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Geometric and Thermo-Gravimetric Evaluation of Bananas during Convective Drying: An Experimental Investigation

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Abstract: Fresh bananas are fruits with high moisture content after harvest and are submitted to a drying process to minimize waste and increase shelf life. This work aims to experimentally study the convective drying of bananas in an oven with hot-air recirculation, evaluating the geometric shape during moisture removal and product heating. Hand-peeled whole-banana samples, cut into longitudinal and transversal slices were dried at temperatures of 40 and 70 °C. Results of drying kinetics, heating and dimensional variations in terms of surface area and volume are presented and analyzed. It was found that cut bananas dry, heat up and change their dimensions faster than bananas in their natural form and that the area/volume relationships and the air temperature influence the drying kinetics, heating and volumetric variations of the fruit.

Keywords: banana; heat; mass; dimensions; experimental

1. Introduction

The banana is considered an important food globally due to the benefits it can offer. It is a fruit of high nutritional value and a good energy source, possessing high contents of carbohydrates, starch and sugars. They also contain considerable amounts of vitamin A, B1 (thiamine), B2 (riboflavin), C and mineral salts, such as potassium, phosphorus, calcium, sodium and magnesium, in addition to others in smaller amounts [1–4]. The inclusion of bananas, rich in potassium, in the usual diet of adults and elderly people is recommended by doctors and nutritionists. Recent studies reveal the importance of minerals in proper muscle function, including the heart [5]. Including bananas in the usual diet reduces the risk of stroke and blood pressure-related diseases.

Among tropical fruits, the banana stands out as the most consumed fruit. This is due to its nutritional value and versatility in terms of consumption (processed, fried, cooked and especially the large amount consumed *fresh*). In addition to these benefits, bananas have other characteristics that motivate consumption: quality, flavor, pleasant aroma and the hygienic conditions that facilitate *fresh* consumption.

The banana is the most-consumed fruit in the world. This is mainly due to the wide variety of nutrients and vitamins and the possibility of fresh and industrial consumption.

The banana-processing industry represents a very important source of income, generating employment and income for the population that deals with this fruit, mainly in the developing countries of South America and the Caribbean, as well as those in Asia and Africa that work with bananas exports. Bananas can be industrially processed to obtain different products, such as ripe or green banana powder, ripe or green banana flour, raisins, flakes, purees, nectars, jellies, candies, vinegar, wines, dried bananas, liqueurs, juices, cakes, pies and banana rum [6–10] and parts of the plant, for example, bunches, frequently are used for animal feed [11].

From a consumption point of view, fruits and, particularly, bananas are aromatic plant products that are naturally sweet or usually sweetened before eating them. Apart from the fact that they supplied flavor and diversity to the human diet, they also deliver an important and indispensable source of vitamins, minerals and proteins. Due to these reasons and allied to population growth, the consumption of processed bananas expands every day.

Similarly to any other fruit, bananas have a high moisture content when picked, which requires timely consumption. From the harvest to the final consumer, the banana needs to be transported and handled, which generates losses due to mechanical handling. Other sources of losses come from fruits that do not comply with the export standard due to variations in size or stains or even resulting from excess production, which provides a greater supply of the product than the demand. Therefore, as consumption is lower than the amount produced, the surplus of the fruit is destined to rot, culminating in a total loss of the same amount. This problem can be minimized by using a treatment that preserves the initial characteristics of the fresh fruit, thus prolonging its shelf life and, consequently, the time for consumption.

Due to the increase in the number of bananas harvested and consumed, there are many losses in this fruit for the reasons mentioned above. In this manner, it is extremely important to carry out effective research studies related to the issue of banana preservation. The researchers, worried with the high levels of lost bananas, especially after harvesting, suggest that government agencies, technicians and researchers define an action strategy for a system of treatment and improvement of the fruit, ranging from pre-harvest to commercialization.

One of the oldest food preservation techniques used by man is moisture removal from food by using a drying process. During the drying process of biological products, their physical and chemical characteristics change; depending on the temperature, the biological products can be affected in their structures, and the seeds can lose their germination power or even incur a total loss of the products. The moisture removal causes a decrease in the water activity of the fruit, reducing the growth of microorganisms and minimizing physical–chemical deterioration.

The application of a production surplus conservation method for extremely perishable fruits is justified. Industrialization is undoubtedly an excellent alternative for the full use of bananas. Among the processes of industrial use of bananas, the production of dried bananas is one that requires a low initial investment cost and a perspective of profitability that is compatible with the investment. The domestic market is expanding and the foreign market remains practically unexplored by Brazil. The natural or artificial drying of wet ripe banana originates raisin banana, i.e., dried banana. Generally, the banana used in the production of raisin bananas is the dwarf banana or “nanicão” type. The raisin banana is characterized by its high sugar content and moisture content between 20 and 25% of the initial moisture content of the fruit.

Fruit drying operations are complex and poorly understood, mainly regarding the selection and control of process to ensure the desired quality for the product after drying. With the increase in consumer demand, products that maintain a good part of their initial nutritional characteristics are more successful in sales. In this sense, it becomes necessary for industries to develop operations that reduce the defects associated with the drying process.

In the drying period, the core of the product shrinks less than its surface, generating internal stresses that are responsible for permanent damage on the product. Furthermore, non-volatile compounds mixed with water move and precipitate, forming a crust on the surface of the fruit [12] and affecting shrinkage phenomena. Therefore, the volumetric variation phenomena affect the transport parameters, becoming an important effect that must be considered in the drying analysis.

Therefore, due to its importance, several researchers have studied the drying of bananas [13–18]. Regarding the product's shape and their effects on moisture removal, different research studies can be found in the literature [19–21].

Aiming to contribute to this area of knowledge, the purpose of this work is to study the convective drying of entire banana and when it is cut lengthwise (slices) and transversally (round). The innovative and relevant idea lies in the verification of issues that are still minimally explored in academia and industry, such as the effect of fruit shape on drying kinetics, heating and dimensional variations, and finally, the quality of the final product.

2. Methodology

2.1. Material and Experimental Procedures

The raw material investigated in this work is the banana (Musa species and "prata" variety) acquired in the local commerce of the city of Campina Grande, Brazil. The first step was to select the bananas in terms of size, degree of ripeness (yellow peel with black spot in minimal quantity) and quality. Just before each experiment, the bananas were peeled and some of them were longitudinally sliced in half and others cut transversally (cylindrical parts). It can be observed that technical methods for fruit selection such as total soluble solids and firmness can also be used properly.

