DETERMINATION OF VOLUMETRIC CONTRACTION AND DRYING KINETICS OF THE DRYED BANANA

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Abstract: Banana *(Musa spp.)* is one of the most nutritious and consumed fruits, especially in tropical countries. The drying of the fruit is an alternative against the injuries suffered, mainly during the post-harvest process. Thus, the knowledge of the physical properties of the product that is intended to be processed has a big importance for the dimensioning of equipment. Therefore, the objective of this work was to study the drying kinetics of the banana, transforming it into dried banana, besides evaluating the volumetric contraction suffered during drying. The bananas were dried in an oven at temperatures of 70, 60 and 50 ºC. The volumetric measurements were carried out before and after drying to determine the volumetric contraction during the process. After drying, the experimental data were modeled by nonlinear regression analysis by the Quase-Newton method, to adjust 4 mathematical models of moisture ratio and 5 mathematical models of volumetric contraction. Among the models tested, the best fit for the prediction of the Moisture Ratio was the exponential model, and for the Volumetric Contraction was the modified BALA and WOOD model.

Index terms: *Musa spp.*, drying curves, mathematical modeling.

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INTRODUCTION

The banana (*Musa spp*.) is an edible fruit, very nutritious, because it is a source of minerals such as potassium, calcium, phosphorus, iron, magnesium, as well as vitamins, making it one of the most consumed fruits in Brazil and around the world. Banana drying process is an alternative to losses caused during the post-harvest process, damages in transportation, handling and storage, as well as adding value to the product (Ribeiro, 2014).

Banana is a highly hygroscopic biological product. Hygroscopic products have the property to carry out water changes, in the form of vapor or liquid with the surrounding environment, by absorption or desorption (Lima et al., 2000).

Many researchers have used mathematical approximations and models in an attempt to better represent the phenomenon of volumetric contraction and drying kinetics in products of a biological nature.

According to Siqueira et al. (2012), the volumetric contraction index represents the ratio of the fruit volume or grain for each water content by the initial volume. This parameter has a fundamental importance in drying processes in dryers, since it allows better prediction of the behavior of the product in the process of volumetric reduction during the loss of water content.

Alexandre et. al (2013) affirmed that among the research carried out by food technology is the search for an increase in the useful life of the food product, in order to convert them into more stable products, with storage for longer periods, using as main techniques the freezing and drying of food. The banana is obtained by natural or artificial drying of the mature fruit, usually from the banana nanica, which has high sugar contents.

According to Brooker et al. (1992) drying is the simultaneous process of heat and mass transfer, heat transfer from the air to the product and the water content of this to the air. The conservation of food by drying is based on the fact that with the reduction of available water in the products there is a reduction of water activity and the rate of chemical reactions, such as the development of microorganisms (Christensen and Kaufmann, 1974).

Bansal and Garg (1987) recommend that the maximum temperature for drying the banana is 70 ºC, the initial water content of the banana is usually around 80 % wet basis (w.b.) and the final one, recommended by the authors, of 15 % (w.b.). Dried bananas are stable to the action of microorganisms if the water content is less than 23% (w.b.). The use of suitable drying techniques can lead to the obtainment of a product of light color, soft consistency and pleasant taste and aroma (Medina et al., 1978).

The mathematical modeling has been studied by several researchers using different agricultural products and it is therefore of great importance the use of mathematical models to represent the drying processes. In addition to such information, they are valid for the development of equipment with better efficiency and more accurate predictions in drying time (Faria et al., 2012).

Several researches were created with the objective of knowing the drying kinetics of fruits and agricultural products: apple banana (Silva et al., 2009), leaf of aroeira (Goneli et al., 2014); star fruit (Leite et al., 2016); coffee (Siqueira, 2017); quinoa grains (Moscon et al., 2017).

Due to the importance of the physical properties of the agricultural products and their transformations during processing, this work had as objective to evaluate the volumetric contraction of the banana (*Musa spp.*) during the drying process in order to obtain the dried banana. Besides determine the drying curve and show the rate of water reduction of the banana at three different drying air temperatures.

MATERIAL AND METHODS

The work was realized at the Technological Center in the Department of Agricultural and Environmental Engineering and at the Grain Processing and Storage Laboratory of the Fluminense Federal University - Niterói - RJ.

For the work were used bananas nanica (*Musa spp.)* mature acquired in the local commerce, which were completely yellow, with coffee areas in the stadium of color 7 (Chitarra and Chitarra, 1990), ideal for making dried bananas.

