Kinetics drying of silver banana (*Musa* spp.) in hybrid dryer[1]

Cinética de secagem da banana prata (*Musa* spp.) em secador híbrido

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ABSTRACT - The search for the reduction of production costs and for the diversification of the commercialization of agricultural products is necessary when looking to ensure autonomy and increase income for farmers. The use of solar dryers for the dry fruits production provides an excellent alternative for consideration. However, in order to introduce this technology, one must understand the drying kinetics for a given product. This paper's purpose was to study the intermittent drying kinetics of banana in a hybrid dryer. The drying was performed in a hybrid dryer composed of a solar collector (photothermal energy), a drying chamber containing Banana-Prata cut into cylindrical and disc shapes and a power-driven exhaust system. The process occurred during four sequential days, totaling 78 h of operation and 12 h of intermittence. The effective drying period took 39 h, with a temperature and relative humidity inside the drying chamber of 43.4 °C and 45.3%, respectively, and an air speed of 1.0 m.s^{-1}. In the first few hours of drying, a sharp decrease in the moisture content was verified. During this period, the maximum and minimum drying temperatures were approximately 42 and 28 °C, respectively. A higher reduction in the moisture content of the disc samples was observed when compared to the cylindrical shape. After the intermittence period, a peak of moisture ratio was observed, followed by a marked loss of water in the fruit in both formats. The results have shown that the Page model is the one that better applies to the experimental data for the intermittent solar drying of banana in both shapes.

Key words: Dryer solar. Solar energy. Intermittent drying. Dried fruit. Dehydrated banana.

RESUMO - A busca pela redução de custos de produção e diversificação de comercialização de produtos agrícolas torna-se necessária para autonomia e aumento de renda dos produtores rurais. A utilização de secadores solares para produção de frutas secas consiste em excelente alternativa a ser adotada. No entanto, para a introdução desta tecnologia deve-se ter conhecimento da cinética de secagem para determinado produto. Objetivou-se estudar a cinética de secagem intermitente da banana em secador híbrido. A secagem foi realizada em secador híbrido composto por coletor solar (energia fototérmica), câmara de secagem contendo banana prata nos formatos cilíndrico e disco e sistema de exaustão (energia elétrica). O processo ocorreu em quatro dias seguidos, totalizando 78 h de operação e 12 h de intermitência. O período efetivo de secagem ocorreu durante 39 h, com temperatura e umidade relativa média no interior da câmara de 43,4 °C e 45,3%, respectivamente, e velocidade do ar 1,0 m.s^{-1}. Verificou-se nas primeiras horas de secagem acentuada redução da razão de umidade. Nesse período, a temperatura máxima e mínima de secagem foi aproximadamente de 42 e 28 ºC, respectivamente. Observou-se maior redução do teor de água das amostras em disco quando comparado ao formato cilíndrico. Após o período de intermitência, constatou-se pico de razão de umidade, seguido de acentuada perda de água pela fruta em ambos os formatos. Os resultados evidenciaram que o modelo de Page é o que melhor se ajusta aos dados experimentais da secagem intermitente solar da banana em ambos formatos.

Palavras-chave: Secador solar. Energia solar. Secagem intermitente. Frutas secas. Banana desidratada.

INTRODUCTION

The banana is a highly perishable product, with a maximum shelf life of three weeks under an optimal temperature and relative humidity of 12 ºC and 90% respectively (EMBRAPA MANDIOCA AND FRUTICULTURA TROPICAL, 2006). As such, marketing should be expedited and handled correctly in order to avoid significant losses. According to Lichtemberg, Villas Boas and Dias (2008), post-harvest losses can amount to 60% of production. In order to diversify commercialisation of the fruit, it is possible to adopt a drying process to produce different products to meet the requirements of ever more-demanding consumers (CANO *et al*., 2016; OLIVEIRA, AFONSO; COSTA, 2011). For the rural producer, the production of dried fruits at the farming level means adding market value, with a consequent increase in income, in addition to the possibility of processing surplus production that can be sold at negligible prices during periods of good harvest (OLIVEIRA; AFONSO; COSTA, 2011).