Following, the relative humidity and temperature (Thermohygrometer, ICEL, model HT 208, accuracy ±0.1 °C) of the ambient air outside the oven (Fanem, model 320E), as well as the mass (digital balance, Marte, accuracy 0.001 g), dimensions (digital caliper, Messen, accuracy 0.01 mm) and surface temperature (digital infrared thermometer, model TI 890, accuracy ±2 °C) of each sample, were obtained. Moreover, air velocity inside the oven was measured (digital anemometer, Instrutemp, model AMI 300, accuracy ±2%). After the samples were placed within the oven, the samples were dried at different temperatures (40 and 70 °C) with parameters controlled at pre-defined intervals (from 5 to 5, 10 to 10, 30 to 30 and 60 to 60 min). At the end of each period, the fruits were taken out from the oven and their temperature, mass and dimensions were measured. By the time the masses of the samples have attained a level of moisture close to the equilibrium moisture, the measurements were halted, and the fruits were maintained in the oven under the same temperatures for 24 h to obtain the equilibrium condition. Subsequently, the temperature of the oven was modified to 70 °C while the fruits were maintained inside for 24 more hours to reach the dried product mass. This entire drying procedure was performed for the three geometries (whole banana, cut transversally and longitudinally sliced in half).

The arrangement of the samples in the oven was performed in the following way: a pilot sample placed on a small wire mesh screen and six samples on a large wire mesh screen with identified places for each sample. In the first 40 min, with an interval of 5 min, from 40 min up to 120 min with an interval of 10 min, from 120 min up to 390 min with an interval of 30 min, and from 390 min up to the final of the process with an interval of 60 min, the parameters dimensions, mass and temperature were measured only for the pilot sample. At the end of each drying time interval (40, 120, 390 and at the end of the drying), temperature, mass and dimensions were measured in each sample. Experiments were carried out without repetition.

Figure 1 illustrates all the equipment used in the drying experiments. In Figure 2, the whole, longitudinally sliced in half and transversally sliced bananas are illustrated, and in Figure 3, the samples used are schematically illustrated, as well as geometrical parameters C, D and L, properly identified, and the positions where the measurements of the geometrical parameters and temperature at the surface of the banana were conducted. Figure 4 shows the arrangement of the samples inside the oven.

Figure 1. Equipment used in drying experiments: infrared thermometer, balance; thermohydrometer, anemometer, caliper and oven.

(**a**) (**b**) (**c**)

Figure 2. Banana samples used in the experiments: (**a**) whole banana, (**b**) banana sliced lengthwise and (**c**) banana cut transversally.

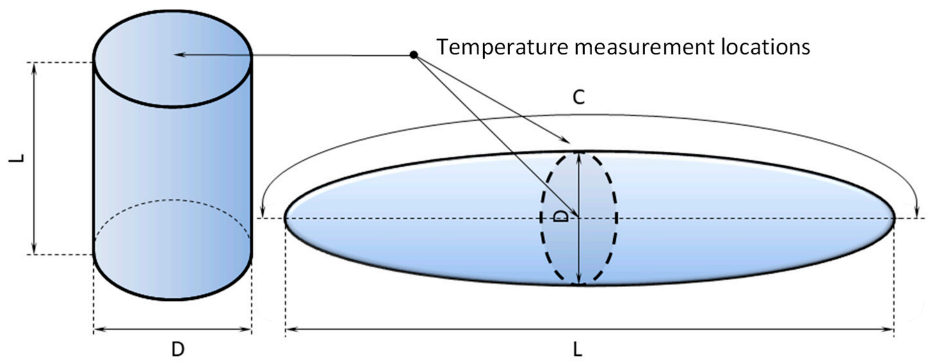


Figure 3. Model of banana samples showing the geometrical parameters and temperature measurement site.

Figure 4. Internal view of the drying oven with air renewal/circulation.

2.2. Auxiliary Parameters

After drying all samples, based on the temperature, mass and dimensions of the bananas, some auxiliary calculations were made to determine new parameters, which are important for obtaining the results and discussion of the present work.

(a) Mass of water

The amount of water in each banana (m_w) at each moment of drying is a function of the initial mass of the fruit (m_o) and the dry fruit mass (m_d), according to Equation (1).

$$m_w = m_o - m_d. \tag{1}$$

(b) Moisture content on a wet basis

The moisture content of the sample (M_w) at each moment of drying is obtained as a function of the water mass of the banana (m_w) and the wet banana mass ($m = m_w + m_d$) as follows:

$$M_w = m_w/(m_w + m_d). \tag{2}$$

where m_d represent the mass of the banana without water.

(c) Moisture content on a dry basis

The moisture content of the sample (M) at each moment of drying is a function of the water mass of the banana (m_w) and the dry banana mass (m_d), as shown in Equation (3).

$$M = m_w/m_d. \tag{3}$$

(d) Dimensionless moisture content

The dimensionless moisture content of the sample (M^*) at each moment of drying is a function of the moisture content (M), the initial moisture content (M_o) and the equilibrium moisture content (M_e) on a dry basis according to Equation (4).

$$M^* = (M - M_e)/(M_o - M_e). \tag{4}$$

(e) Dimensionless temperature

The dimensionless temperature of the sample (θ^*) at each moment of drying is a function of the surface temperature of the banana (θ), the initial temperature (θ_o) and the equilibrium temperature (θ_e), as indicated in Equation (5).

$$\theta^* = (\theta - \theta_o)/(\theta_e - \theta_o). \tag{5}$$

(f) Volume and surface area of the banana

The surface area (S) and volume (V) of the banana at each moment of drying are obtained as a function of its dimensions using the following mathematical formulations:

- For the whole banana (considered as a prolate spheroid, Figure 3)

$$(V)_t = \frac{4}{3}\pi\left(\frac{L}{2}\right)_t\left(\frac{D}{2}\right)_t^2, \tag{6}$$

$$(S)_t = \frac{1}{2}\pi(D)_t(L)_t\left\{\frac{(D)_t}{(L)_t} + \frac{\arcsin\left[\sqrt{\left[1-\left(\frac{(D)_t}{(L)_t}\right)^2\right]}\right]}{\sqrt{\left[1-\left(\frac{(D)_t}{(L)_t}\right)^2\right]}}\right\}. \tag{7}$$

- For the banana cut lengthwise in half:

$$(V)_t = \frac{2}{3}\pi\left(\frac{L}{2}\right)_t\left(\frac{D}{2}\right)_t^2, \tag{8}$$

$$(S)_t = \frac{1}{4}\pi(D)_t(L)_t\left\{\frac{(D)_t}{(L)_t} + \frac{\arcsin\left[\sqrt{\left[1-\left(\frac{(D)_t}{(L)_t}\right)^2\right]}\right]}{\sqrt{\left[1-\left(\frac{(D)_t}{(L)_t}\right)^2\right]}}\right\} + \pi\left(\frac{D}{2}\right)_t\left(\frac{L}{2}\right)_t. \tag{9}$$

- Banana cut transversally (considered as a finite cylinder).

$$(V)_t = \pi(L)_t\left(\frac{D}{2}\right)_t^2, \tag{10}$$

$$(S)_t = 2\pi\left(\frac{D}{2}\right)_t(L)_t + 2\pi\left(\frac{D}{2}\right)_t^2. \tag{11}$$

where V is denotes volume and S denotes area.