The initial water content was determined gravimetrically, by mass loss in the oven at 105 ± 1 ºC located at the Laboratory of Soil Mechanics of the Federal Fluminense University until constant weight (Instituto Adolfo Lutz, 1985).

To measure the initial volume of the banana, was used volume equations of known geometric shapes that most resembled the banana. Therefore, the banana was divided into 6 parts to find a similar geometric shape and to make the error minimum.

For the banana extremity the volume equation of a semi-ellipsoid (Figure 1a) was used, due to the great similarity. For the central part of the banana, divided into four parts, the equation of the volume of a cone trunk (Figure 1b) was used.

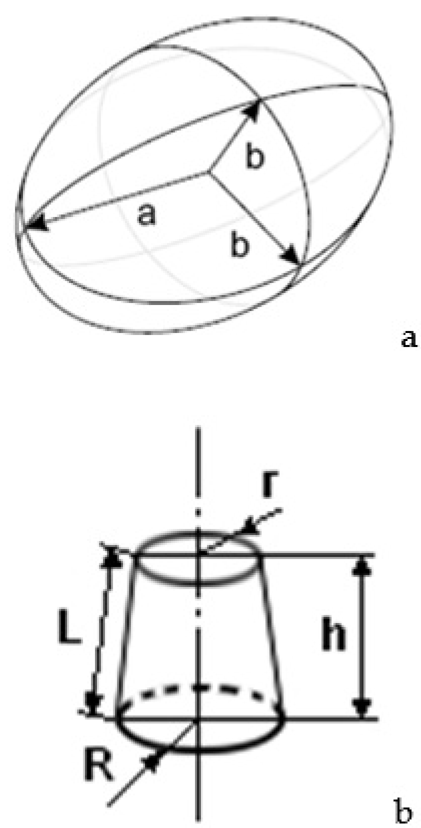

Figure 1: a) Geometric shape of an ellipsoid; b) Geometric shape of a cone trunk.

According to Forbes (2000), the volume of an ellipsoid is (Equation 1):

$$V = (4/3)\pi ab^2 \quad (1)$$

The extremity of the banana resembles a semi-ellipsoid and therefore the equation used to calculate the volume of the banana extremity was (Equation 2):

$$V = (4/6)\pi a(b/2)^2 \quad (2)$$

where,
a = average height of the banana tip;
b = mean diameter of the banana tip.

The equation for cone trunk volume is (Equation 3):

$$V = \frac{\pi}{12} h(2R^2 + 2R\,x\,2r + 2r^2) \quad (3)$$

where,
h = average height of a part of the banana;
R = mean radius of the major base;
R = mean radius of the minor base.

The diameters and heights of the banana parts were measured with a PANTEC brand digital caliper with scale in millimeters.

In order to assess the results, the volume of each part of the banana was determined from the volume of water displaced by the introduction of the fruits into test tubes of different volumes, according to the size of the parts of the banana described by Machado (1989).

The calculation of the volume using the geometric formulas, as well as the measurement of the volume of each part of the fruit through the volume of displaced water, was carried out in three replications.

Then, the difference between the calculated volume and the measured volume of each part of the fruit was calculated and the differences were added. The error found was less than 5%, which makes it possible to use the geometric formulas to calculate the fruit volume.

The experiment was carried out for three distinct air temperatures usually used for banana drying, 50, 60 and 70 ºC and with average relative humidity of 18.68; 11.72 and 7.64% respectively for each temperature. The relative humidity was calculated by the GRAPSI program. To measure them, the dry bulb temperature and the wet bulb temperature of the ambient air were recorded at each weighing using mercury thermometers.

The drying process takes place in three stages, in the first, the product is very humid so the water of the more superficial layers are easily removed. In the second stage, the water that lies in the innermost layers migrates to the surface and is then removed. In the third stage, the remaining water is in the interstices of the product and is thus hardly removed, requiring high temperatures.

Very mature bananas were chosen for the experiment. In each drying, 10 bananas were used and the sums of the weights were used for the calculations. The drying took place in the stove with forced air circulation and the product was weighed using a digital scale with precision of two decimal places.

For the adjustment of the mathematical models to the experimental data of humidity ratio, in order to estimate its parameters, a non-linear regression analysis was performed by the Quasi-Newton method, using the program STATISTICA 5.0®.