Generally, commercial fruit dryers obtain heat energy by means of an electrical resistance, burdening production costs with the acquisition and consumption of conventional electrical energy, without heeding the call for environmentally correct processes. Accordingly, dryers that operate using photothermic energy can be employed. These allow the drying of agricultural products in an ecologically viable way, and usually have low installation, operating and maintenance costs (BELESSIOTIS; DELYANNIS, 2011; BUSATTO *et al*., 2013; MUSTAYEN; MEKHILEF; SAIDUR, 2014; PRAKASH; KUMAR, 2013).

In view of the main effect of the sun heating the air for drying occurring during the day, it is possible to adopt intermittent drying for fruit. This type of process is based on the discontinuous passage of the heated air over the product throughout the drying time. As such, at times when the product is not under the action of the heated air, homogenisation of the moisture takes place due to the water migrating from the interior to the periphery of the product. As a consequence, the peripheral water evaporates smoothly and evenly (ELIAS, 2002; SIMIONI *et al*., 2007). Studies have shown that the intermittent drying of grain with a high water content is an efficient technique, since in addition to reducing energy consumption, it does not compromise physical-chemical or sensory characteristics (BORÉM *et al*., 2014; ISQUIERDO *et al*., 2011; ISQUIERDO *et al*., 2012; MENEGHETTI *et al*., 2012).

In order to evaluate the performance of dryers it is necessary to study drying kinetics using mathematical models (SILVA *et al*., 2009; SIQUEIRA; RESENDE; CHAVES, 2013). Mathematical modelling allows the time and operational costs to be reduced by determining the ideal drying time for agricultural products (SIQUEIRA;

RESENDE; CHAVES, 2013). Among the models that have been studied, of note are Page, Henderson and Pabis, and the Logarithmic model for the Oiti mango and pulp (DISSA *et al*., 2011; SOUSA *et al*., 2011), Page and Midilli, Kucuk and Yapar for cupuassu pulp and the plantain (PEREZ *et al*., 2013; SANTOS *et al*., 2010a), and Page and Henderson and Pabis for the apple banana (SILVA *et al*., 2009) and carambola (SANTOS *et al*., 2010b). For intermittent drying, the Midilli model best represented this process in whole-grain rice (MENEGHETTI *et al*., 2012).

However, mathematical models to describe the intermittent drying of fruit using solar energy have not been verified. The aim of this work was to study the kinetics of intermittent drying of the 'prata' banana in a hybrid dryer, which works with photothermic energy for the solar collector and conventional electrical energy for the extractor fan.

MATERIAL AND METHODS

The drying process using a hybrid dryer was carried out in the experimental area and the Laboratory of Rural Electrification and Alternative Energies of the Department of Engineering (DE)/Institute of Technology (IT) of the Federal Rural University of Rio de Janeiro (UFRRJ), Seropédica campus, from October to December of 2015. According to the Köppen classification, the climate in the region is classified as type A, tropical with rainfall during the summer (VILLA *et al*., 2016).

The experiment was conducted using bananas (*Musa* spp.) of the 'prata' variety, purchased from local markets in the district of Seropédica, Rio de Janeiro. The fruit was selected based on uniformity of maturation, skin colouration and the absence of physical damage. The fruit was washed in running drinking water, and manually cut into discs (0.03 m in diameter x 0.02 m thick) and cylinders (0.03 m in diameter x 0.10 m in length x 0.02 m thick). The fruit was sanitised in a solution of mineralised water and bleach in the proportion of 1:10 for 300 s (CORNEJO; NOGUEIRA; WILBERG, 2003). The samples were then drained, separated by shape and arranged in removable screen-bottom trays to allow the drying air to pass in an orderly way through the mass of the product.

The banana-drying process occurred over four consecutive days; on the first day, the drying time was from 12:00 to 18:00 h, on the following days from 08:00 to 18:00 h, totalling 78 h of operation with an intermittent period of 12 h. The effective drying time was 39 h. Before and after drying, the water content of the samples was determined in an oven at 105 °C to constant weight.