2.3. Experimental Drying Conditions

Tables 1–3 present, for each experiment, the banana and the drying air data used in the oven. In these tables, T is the air temperature, RH is the air relative humidity, v represents the air velocity, and t is the total process time. The subscripts $\underline{o}$, $\underline{e}$ and $\underline{f}$ represent initial, equilibrium and final. The geometrical parameters C, D and L can be seen in Figure 3.

Table 1. Experimental parameters of air and whole banana for each drying test.

Air			Banana (Whole)								
T (°C)	RH (%)	v (m/s)	C (mm)	L (mm)	D (mm)	M_o (d.b.)	M_f (d.b.)	M_e (d.b.)	θ_o (°C)	θ_f (°C)	t (min)
40	29.58	0.04	110	112.76	29.65	2.0534	0.2911	0.1441	26.7	40.0	2670
70	6.93	0.07	115	105.36	27.83	2.5541	0.0574	0.0015	27.6	67.7	1450

Table 2. Experimental parameters of air and banana cut lengthwise in half for each drying test.

Air			Banana (Whole)								
T (°C)	RH (%)	v (m/s)	C (mm)	L (mm)	D (mm)	M_o (d.b.)	M_f (d.b.)	M_e (d.b.)	θ_o (°C)	θ_f (°C)	t (min)
40	29.60	0.04	133	119.04	25.34	2.2366	0.2256	0.0749	25.6	40.0	1365
70	7.30	0.07	112	95.55	21.62	2.3587	0.0079	0.0080	26.7	68.6	630

Table 3. Experimental parameters of air and banana cut transversally for each drying test.

Air			Banana (Whole)								
T (°C)	RH (%)	v (m/s)	C (mm)	L (mm)	D (mm)	M_o (d.b.)	M_f (d.b.)	M_e (d.b.)	θ_o (°C)	θ_f (°C)	t (min)
40	29.48	0.04	----	15.18	30.22	2.1037	0.2603	0.1181	28.1	40.0	1275
70	8.09	0.07	----	18.64	26.99	2.3405	0.0179	0.0010	28.3	68.9	750

3. Results and Discussion

Figures 5 and 6 show the transient behavior of the dimensionless moisture content (dry basis) of bananas with different geometric configurations (whole, longitudinal and transversal slices) being dried at temperatures of 40 and 70 °C.

From the analysis of these figures, it is evident that the temperature significantly influences the drying kinetics: the average moisture content decreases faster with time for the case with higher temperature (70 °C). Thus, drying at 40 °C allows a reduction in the product's water content more slowly than at 70 °C, reaching the hygroscopic equilibrium condition in a much longer period of time. This happens for all analyzed geometric shapes. We realized that because the moisture content results are presented in dimensionless form, they are not dependent of the initial and equilibrium moisture content of the banana at each moment of the drying. It is also verified that the banana presents an accentuated loss of humidity as a function of the temperature and also of the geometric shape; when the banana is cut lengthwise, the product has a higher drying rate and, therefore, reaches the equilibrium average moisture content in a much shorter period of time than when used in its natural form. This behavior was verified in all drying conditions studied.

Figures 7 and 8 present the dimensional variations suffered by the banana over time for drying temperatures of 40 and 70 °C. It can be seen that the volume varies faster with time for the temperature of 70 °C, when compared to those variations verified at the temperature of 40 °C, and that when the banana is dried in its cut shape, this geometry favors a greater loss of moisture from the product.

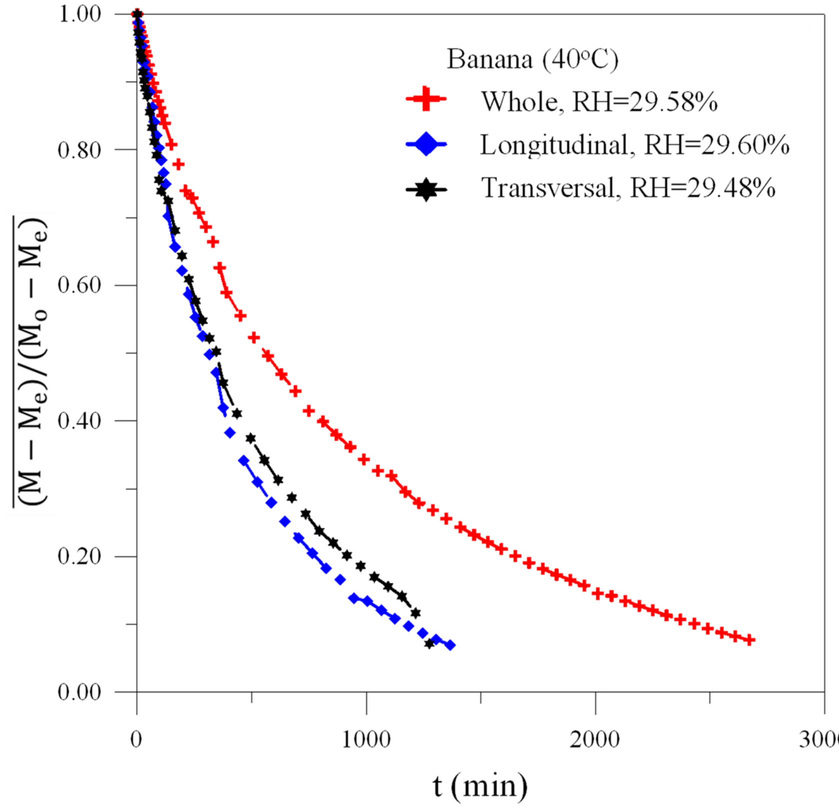


Figure 5. Variations in the dimensionless average moisture content of bananas during drying at 40 °C.