According to bibliographical research based on the latest studies, equations were adopted that best fit the experimental data to express the Ratio of Moisture as a function of temperature and drying time, and also due to its relative precision and generality, as described in Table 1, where the equations 4 to 7 are presented.

Table 1: Mathematical models of reason of humidity used in the work.

Model	Equation	
Exponential	$MR = \exp(-kt)$	(4)
Page	$MR = \exp(-kt^a)$	(5)
Thompson	$MR = A \ln(MR) + B (\ln(MR))^2$	(6)
Waste modified	$MR = (a \exp(-bt) + c \exp(-dt))T^e$	(7)

The equation for determining the Equilibrium Moisture "(Me)" used for the MR calculation was the Modified Halsey equation. This equation was the most suitable for the banana, according to Andrade et al. (2010).

$$MR = \frac{M - Me}{Mo - M} \tag{8}$$

where,
MR = Moisture Ratio (dimensionless);
M = Moisture content at time t (d.b.);
Mo = Initial moisture content (d.b.);
Me = Equilibrium Moisture (d.b.)

$$Me = \frac{\exp^{(a-bT)}}{-\ln (aw)^{1/c}} \tag{9}$$

where,
t = time (h);
$k = a \ \exp\frac{-b}{273.15 + T}$;
T = Drying air temperature (ºC);
A = –a + bT;
B = a exp(bT);
Aw = water activity (decimal);
k,a,b,c,d,e,A,B = Constants that depend on the product.

The water activity (Aw) was considered to be equal (in decimal) relative humidity, according to Sauer (1992).

In order to select the model that best represented the moisture ratio of the product, the experimental data were compared with the values estimated by each model, by the mean relative error (P) and estimated mean error (SE), equations 10 and 11. The capacity of the model describe the physical process is inversely proportional to the value of SE (Draper and Smith, 1981, Douglas and Donald, 1988; Chen and Morey, 1989; Chen and Jayas, 1998).

$$P = \frac{100}{n}\sum\frac{|Y - Y_0|}{Y} \tag{10}$$

$$SE = \sqrt{\sum\frac{(Y - Y_0)^2}{GLR}} \tag{11}$$

where,
Y = experimental value observed;
Y_0= value calculated by the model;
GLR = degrees of freedom of the model;
N = number of experimental observations.

According to Corrêa et al. (2001), the Water Reduction Rate (WRR) can be defined as the amount of water that a product loses per unit of dry matter per unit of time.

$$WRR = \frac{Ma0 - Mai}{Ms(ti - t0)} \tag{12}$$

where,
WRR = Water Reduction Rate (kg water kg dry matter $^{-1}$ h^{-1});
Ma0 = Previous total mass of water (kg);
Mai = Current total mass of water (kg);
Ms = Dry matter (kg);
t0 = Total previous drying time (h);
ti = Current total drying time (h).

The data necessary for the study of the volumetric contraction of the banana were obtained during the banana's drying. The bananas used for the calculation of volumetric contraction were distributed in 6 parts to obtain the initial volume and were placed in the oven at temperatures of 50, 60 and 70 ºC.

The volumetric contraction of the banana (Ψ) was determined by the relation between the volume for each water content at the time and the initial volume, according to the Equation 13:

$$\Psi = \frac{V - V0}{V0} \tag{13}$$

The volume of each part of the banana was determined by volume equations of known geometric shapes (Equations 2 and 3).

To the experimental data of volumetric contraction (Ψ) were adjusted the mathematical models Linear modified, Exponential modified, Bala and Woods modified, Rahman modified and Corrêa et al modfied, as follows in Table 2 (Equations from 14 to 18):

Table 2: Mathematical models of Volumetric Contraction used in the work.

Model	Equation	
Linear modified	$\Psi = a (+ (bU)) T^c$	(14)
Modified Exponential	$\Psi = a (\exp (bU (T^c)))$	(15)
BALA & WOODS modified	$\Psi = (1-(a (1 - \exp (-b(U_0-U)))))T^c$	(16)
RAHMAN modified	$\Psi = (1+(a (U-U_0))) T^b$	(17)
CORRÊA et al modified	$\Psi = (1/(a+(b \exp U)))T^c$	(18)

where,
Ψ = Volumetric contraction index (decimal);
U = Moisture content (d.b.);
U0 = Initial moisture content (d.b.);
T = Drying air temperature (ºC);
a, b, c = Constants that depend on the product.