The analysis was carried out in triplicate (INSTITUTO ADOLFO LUTZ, 2008).

The hybrid dryer comprised a solar collector, drying chamber and extractor system. To form the solar collector, a rectangular metal box, 0.14 x 0.68 x 3.00 m in size (width x length x height) was used. An absorbing surface was placed inside the box, made of pleated aluminium and painted matte black. The solar energy in the collector was used to generate heat energy (photothermic) in order to convert the ambient air into drying air. To achieve this, the ambient air was routed through the lower channels of the absorbing surface to acquire heat energy and then through to the drying chamber. At the top of the solar collector a clear, colourless glass cover, 0.004 m thick, was used. The drying chamber was made from a deactivated laboratory oven, 0.77 x 0.64 x 0.80 m in size (width x length x height). A cut was made at the lower back of the drying chamber to connect the solar collector. The extractor system was constructed from a reusable air purifier with a power of 152 W to force air circulation inside the drying chamber. This system was driven by conventional electrical energy. The purifier was protected from the ambient conditions by a 0.26 x 0.43 m pipe cover (diameter x height) and the lid from a milk jug, 0.06 m³ in size. To optimise the use of the solar radiation, the dryer was positioned facing north, and the collector arranged in such a way that it made an angle of 32° with the horizontal.

During the drying process, the air speed, light intensity, and temperature and relative humidity of the drying air and ambient air were monitored. The drying-air speed was measured at the exit of the exhaust fan of the drying chamber with the aid of a Minipa MDA II digital anemometer. The light intensity in the solar collector was measured with a Minipa MLM 1010 digital lux meter. To monitor the temperature of the drying air, thermocouples connected to a millivoltmeter with an accuracy of ± 0.1 °C were placed at the connection between the drying chamber and the solar collector, at the lower, mid and upper part of the drying chamber, and at the electric extractor. In addition, the ambient air temperature was measured. A Minipa MTH-1380 hygrometer was used to monitor the relative humidity of the ambient air and the drying air. The curves for the temperature and relative humidity of the drying air and ambient air, for the difference between these two parameters, and for luminosity as a function of drying time were plotted using the SigmaPlot 10.0 computer software. In this case, the drying time was considered to include each day of dryer operation, i.e. 78 h.

In studying the kinetics, the weight reduction in the samples during the drying process was monitored by gravimetry, where the tray and fruit were weighed together every hour on a semi-analytical balance with a resolution of 0.001 g. Weighing continued until the samples reached hygroscopic equilibrium with the conditions of the drying air, i.e. when the variation in weight was constant. From the experimental data, the values for moisture ratio (Equation 1) were calculated.

$$MR = \frac{X^* - X_e^*}{X_i^* - X_e^*} \tag{1}$$

Where: MR = Moisture ratio, dimensionless; X^* = Water content of the product (%, d.b.); X_i^* = Initial water content of the product (%, d.b.); X_e^* = Equilibrium water content (%, d.b.).

To study the drying kinetics, the experimental data were adjusted to the mathematical models of Page (Equation 2), Henderson & Pabis (Equation 3), Midilli, Kucuk and Yapar (Equation 4) and the Logarithmic model (Equation 5) as a function of the effective drying time (39 h).

$$MR = e^{(-kt^n)} \tag{2}$$

$$MR = ae^{(-kt)} \tag{3}$$

$$MR = ae^{(-kt^n)} + bt \tag{4}$$

$$MR = ae^{(-kt)} + b \tag{5}$$

Where: t = drying time (h); k = drying constant; a, b, n = coefficients of the models.