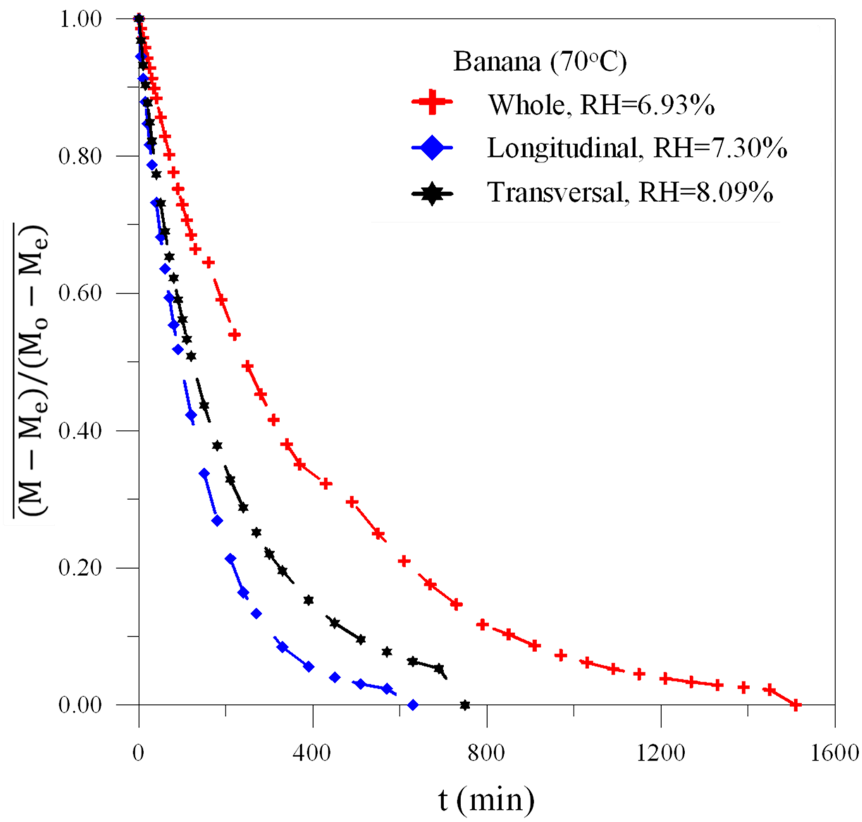


Figure 6. Variations in the dimensionless average moisture content of bananas during drying at 70 °C.

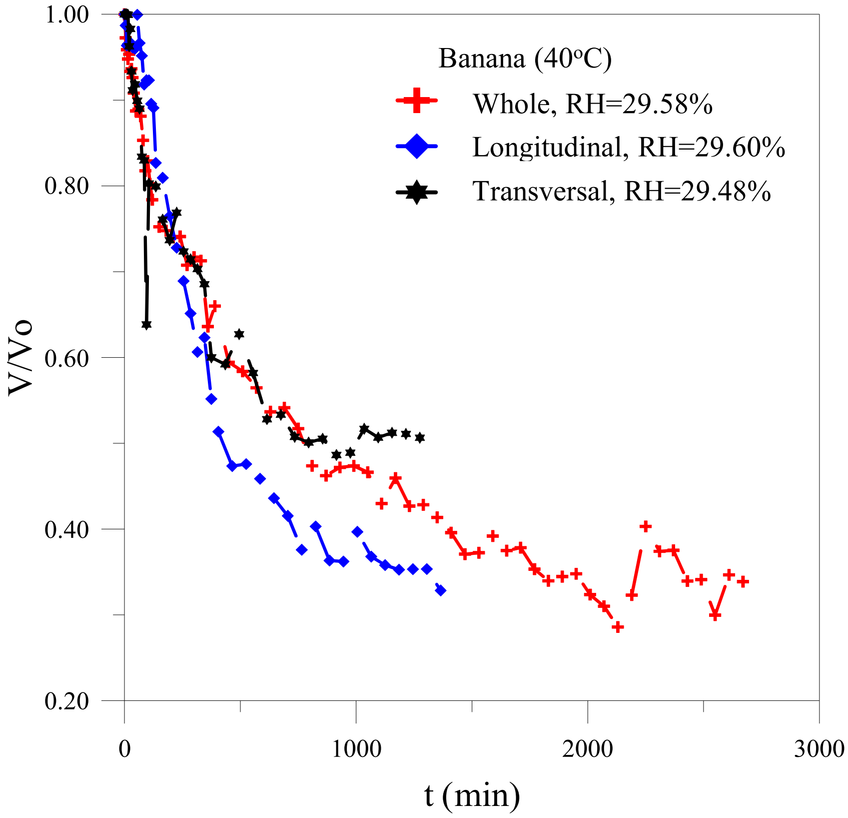


Figure 7. Ratio between measured and initial volume of banana samples as a function of time during drying at 40 °C.

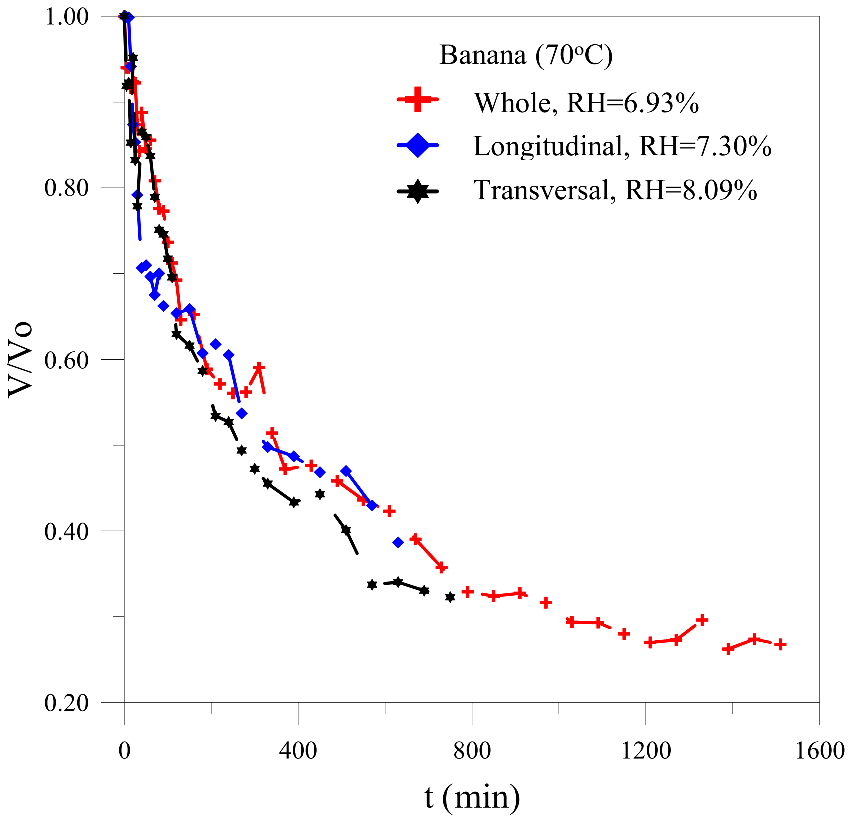


Figure 8. Ratio between measured and initial volume of banana samples as a function of time during drying at 70 °C.