For the adjustment of the models to the experimental data, the STATISTICA 5.0® program was used. Non-linear regression analysis was performed using the Quasi-Newton method. The experimental data were compared with the values calculated by the models, by average error relative (P) and estimated (SE) average errors, according to equations 10 and 11 previously described.

RESULTS AND DISCUSSION

Figure 2 shows the experimental drying values for the banana submitted to drying air temperatures of 70, 60 and 50 ºC.

It is possible to notice that with the increase of drying air temperatures, a higher water removal rate of the product occurred, which is equivalent to the result of drying kinetic studies for other products. Such as coffee (Alves et al., 2013), red rice (Santos and Oliveira, 2013), fig (Corrêa et al., 2015), garlic (Cagnin et al., 2017), quinoa (Moscon et al., 2017), bean (Quequeto et al., 2017). The time used for drying for the three temperatures was over 20 hours. For the temperature of 70 ºC the drying time was of 20 hours and 40 minutes. At 60 °C the time was 27 hours and 30 minutes and for the temperature of 50 °C the drying took 32 hours.

It is observed that the drying of the dried banana occurs in the period of decreasing drying rate, demonstrating that there is difficulty in the transfer of heat and mass from the interior of the product to the surface, so that diffusion is the main mechanism in the water movement during drying (Kashaninejad et al., 2007).

With the experimental values obtained with the 3 temperatures and 3 relative humidity, the drying curve for the banana was obtained by non-linear regression.

The Table 3 presents the moisture content data (MR) of the banana-pass obtained experimentally through equation (08) for the temperatures of 50, 60 and 70 °C, the initial moisture, the equilibrium moisture obtained through equation (09) and the WRR obtained by equation (12).

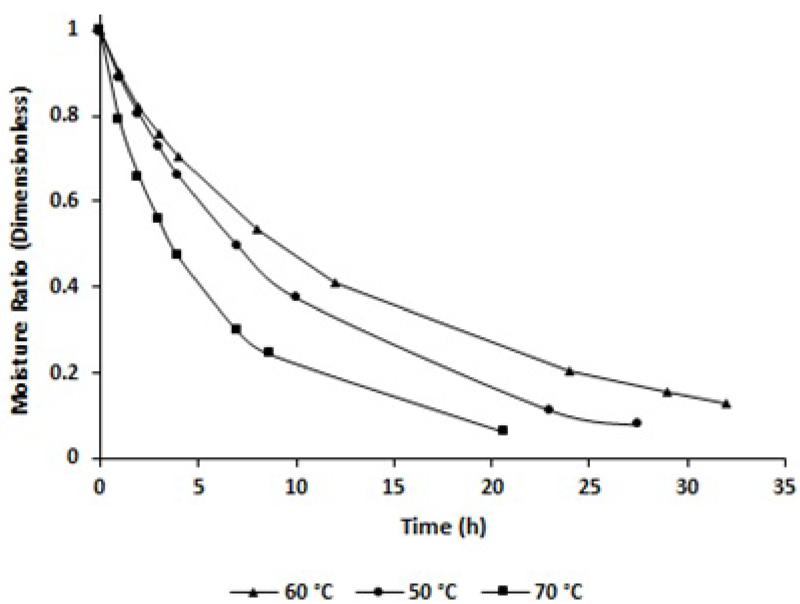

Figure 2: Variation of the Moisture Ratio at drying air temperatures of 70, 60 and 50 ºC.

Table 3: Table with equilibrium moisture data, experimental data of moisture ratio and water reduction rate.

t (h)	$a_{w\ (decimal)}$	Me(d.b.)	MR	WRR ($kg\ kg^{-1}\ h^{-1}$)
T= 70 ºC				
0	0.081	0.06508381	1.000	-
1	0.072		0.78844	0.6624059
2	0.072		0.65780	0.4090341
3	0.072		0.55730	0.3146873
4	0.072		0.47052	0.2717005
7	0.081		0.29761	0.1804743
8.67	0.081		0.24301	0.1023703
20.67	0.081		0.06086	0.0475251
mean	0.0764			
T= 60 ºC				
0	0.1148	0.08020462	1.000	-
1	0.1148		0.8898	0.4092097
2	0.1148		0.8044	0.3167213
3	0.1148		0.7284	0.2823722
4	0.1148		0.6610	0.2499947
7	0.1220		0.4972	0.2026479
10	0.1220		0.3744	0.1519713
23	0.1148		0.1120	0.0749094
27.5	0.1220		0.0779	0.0281569
mean	0.1172			
T= 50 ºC				
0	0.1779	0.10212197	1.000	-
1	0.1779		0.9006	0.268996662
2	0.1890		0.8224	0.211547281
3	0.1890		0.7595	0.169923924
4	0.1890		0.7046	0.148700586
8	0.1890		0.5370	0.113343603
12	0.1890		0.4080	0.087237525
24	0.1779		0.2043	0.045907666
29	0.1890		0.1567	0.025742445
32	0.2007		0.1294	0.024638588
mean	0.1868			