The SigmaPlot 10.0 software was used in fitting the mathematical models to the experimental data through non-linear regression analysis. For the significance of the regression coefficients by t-test, a 5% level of significance was adopted. In selecting the best models to represent the drying kinetics of the fruit, the following were considered: the magnitude of the coefficient of determination adjusted by the model (R^2), mean square deviation (MSD) (Equation 6), estimated mean squared error (MSE) (Equation 7), chi-square (χ^2) (Equation 8) and magnitude of the relative mean error (P) (Equation 9).

$$MSD = \sqrt{\frac{\sum (MR_{pred} - MR_{exp})^2}{n}} \tag{6}$$

$$MSE = \sqrt{\frac{\sum (MR_{exp} - MR_{pred})^2}{DF}} \tag{7}$$

$$X^2 = \frac{\sum (MR_{exp} - MR_{pred})^2}{DF} \tag{8}$$

$$P = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{MR_{exp} - MR_{pred}}{2} \right| \tag{9}$$

Where: MRpred = moisture ratio predicted by the model; MRexp = observed experimental moisture ratio; n = number of the observation; DF - degree of freedom (number of experimental observations minus the number of model coefficients).

RESULTS AND DISCUSSION

Figure 1 shows the drying-air temperature, ambient temperature and the difference between these two parameters as a function of drying time, for each day when drying data was collected for the bananas in cylindrical and disc format.

Figure 1 - Temperature (T °C) of the air in the drying chamber ($T_{drying\,air}$), ambient air ($T_{ambient\,air}$) and the difference between these two parameters as a function of drying time
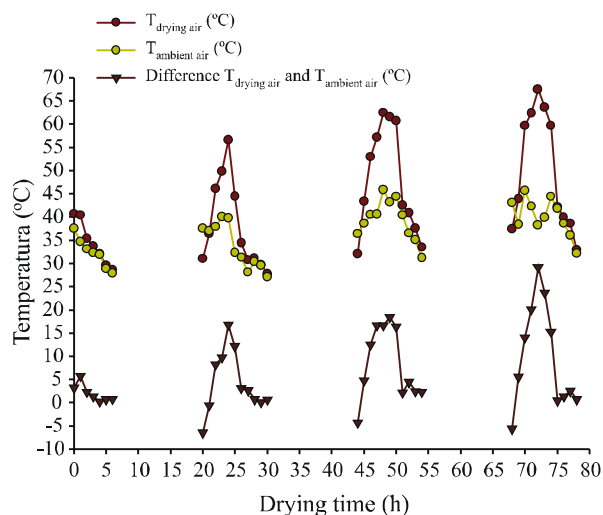
The lowest temperatures occurred at the beginning and end of the day, while the highest temperatures occurred from 10:00 to 16:00 h (Figure 1). The minimum temperature inside the drying chamber reached 27.8 °C at 18:00 h on the second day. At the same time, the ambient air had a temperature of 27.1 °C, i.e. an increase of 0.7 °C (Figure 1). The maximum temperature in the drying chamber reached 67.5 ℃ at 12:00 h on the fourth day, with an ambient-air temperature of 38.3°C, showing an increase of 29.2 °C (Figure 1). The mean variation in temperature increase between the drying air inside the chamber and the ambient temperature was 7.1 °C.

In addition to the increase in temperature, the drying air showed the greatest reduction in relative humidity, of 12.1% at 11:00 and 12:00 h on the fourth day (Figure 2). The mean variation for the reduction in relative humidity between the drying air inside the chamber and the ambient air was 3.2%.

During solar drying of the banana, the mean luminosity recorded in the solar collector was 35.5 Lux, with a maximum of 99.6 Lux at 11:00 and a minimum of 0.5 Lux at 18:00 h (Figure 3).