Figures 9 and 10 illustrate the dimensional variations in the banana in the various geometric shapes for each value of the average moisture content along the process, for temperatures of 40 and 70 °C. Note that for all cases, at the earlier stage of the process, there is a large quantity of moisture removal, particularly for bananas cut transversally. Therefore, the dimensions of the banana change from a high shrinkage rate to zero. However, by comparing the graphs, it can be seen that, for the drying temperature of 40 °C, the banana's volume variation occurs more uniformly since the water's removal is slower, causing slower heating and drying. For drying at a temperature of 70 °C, there is a huge loss of water at the earlier stage of the process, causing a high reduction in the volume of banana samples. In addition, there is a linear dependence between the volume and the moisture content, indicating that the amount of water removed is equivalent to a reduction in the volume of the fruit, and that the geometric shape of the banana has a huge impact on the reduction in volume in the drying process; for bananas cut transversally, the effect of volume reduction is much less pronounced.

Figures 11 and 12 show the transient variation of fruit surfaces during the drying process for temperatures of 40 and 70 °C, respectively. Analyzing these figures, it is observed that, at the earlier stage of the process, there is a significant variation in area, because it is in this period that the fruit has a higher moisture content and, consequently, greater water loss. It was found that, in general, area reductions occur faster when using a higher temperature. This phenomenon of area reduction as a function of time that not only depends on the temperature level but also on the geometric shape of the product. It is verified that the banana cut transversally presents a much greater reduction in area in a shorter period of time than when it is dried whole.

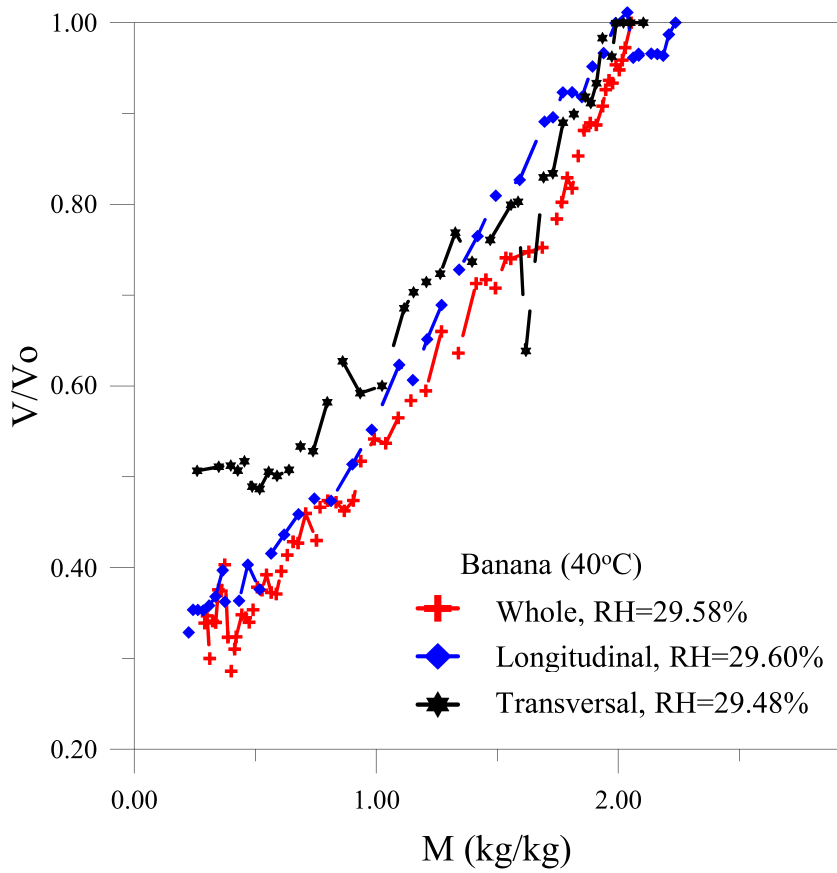


Figure 9. Ratio between measured and initial volume of banana samples as a function of moisture content (dry basis) during drying at 40 °C.

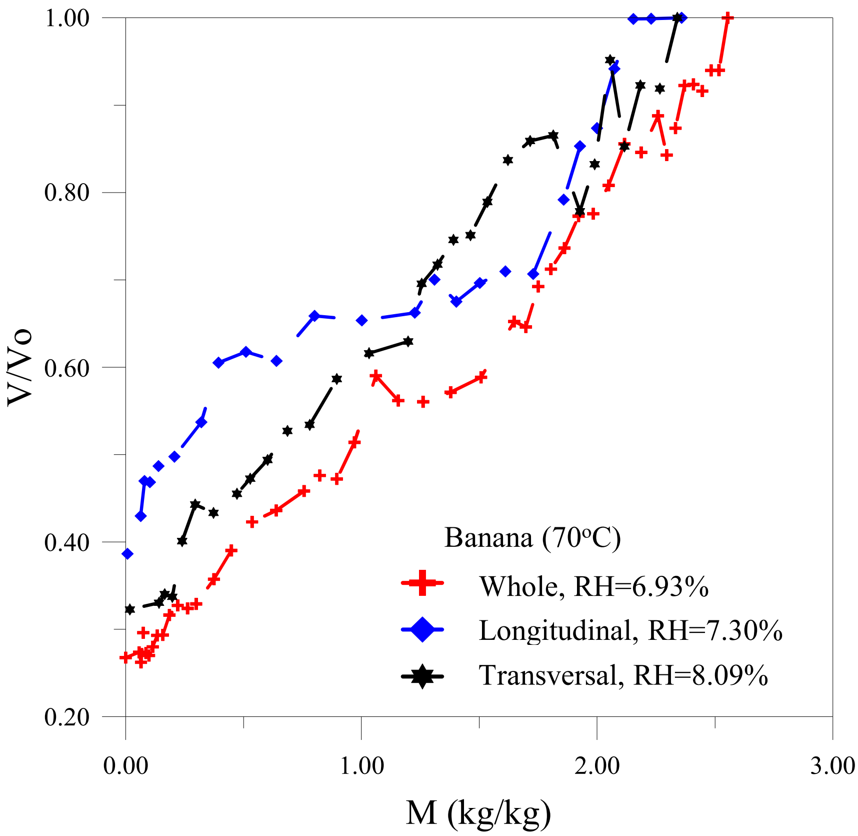


Figure 10. Ratio between measured and initial volume of banana samples as a function of moisture content (dry basis) during drying at 70 °C.