In order to have a better evaluation of the nonlinear models it is necessary the joint analysis of several statistical parameters, such as standard deviation of the estimate (SE), coefficient of determination (R2) and relative mean error (P).

According to Kashaninejad et al. (2007), the values of the relative mean error (P) represent the deviation of the values observed in relation to the curve estimated by the model to be adjusted. In accordance, Mohapatra and Rao (2005) argue that models that have a relative mean error above 10 % do not adequately describe a phenomenon.

According to Siqueira et al. (2012), the standard deviation of the estimate (SE) expresses how a model accurately describes a particular physical phenomenon, so that the smaller its value, the more appropriate is the fit of the model in relation to the experimental data.

The results of the estimates of the parameters of the Moisture Ratio models tested for the banana and their respective determination coefficients (R2), relative and estimated mean errors are presented in Table 4.

Table 4: Estimates of parameters of the Moisture Ratio model for the dried banana, with their respective determination coefficients (R2), relative (P) and estimated (SE) errors.

Modelo Exponencial	Parâmetros	R^2 (%)	P (%)	SE (decimal)
70 ºC	K = 0.1840	98.9328	5.6700	0.0757
60 ºC	K = 0.1002	99.8799	4.2331	0.0728
50 ºC	K = 0.0742	98.9337	9.3579	0.1362

From the analysis of the results of the Banana Moisture Ratio, it was observed that among the four mathematical models tested, the Exponential model, with data presented in Table 3, presented coefficient of determination above 99.88%. The best values were for the temperature of 60 °C, which presented the coefficient of determination of 99.88 % and relative mean error of 4.23%. The modified waste model also presented adequate results, with a coefficient of determination above 95%.

With the experimental values obtained with the 3 temperatures and 3 relative humidity, the volumetric contraction curve was obtained by non-linear regression. The volumetric contraction data (Ψ) of the banana obtained experimentally through equation (13) for the temperatures of 50, 60 and 70 °C. The initial water content (Uo) was determined gravimetrically, by oven weight loss at 105 ± 1 °C (Adolfo Lutz Institute, 1985) and water content after drying (U), determined by Equation 19:

$$U = \frac{Wwater}{Wdm} \quad (19)$$

where,
U = Water content;
Wwater: Weight of banana water after a certain drying time
Wdm: Weight of dry matter, calculated by equation: Pms = Pbanana – (Uo * Pbanana) are shown in Table 5.

Table 5: Table of volumetric contraction data obtained experimentally.

T= 70 ºC			
t (h)	V (m^3)	U (d.b.)	Ψ
0	0.0002091	3.196	-
4	0.0001142	1.538	0.454
8.67	0.0000926	0.826	0.557
20.67	0.0000684	0.256	0.673
T= 60 ºC			
0	0.0003273	3.792	-
4	0.0002092	2.534	0.361
10	0.0001519	1.470	0.536
23	0.0001137	0.496	0,653
27.5	0.0001068	0.369	0.674
T= 50 ºC			
0	0.0002312	2.807	-
4	0.0001577	2.008	0.318
12	0.0001156	1.206	0.500
24	0.0000991	0.655	0.571
32	0.0000889	0.452	0.616

The best results of the parameter estimates of the Volumetric Contraction models tested for the banana and their respective determination coefficients, relative and estimated mean errors are presented in Table 6.

By analyzing the results of the Volumetric Contraction of the banana presented, it was observed that among the five mathematical models tested, the modified Bala and Wood model was the one that presented the determination coefficient of 99.14% and a relative mean error of 1.67% for a temperature of 60 °C.

This satisfactory result can be considered due to the already included error of 5% for the calculation of the Banana Volume through Equations 2 and 3.