Figure 2 - Relative humidity (RH %) of the drying chamber ($RH_{drying\,air}$), ambient relative humidity ($RH_{ambient\,air}$) and the difference between these two parameters as a function of drying time
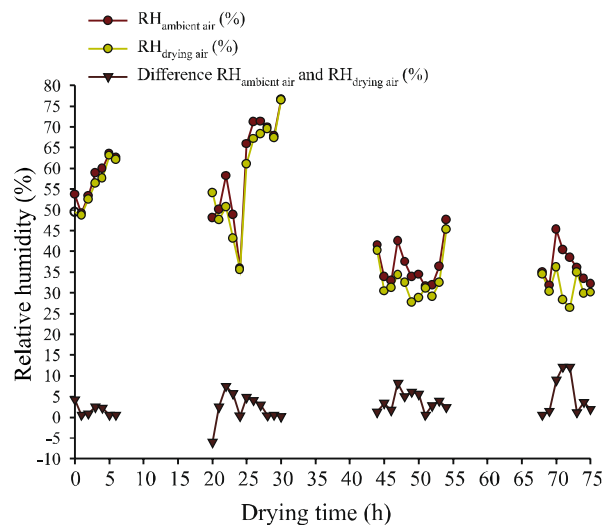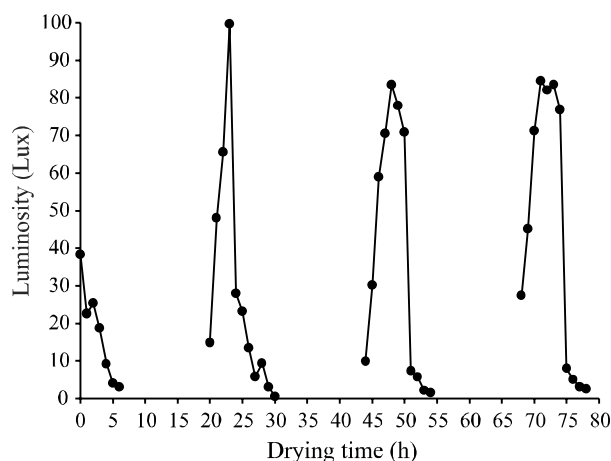

Figure 3 - Luminosity (Lux) incident on the solar collector as a function of drying time

In short, in studying the drying kinetics of the banana in both cylindrical and disc format, the temperature, RH and mean drying-air speed were 44.3 °C, 42.5% and 1.0 m.s^{-1} respectively. The banana samples in both formats had an initial water content of 77.2%.

Figure 4 shows the experimental values for moisture ratio (dimensionless) as a function of drying time (h), represented by the time of operation of the hybrid dryer containing banana in cylindrical and disc format.

Figure 4 - Experimental data for solar drying of the banana in cylindrical and disc format
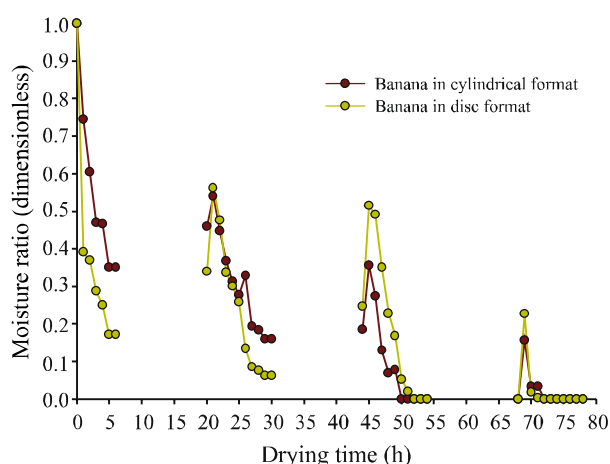
It can be seen that during 3 and 2 h drying on the first day there was a marked reduction in the moisture content of the banana in cylindrical (53%) and disc (63%) format respectively (Figure 4). As such, on the first day the banana in disc format favoured mass transfer, with a reduction in water content and drying time. The rapid reduction of the moisture ratio in both formats demonstrates faster water loss during the first few hours of drying. The same behaviour was seen by Santos *et al*. (2010a), when evaluating drying in the carambola at different temperatures in a tray dryer. Furthermore, a greater reduction in moisture ratio can be seen over 6 h of drying on the first day for the banana cut into discs (83%) when compared to the cylindrical format (65%) (Figure 4).

After 12 h intermittence, the moisture ratio showed higher values than registered the previous day, with the exception of the fourth day (Figure 4). This behaviour may possibly be related to moisture adsorption during the night so as to reach a condition of equilibrium with the environment. Drying the banana discs gave higher rates of moisture adsorption, of 50 and 75% on the second and third day respectively. For the cylindrical format, the adsorption rate was 24% on the second day and 65% on the third. On the last day of drying, there was no moisture adsorption, characterising equilibrium of the dried fruit with the environment (Figure 4).