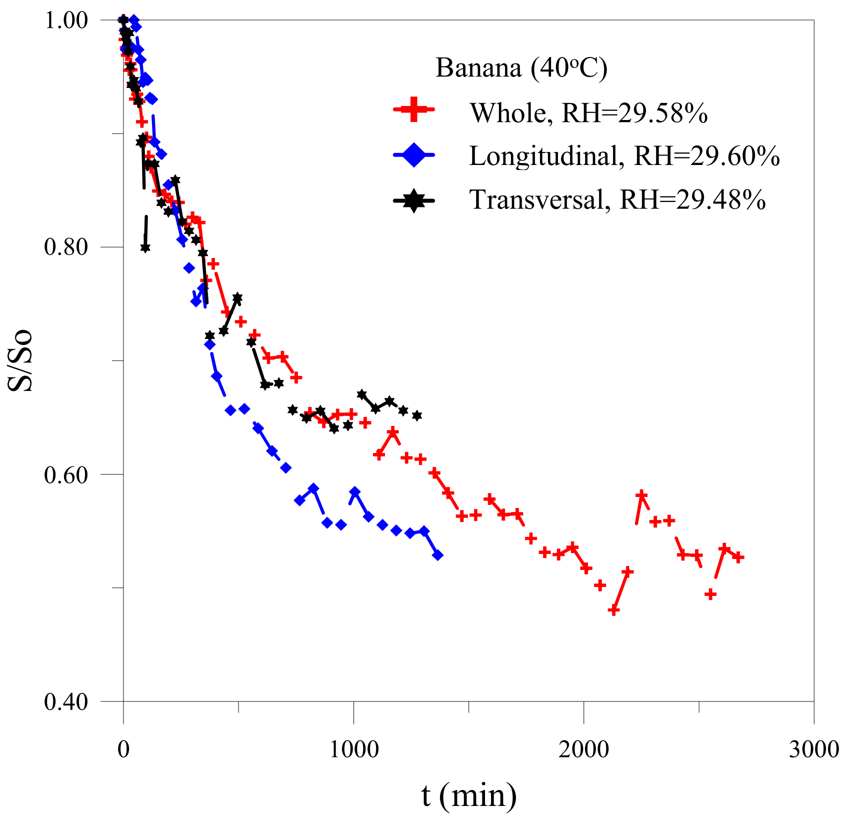


Figure 11. Ratio between surface areas of banana samples as a function of time during drying at 40 °C.

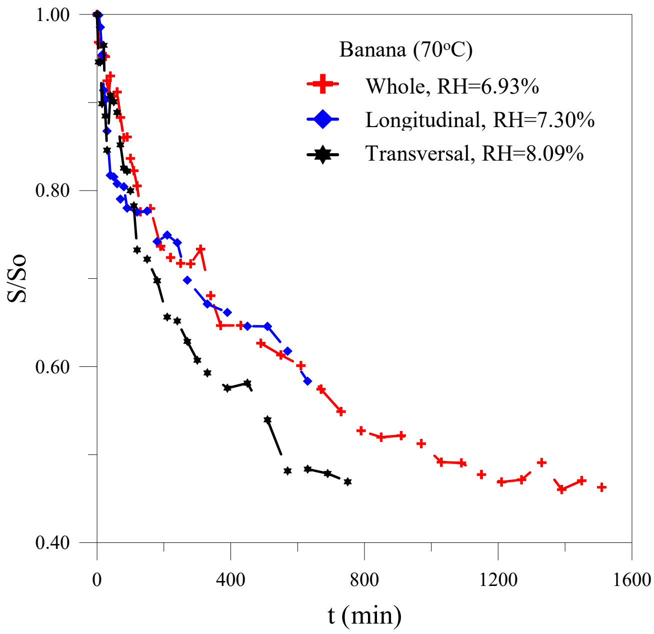


Figure 12. Ratio between surface areas of banana samples as a function of time during drying at 70 °C.

Figures 13 and 14 illustrate the dimensionless variations of the area of the banana for each average moisture content during drying, for air temperatures of 40 °C and 70 °C, respectively, for bananas in different geometric shapes. From the analysis of these figures, it is clear that, for all cases, at the earlier stage of the process, there is a large loss of moisture, especially when the banana is cut lengthwise in half, indicating that the geometric shape has a huge influence on shrinkage phenomena. Thus, area dimensions of the banana change from a high rate at the earlier stage of the process, and this rate decreases in relation to the loss of moisture in the product during the drying process. When the humidity tends to zero, the shrinkage phenomenon ceases to exist. It is important to highlight the importance of the air relative to humidity during drying. The lower its value, the greater the drying potential for the same air temperature.

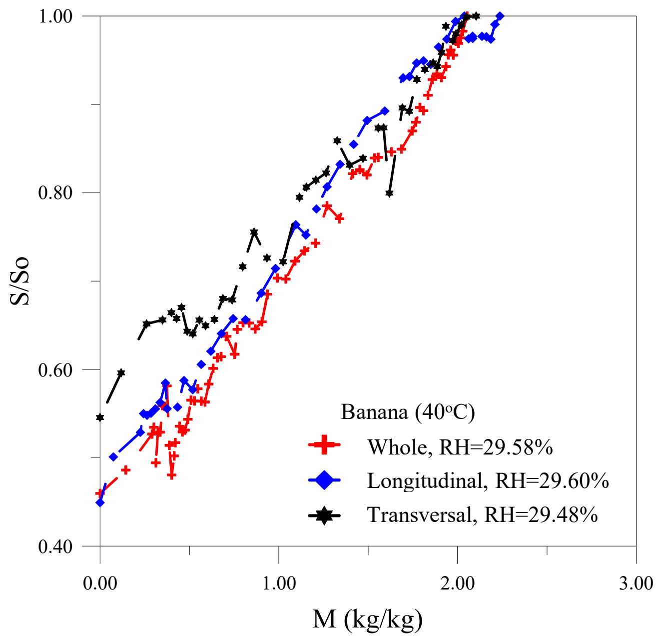


Figure 13. Ratio between surface areas of banana samples as a function of moisture content (dry basis) during drying at 40 °C.