According to Corrêa et al. (2006), observed that the modified Bala and Woods (1984) model was the only one that represented the volumetric shrinkage of wheat grains during drying. Still according to Goneli et al. (2011) recommend that only the modified Bala and Woods (1984) models and the Polynomial second degree model can be recommended to predict the phenomenon of volumetric contraction of castor fruit mass.

Table 6: Estimates of the Volumetric Contraction model parameters for the banana, with their respective determination coefficients (R^2), relative (P) and estimated (SE) errors.

Models: BALA E WOOD modificado	Parameter	R^2 (%)	P (%)	SE (decimal)
70 °C	a= 5.2738 b= 0.0004 c= 0.1909	93.3480	3.7030	0.0400
60 °C	a=1.1114 b=0.5066 c=0.2502	99.1410	1.6740	0.0190
50 °C	a=1.0595 b=0.9269 c=0.2922	99.7470	0.8990	0.0100

Among the mathematical models, the one that presented smaller values of estimated and relative average errors and greater coefficient of determination was the Exponential for the reason of humidity and for the volumetric contraction was the Bala and Wood modified, being thus indicated to represent these phenomena.

The curves of drying, experimental and simulated by the Exponential model, of the banana for the temperatures of 70, 60 and 50 ºC, as well as the Water Reduction Rate (WRR) for the same temperatures are shown below (Figures 3, 4 and 5).

It can be seen in Figures 3, 4 and 5 that the WRR for the first hours is large. This is due to the ease that the drying air has to remove the free water from the banana. With the passage of time, the WRR decreases, as well as the amount of free water available in the fruit.

Regarding the drying curves, it can be noted that the difference of the MR in the beginning of the process for the temperatures of 50, 60 and 70 ºC is not very high, but increases with the drying time.

At the beginning of the process the differences are smaller because a significant part of the water content is free on the surface of the banana and in this way it is easily removed. For the remaining drying times, the differences increase due to the internal resistance to water content transport.

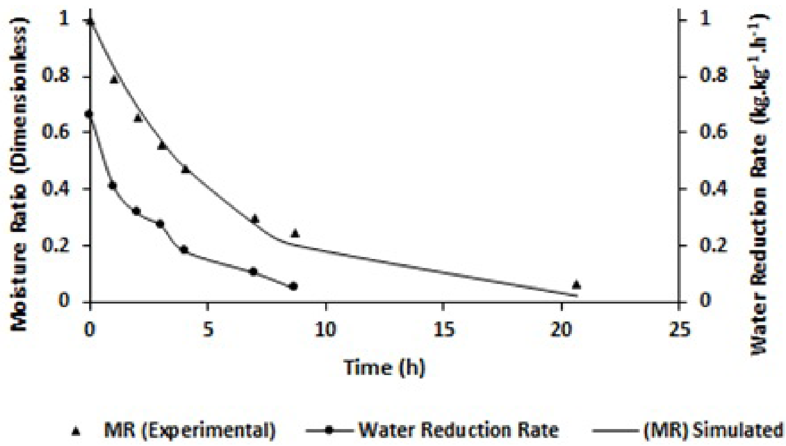

Figure 3: Experimental and simulated values for the Exponential model (04) of the Water Ratio and Water Reduction Rate of the banana as a function of the drying time, for a temperature of 70 ºC.

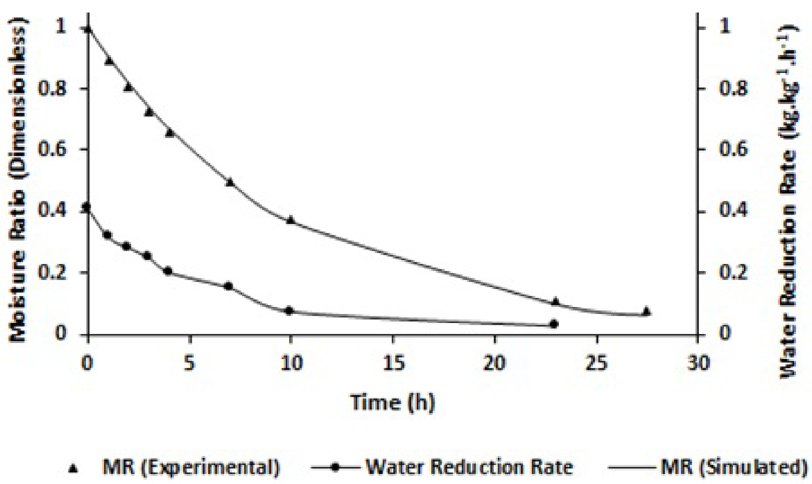

Figure 4: Experimental and simulated values for the Exponential model (04) of the Moisture Ratio and Water Reduction Rate of the banana as a function of the drying time, for a temperature of 60 ºC.