Every day, one hour after the start of data collection in the hybrid dryer, a peak in moisture ratio was seen, followed by a marked loss of water by the fruit in both formats (Figure 4). However, the banana cut into discs showed higher peaks in moisture ratio (0.56, 0.51 and 0.23 after 21, 45 and 69 h drying respectively) when compared

to the cylindrical format (0.54, 0.36 and 0.16 after 21, 45 and 69 h drying respectively) (Figure 4).

As regards water loss throughout the drying period, on the second day there was a reduction of 70 and 100% in moisture ratio for the banana in the cylindrical and disc formats respectively. On subsequent days, there was a 100% reduction in moisture ratio after 50 and 72 h for the cylindrical format, and after 52 and 71 h drying for the disc format (Figure 4). After this time, a trend towards equilibrium was seen, i.e. the moisture ratio remained constant (Figure 4).

According to the results, it can be inferred that the disc format, due to its smaller dimensions and consequently larger total exposed surface, results in a higher reaction rate, showing a higher rate of water withdrawal (BORGES *et al*., 2010). Furthermore, because the disc format has smaller dimensions, it affords a reduction in the resistance found by the moisture when migrating from the interior to the surface of the samples. As such, the drying rate increases with the reduction in banana size (NGUYEN; PRICE, 2007; SILVA *et al*., 2009). With knowledge of these results, it is possible to establish the ideal drying time, as well as conditions for packaging and storing the dried product.

However, the times required for solar drying of the banana in the cylindrical and disc formats to reach a water content of 24% were very close, 72 and 71 h respectively. This behaviour demonstrates that the drying time required for the banana to reach equilibrium moisture ratio does not depend on the shape of the fruit. Studies by Borges *et al*. (2010), evaluating the influence of the disc and cylindrical formats on drying in the 'prata' banana at different temperatures, agree with the results found in this work.

Table 1 shows the parameters for the models used to represent the solar-drying process of bananas in the cylindrical and disc formats.

The results obtained by the drying kinetics of the banana in cylindrical and disc format show that the greatest value for the coefficient of determination (R^2) was Midilli, Kucuk and Yapar, followed by Page (Table 1). The low values for R^2 shown by the models relative to the disc format can be attributed to the higher rate of moisture adsorption (Figure 4). However, the coefficient of determination is not the only criterion for selecting models analysed by means of non-linear regression (COSTA *et al*., 2015).

The Page and Midilli, Kucuk and Yapar models presented lower MSD and MSE values for both formats (Table 1). According to Silva *et al*. (2009), the lower the MSD value the better the representation of the model used. The low MSE value validates the proposed models,

Table 1 - Statistical analysis of the kinetic models used to represent solar drying of the banana in cylindrical and disc format

Kinetic Models	Cylindrical					Disc				
	R^2	MSD	MSE	χ^2	P	R^2	MSD	MSE	χ^2	P
Page	0.88	0.07	0.07	0.01	3.40	0.58	0.15	0.15	0.02	6.76
Henderson &Pabis	0.88	0.08	0.08	0.01	3.40	0.48	0.17	0.17	0.03	6.93
Midilli, Kucuk e Yapar	0.91	0.07	0.07	0.01	2.78	0.66	0.15	0.15	0.02	5.54
Logarithmic	0.88	0.08	0.09	0.01	2.95	0.42	0.19	0.19	0.04	7.73

R^2 - Coefficient of determination; MSD - Mean square deviation; MSE - Mean error; χ^2 - Chi-Square

characterising less deviation of both the experimental and estimated values (SIQUEIRA; RESENDE; CHAVES, 2013).

It can be seen that there was no change in the values for χ^2 for the formats under analysis (Table 1). All the models, regardless of format, showed values for P of below 10%, as recommended by Mohapatra and Rao (2005).

In short, when analysing the statistical parameters, the simplicity of the equation (COSTA *et al.*, 2015) and the coefficients significant at 5% by t-test, the Page model was seen to best fit the experimental data for the intermittent solar-drying process of the banana in both the cylindrical and disc formats.