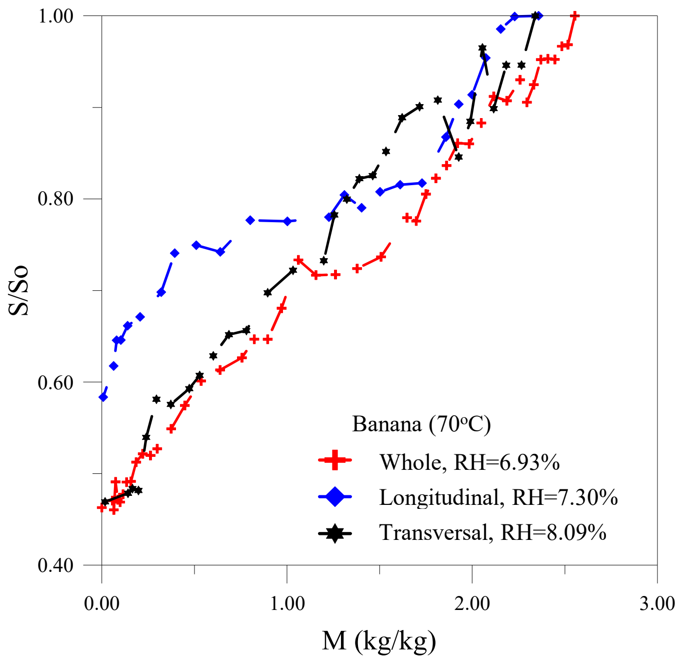


Figure 14. Ratio between surface areas of banana samples as a function of moisture content (dry basis) during drying at 70 °C.

Figures 15 and 16 show the variations in banana surface temperature with time for both drying temperatures evaluated. It is verified that, in the first hours of drying, the rates of temperature change are higher in comparison with the rates of change in the moisture content. Approximately after 5 h of drying, a trend reversal occurs: The rates of change of the moisture content become higher than the rates of temperature change. Finally, in the final stage of drying, all rates are small, decreasing as the equilibrium condition approaches. This is valid regardless of the banana's geometric shape and the process temperature.

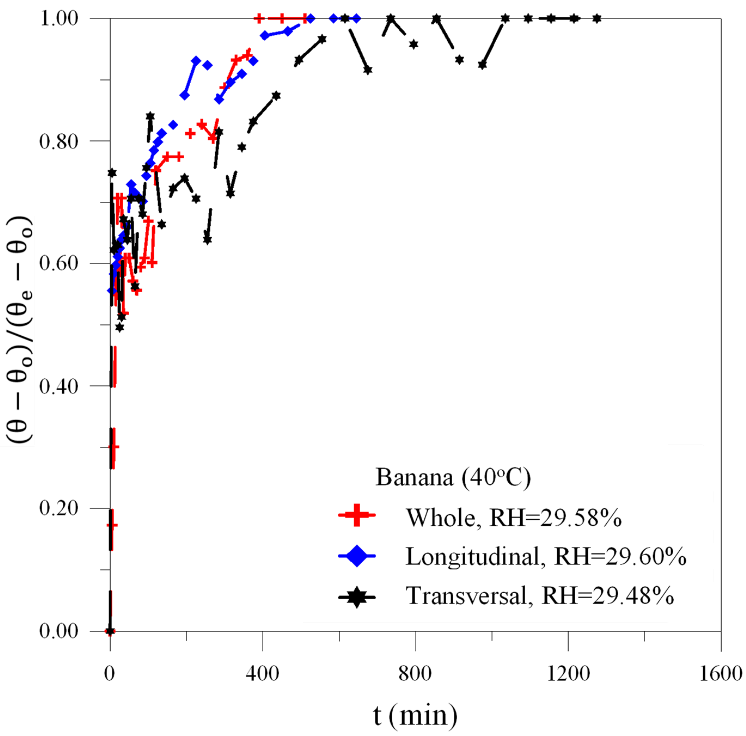


Figure 15. Dimensionless temperature variation on the banana surface during drying at 40 °C.