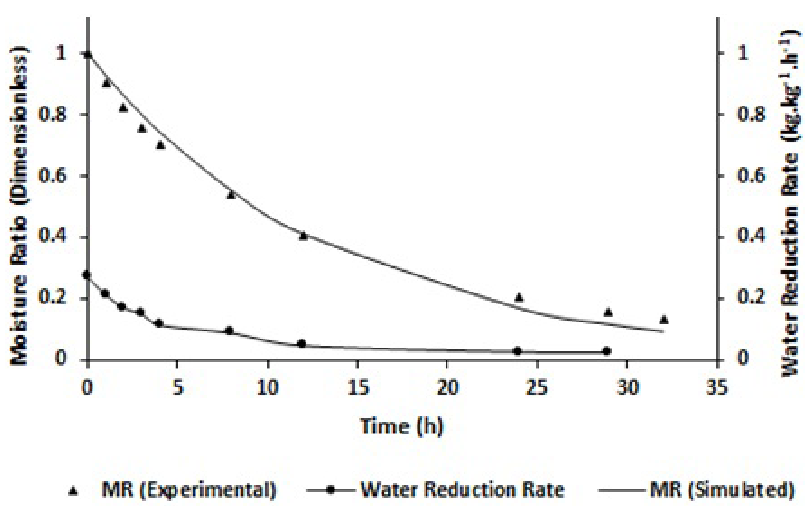

Figure 5: Experimental and simulated values for the Exponential model (04) of the Moisture Ratio and Water Reduction Rate of the banana as a function of the drying time, for a temperature of 50 ºC.

Figure 6 shows the graph for the Volumetric Contraction curves versus time for the drying air temperatures of 50, 60 and 70 °C:

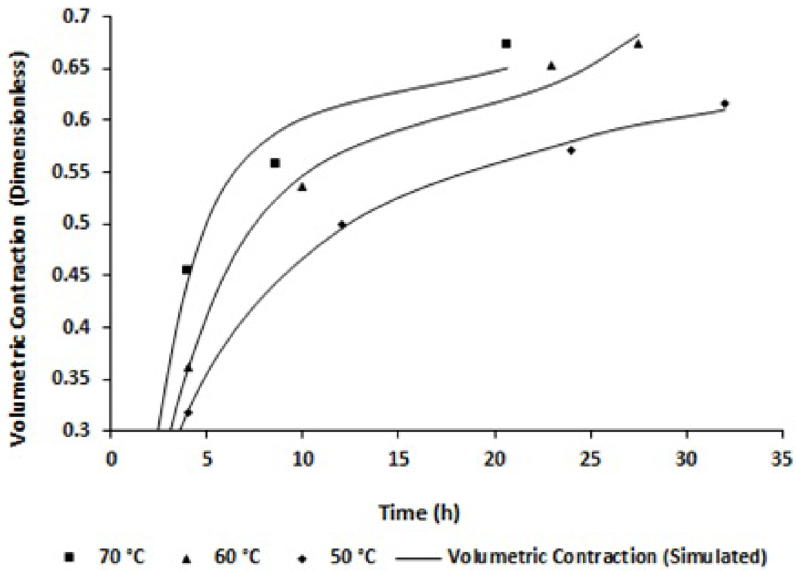

Figure 6: Values collected in the experiment and simulated by the Bala and Wood modified model (16) of the Volumetric Contraction of the banana as a function of the drying time, for different temperatures.

It is observed in Figure 6 that for higher drying temperatures, the greater the volumetric contraction of the banana. And also, that at the beginning of the drying process, the volumetric contraction is more pronounced and decreasing with the passage of time.

CONCLUSIONS

According to the conditions that the present work was developed, was conclude that: among the models tested, the one that best fit the results in the prediction of the Moisture Ratio was the Exponential model, and for the Volumetric Contraction was the modified Bala and Wood model.

The Water Reduction Rate (WRR) is great for the first few hours of drying due to the large amount of free water in the product.

Volumetric shrinkage is higher at higher temperatures.

The Volumetric Shrinkage is more intense for the first few hours of drying.

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