The Page model was the most suitable to represent the drying kinetics of the kiwi (SIMAL *et al.*, 2005), apple banana (SILVA *et al.*, 2009), cupuassu (PEREZ *et al.*, 2013), pineapple (ALEXANDRE *et al.*, 2009) and carambola (SANTOS *et al.*, 2010a). For modelling the intermittent process, the Page model presented a good fit to the experimental data for the intermittent drying of rice husks (MENEGHETTI *et al.*, 2012).

Figure 5 shows the curves for moisture ratio as a function of effective drying time (h) represented by the experimental and estimated values by the Page model.

The parameters of the Page model fitted to the experimental data for the drying kinetics of the banana in different formats are shown in Table 2.

It was found that the parameters estimated by this model gave a higher value for the k constant and lower values for the n coefficient of the banana cut into discs than for the cylindrical format (Table 2). According to Duarte *et al.* (2012), Perez *et al.* (2013), Silva *et al.* (2015), and Siqueira, Resende and Chaves (2013), the k constant, known as the diffusion coefficient, represents the diffusivity of the process, while n reflects the internal resistance to drying. As such, these results confirm the behaviour seen during the experiment, in which greater mass transfer was obtained with the banana in disc format.
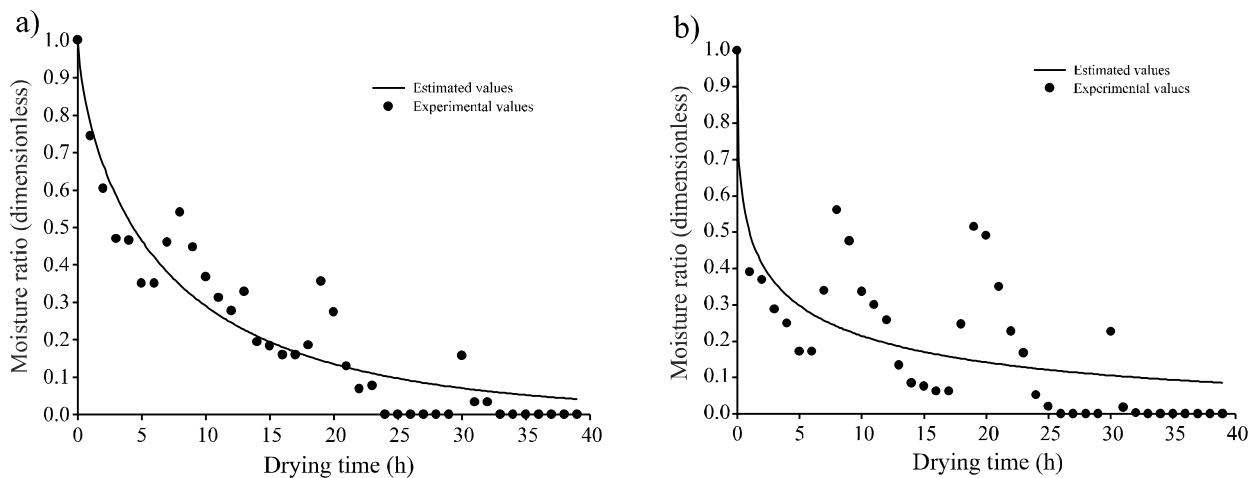
Figure 5 - Graphical representation of the Page mathematical model for the banana in a) cylindrical and b) disc format

Table 2 - Parameters of the Page model adjusted for solar drying of the banana in cylindrical and disc format

Banana Format	Parameters	
	k	n
Cylindrical	0.2506*	0.6937*
Disc	0.6954*	0.3445*

k - drying constant; n - model coefficients; *Significant at 5% by t-test

CONCLUSIONS

1. The Page model best represents the experimental data, and can be used to predict drying kinetics in a solar dryer for banana in different formats;

2. Banana in disc format tends to result in higher drying rates, which can be attributed to the larger contact surface;

3. The time required for solar drying of the banana to reach equilibrium does not depend on the format of the fruit.

ACKNOWLEDGEMENTS

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