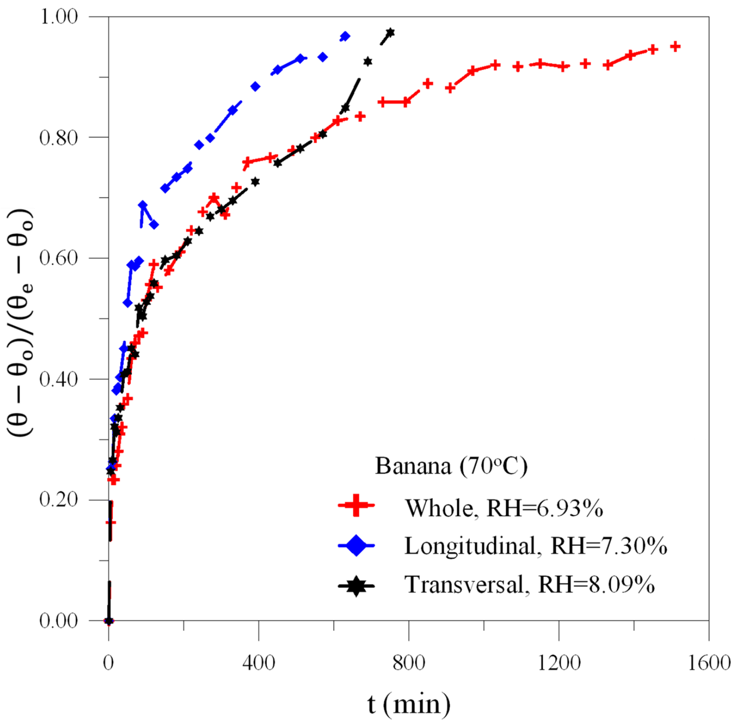


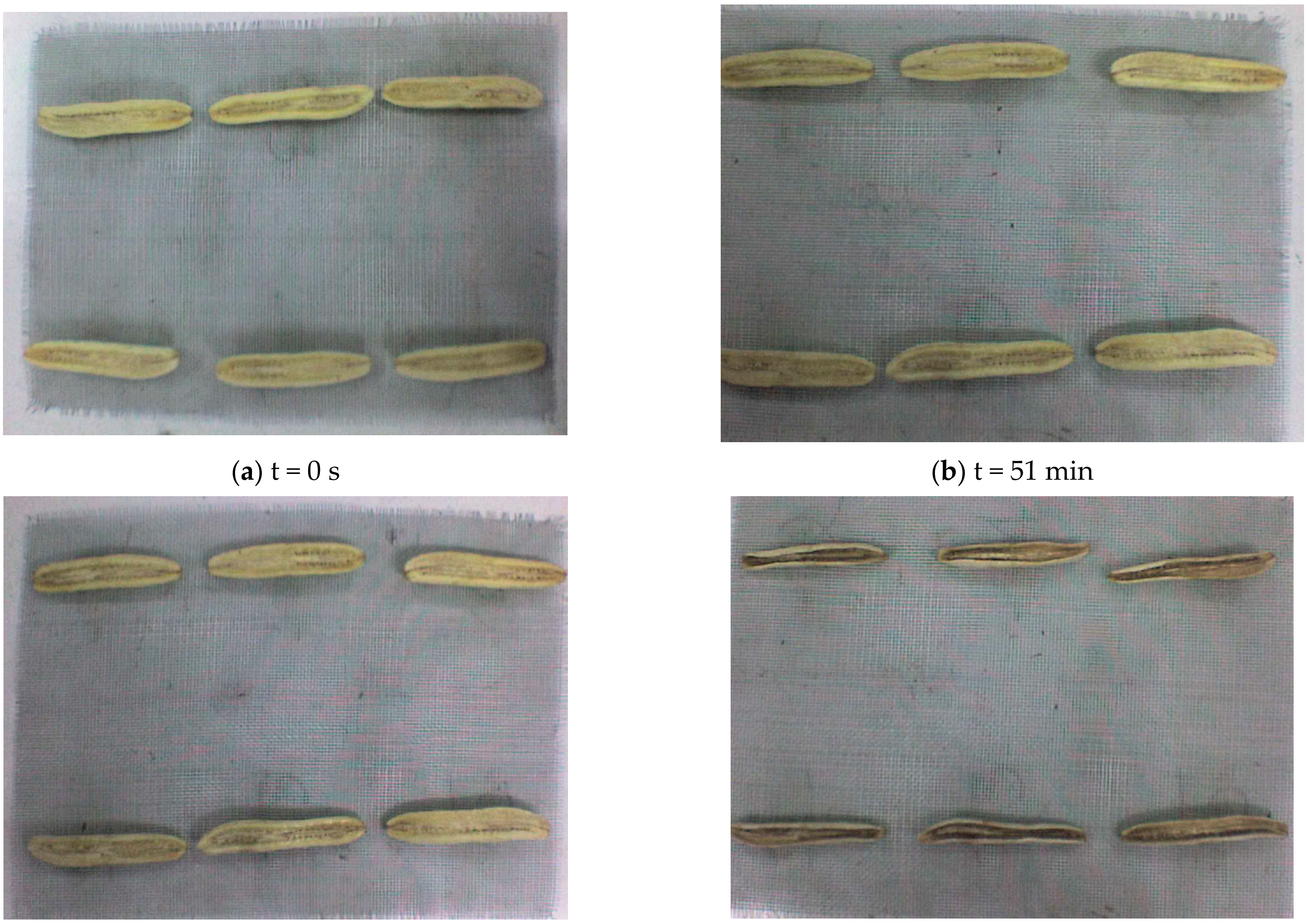
Figure 16. Dimensionless temperature variation on the banana surface during drying at 70 °C.

It can be observed that the temperature measurement was made at the sample's surface, and due to the different height among them, it would be incorrect to compare them. Because of this particular situation, results are presented in a dimensionless form. Thus, they are independent of the initial and final temperature.

By analyzing Figures 1, 2, 15 and 16 together, it can be stated that banana drying occurred at a decreasing rate, which corresponds with the literature [22–27]. According to the literature, during the entire constant-rate drying stage, the fruit's temperature remains constant mainly in the initial moments of drying, in which the loss of water is more accentuated. This statement is inconsistent with the results obtained in this research. Observing the figures previously mentioned, it is verified that for cases of higher temperatures (70 °C), the curves are more accentuated, suggesting that the thermal diffusivity is greater for a higher air temperature. In this manner, the local temperatures inside the solid must also influence the value of thermal diffusivity. Furthermore, an increase in the convective heat transfer coefficient or even a combination of an increase in both coefficients also can occur.

Figure 17 illustrates the transient behavior of the banana sliced lengthwise during drying at 40 °C. Upon examining Figure 17, it can be clearly observed that the banana has different effects during the drying process, such as darkening and severe deformations, caused by water and thermal stresses mainly in the transverse direction. The hardening of the banana surface was visually verified during and after the experiments.

Table 4 presents the total drying time for each experimental test and their respective relative shrinkage data in terms of length, surface area and volume. Analyzing the dimensional data obtained in the experiments, it was observed that the banana volume varied in at averages (of the three geometries) of 39.12 and 37.76% for the temperatures of 40 and 70 °C, respectively. Moreover, it can be seen that the relationships between the final and initial diameters (D_f/D_o) of the whole and longitudinal sliced bananas were smaller than the length ratio (L_f/L_o); i.e., the relative linear shrinkage is greater in the radial direction than in the length direction. This result suggests that moisture diffuses faster in the radial direction due to the greater mass diffusivity in this direction than in the axial direction. For bananas cut transversely, the reverse occurs: relative linear shrinkage is greater in the length direction.



(**a**) t = 0 s (**b**) t = 51 min (**c**) t = 129 min (**d**) t = 1460 min

Figure 17. Photographs of banana slices at different times during drying at 40 °C.

Table 4. Relative shrinkage data during banana drying in different geometric shapes.

Geometric Shape	T (°C)	t (min)	D_f/D_o	L_f/L_o	S_f/S_o	V_f/V_o	S_o/V_o
Whole	40	2670	0.6361	0.8374	0.5269	0.3388	0.1634
	70	1450	0.5738	0.8313	0.4705	0.2737	0.1741
Longitudinal slice	40	1365	0.6156	0.8667	0.5288	0.3285	0.1895
	70	630	0.6563	0.8973	0.5835	0.3865	0.2226
Transversal slice	40	1275	0.8345	0.7272	0.6516	0.5065	0.2641
	70	750	0.6784	0.7012	0.4692	0.3227	0.2555

Regarding the processing time, it is observed that, for the whole banana, drying times increased around 20.3 h with a 30 °C reduction in temperature. Thus, the drying time at 40 °C is 84% longer than at 70 °C. For bananas sliced longitudinally, the drying time increased around 12.3 h with a 30 °C reduction in temperature. Then, the drying time at 40 °C is 117% longer than at 70 °C. For banana sliced transversally, the drying time increased around 8.7 h with a 30 °C reduction in temperature. Thus, the drying time at 40 °C is 70% longer than at 70 °C. These results show the importance of the study related to the shape of the fruit during drying.

4. Conclusions

In this research study, the process of drying a fruit has been studied. Emphasis is placed on the effect of the fruit's shape on moisture removal capacities, heating and dimension variations during the process. Based on the work carried out in this research study, the following can be concluded:

(a) Banana drying occurs in a decreasing rate period, regardless of the drying air temperature and for a relative humidity of the drying air lower than 100%;
(b) Drying air temperature and geometric shape have a strong effect on banana drying, heating and shrinkage kinetics;
(c) The higher the temperature, the faster drying occurs;
(d) In general, the higher the area/volume relationships, the faster drying occurs, which fixed the other experimental conditions and for a relative humidity of the drying air lower than 100%;
(e) The volumetric shrinkage of the banana shows a linearly decreasing trend with the loss of water from the product.
(f) Product quality is strongly affected by thermal effects, and a browning process has been observed in all drying conditions and fruit shapes.

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