements were done every 10 minutes during the first 2 hours and every 30 minutes for the rest of the time.

4 RESULTS AND DISCUSSION

The initial humidity content of all samples was 2.17 kg water/kg dm and the final value was 0.012 kg water/kg dm. For air at 60 °C and 3 m/s, the round slices became dry in approximately 5 hours. The resulting curve is presented in figure 2. The final dimensions of the samples in round slices were 0.8 mm thickness and 3.6 cm diameter.

A period of constant velocity within the range of 0.0013 and 0.0017 kg_{water}/kg_{dm} min was detected at 60 °C (figure 3). The maximum drying velocity was observed at the beginning of the process, amounting to 0.049 kg_{water}/kg_{dm} min. No warming-up of the samples was noted. The second half of the process had a constant rate of mass loss, its value was 0.0005 kg_{water}/kg_{dm} min.

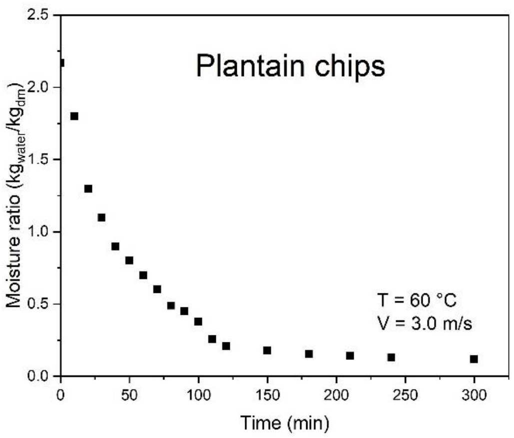


Figure 2. Drying curve for plantain with air at 60 °C and 3 m/s.

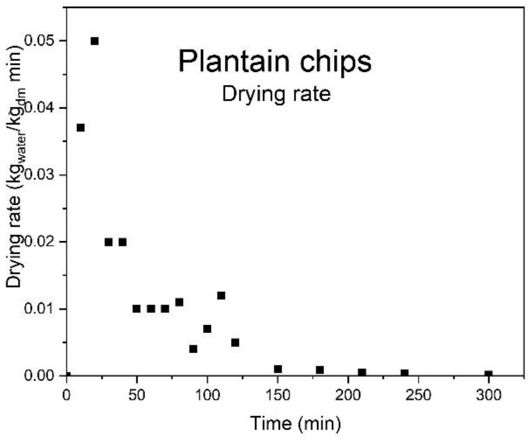
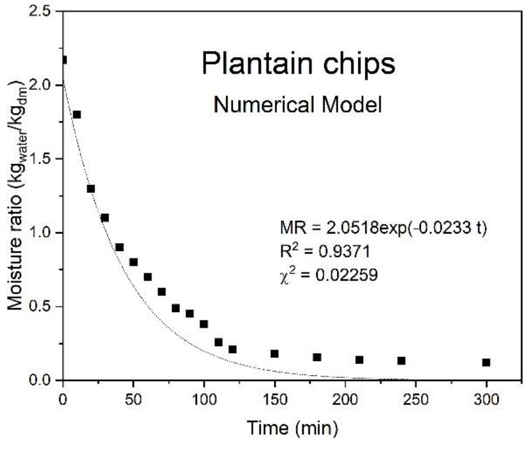


Figure 3. Drying rate versus water content for T = 60 °C.

In the numerical models presented in Table 1, the experimental data obtained are adjusted to select the one that best suits the course of the process, and it was found that the Henderson and Pavis model provided the best approximation, using the imposed criteria. These values are: R^2 = 0.9371, which is close to the unit and a c^2 = 0.02259 is the lowest value. Both the experimental and adjusted curves are presented in figure 4. The drying constant has a value of -0.0233.

Figure 4. Numerical model for T = 60 °C.



About the evaluation of the organoleptic properties of the chips, color, smell, and taste were examined.

The Hunter´s method used to analyze the change in color during the drying process is meant to determine the following ratios: black/white, L; red/green, a; and yellow/blue, b; also, the total color change ΔE and the chroma, which indicate the color saturation (Tijskens *et al.*, 2001). These are calculated as:

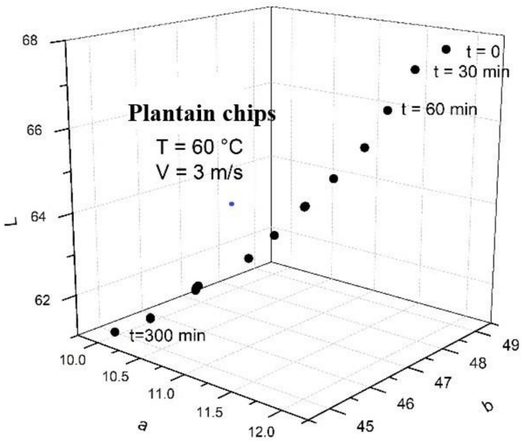
$$\Delta E = \sqrt{(L_0 - L_t)^2 + (a_0 - a_t)^2 + (b_0 - b_t)^2} \quad (3)$$

where the 0 subindex corresponds to the initial value and t is the time of evaluation, and

$$Chroma = \sqrt{a_t^2 + b_t^2} \quad (4)$$

The measured values of Hunter's variables, a, b and L, for plantain chips, dried at 60 °C, are presented in figure 5. The initial values, (at t = 0) were 12, 49, and 68, and the final values at t = 300 min, were 11, 45, and 61. The color changes were gradual, at no time was there a sudden change of the variables L, a and b. With these values and based on equations (3) and (4), the total color change and variations of the chroma were calculated (figures 6 and 7).

Figure 5. Change in Hunter's variables (a, b, L) for plantain chips.



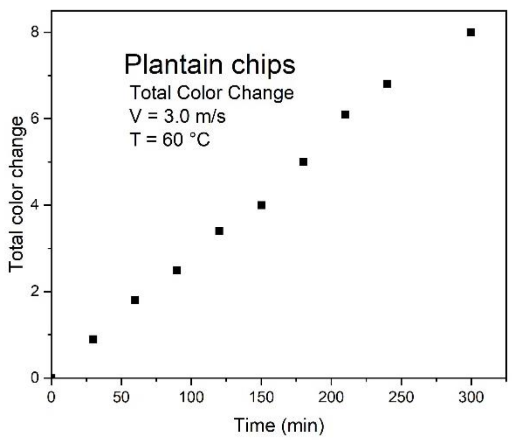


Figure 6. Total color change versus drying time for T = 60 °C.

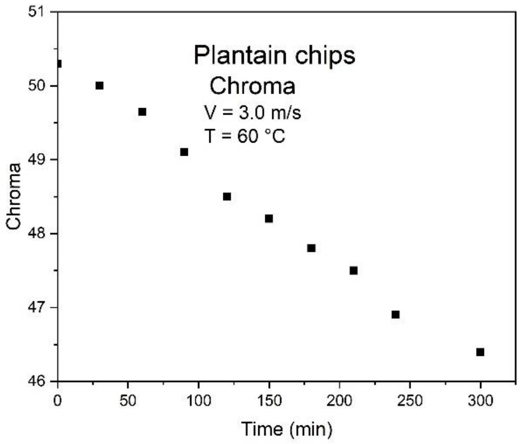


Figure 7. Chroma versus drying time for T = 60 °C.

The difference between the initial and final values of the color change was not significant since the color of the chips at the end was slightly darker than at the beginning of the experimentation. These changes were similar in the intensity of the color, with minimal variations.

For the taste, twenty volunteers who were not related to the project were selected and their eyes were covered so that they did not know what kind of food they were given to try. First, they were asked to attempt to recognize the product only through its smell. Just four people identified the product. After tasting the chips just eight people did succeed to identify the taste of the banana. We concluded that the product would require the addition certain locally used seasoning (*i. e.* sugar, salt, hot pepper, lime), to improve its flavor and acceptance, as expressed by all the twenty participants, after such addition.

5 CONCLUSIONS

Samples of plant chips were dehydrated with air at a T = 60 °C and V = 3.0 m/s, from an initial value 2.17 kg_{water}/kg_{dm} to a final value of 0.012 kg_{water}/kg_{dm}. The initial sizes of the samples were 4.0 cm in diameter and 1.5 mm in thickness. The final values were 3.6 cm and 0.8 mm respectively, after 50-min drying.

The numerical model that better represented the kinetics of drying of plantain was the Henderson and Pabis one in all the performed experiments, following the R^2correlation coefficient tending to the unit and $\chi^2$to zero.

For the quality evaluation of the dried product, its organoleptic properties were used; in terms of color, small variations in the intensity of the chroma and slight changes the total color were observed. Twenty volunteers participated in the organoleptic tests of the plantain chips, only four of them perceived the smell and eight managed to recognize the flavor, therefore we concluded that the product would require the addition of certain locally used seasoning, to improve its flavor and acceptance, as expressed by the twenty participants, after such addition.

NOMENCLATURE

a	red/green ratio	
b	yellow/blue ratio	
L	white/black ratio	
M	moisture content	kg/kg dm
MR	moisture ratio	%
N	number of observations	
R	correlation coefficient	
t	time	s
χ^2	reduced chi-square	
T	temperature	°C

Subscripts

0	initial
exp	experimental
pre	predicted

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