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Determination of Kinetic Parameters in the Convective Drying of Banana Slices AAAea (Musa Sapientum L.)

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Abstract: The search for optimal drying conditions through the prediction of drying kinetics in raw materials as a previous stage that facilitates its use and allows increasing its added value as a response to one of the demands of this productive chain is required in the environment. The convective drying of banana (*Musa sapientum* L.) was evaluated at five temperatures (40, 50, 60, 70 and 80°C), with an average air rate of 1.8 m/s. The samples were prepared with slice geometry of 2.7 cm in diameter and 3.0-mm thickness. The study evaluated the effect of temperature on drying time through three repetitions, yielding a decrease in drying time by 68.75% at 80°C, 50% at 70°C, 31.25% at 60°C, and 12.5% at 50°C with respect to drying time at 40°C. With the results obtained, the drying curves were constructed, where it was observed that this process took place in the decreasing rate period, evidencing that diffusion is the mechanism that governs banana (*AAAea*) drying. The drying curves were fitted to mathematical models, with Newton's empirical model being the one that best describes the drying process (R^2: 0.924–0.970). The D_{eff} values obtained for banana slices were $1.155x10^{-8}$ at 40°C, $1.67x10^{-8}$ at 50°C, $2.54x10^{-8}$ at 60°C, $3.57x10^{-8}$ at 70°C, and $5.40x10^{-8}$ at 80°C (m^2/s); the values obtained are within the adequate range of various food products, 10^{-8} to 10^{-11} m^2/s, reported in the literature. The activation energy value for moisture diffusion in most agricultural food products is between 12 and 110 kJ/mol, which is also the case for banana, where the estimated values of the pre-exponential factor and activation energy were 1,288.32 m^2/s and 29.59 Kj/mol, respectively.
Keywords: diffusivity, activation energy, decreasing drying rate, *Musa sapientum* L.

香蕉片AAAea (香蕉)对流干燥动力学参数的测定

摘要：环境中需要通过预测原材料的干燥动力学作为前一阶段来寻找最佳干燥条件，以促进其使用并允许增加其附加值，以响应该生产链的需求之一。在五个温度（40、50、60、70和80°C）、平均风速为1.8多发性硬化症下对香蕉(香蕉)的对流干燥进行了评估。样品的切片几何形状为直径2.7厘米、厚度3.0毫米。该研究通过三次重复评估了温度对干燥时间的影响，结果显示，80°C时干燥时间减少68.75%，70°C时干燥时间减少50%，60°C时干燥时间减少31.25%，50°C时干燥时间减少12.5%。40°C下的干燥时间。根据获得的结果，构建了干燥曲线，观察到该过程发生在速率下降期间，证明扩散是控制香蕉（AAAea）干燥的机制。干燥曲线符合数学模型，牛顿经验模型是最能描述干燥过程的模型（右2：0.924–0.970）。香蕉片的德夫值在40°C时为1.155x10-8，在50°C时为1.67x10-

8，在60°C时为2.54x10-8，在70°C时为3.57x10-8，在20°C时为5.40x10-8。80℃（平方米/秒）；获得的值在文献报道的各种食品的适当范围内，即10-8至10-11平方米/秒。大多数农产品水分扩散的活化能值在12至110千焦耳/摩尔之间，香蕉也是如此，其指前因子和活化能的估计值为 1,288.32平方米/秒和 29.59千焦耳/摩尔，分别。

关键词：扩散率、活化能、降低干燥速率、香蕉.

Introduction

Banana AAAea (*Musa sapientum*) is a Musaceae belonging to the group of non-plantain cooking bananas, a crop not widely spread globally, although it is a common fruit in the tropical zone. In Colombia, it is used fresh for human consumption and animal feeding. Several studies have demonstrated that banana belongs to *Musa sapientum* and subgroup *Mutika-Lujugira*, which corresponds to the AAAea genetic classification [1-3].

Agroindustrial transformation of Musaceae in Colombia is low, where some of the processed forms normally found in the national and international market are frozen, dehydrated, and flours. Productive units for flour production have a low technological level, mainly due to low technology transfer by national research centers and commercial barriers in terms of marketing channels. According to the above, flours from Musaceae can become an alternative to be considered in the application or use in the formulation of other processed foods. The negative point of Musaceae is that they decompose rapidly after maturation, resulting in large agricultural waste. To overcome the high decomposition rate of this product and reduce its waste, it can be dried. The drying process reduces the product's water activity (a_w) to increase its useful life and diminishes its volume to reduce packing, storage, and transport costs [4-8]. Therefore, dehydrated green Musaceae can become flour with multiple applications in the food industry; these applications are an option for producers who see their profits reduced by poor postharvest management, climate change, and low prices due to oversupply of the fresh product.

Drying is one of the most important and popular conservation methods, which involves eliminating moisture from a material because of applying heat. It is widely applied to reduce the moisture content of vegetables, fruits, herbs, grains, oilseeds, wood, and other agricultural products with high moisture content. It is also one of the key operations in the food industry, where there is an increasingly greater effort to reduce postharvest losses of agricultural products, which represent around 30%–40% of the total production in developing countries [6-12].

Convection drying is a unit operation that eliminates water with air through simultaneous transfer of heat, mass, and momentum. The heat required is conducted to the food by a hot air current. Energy is transferred to the product's surface through convection and within the product through diffusion or convection, depending on the product's structure. This heat flow provokes an increase in the product temperature and water evaporation. Moisture is transferred from the product's surface to the air through convection as water vapor and from within the product through diffusion, convection, or capillarity. The drying rate and properties of the dry product depend on the external conditions of the process, such as air temperature, moisture, and rate and direction of the air flow. Moreover, the drying rate depends on the internal conditions, such as the geometry, thickness, shape, and structure of the product. The complexity of the structure and composition of fruits, variety of transport phenomena, and biological variability make drying of fruits a challenge [6, 13, 14].

Various types of drying methods are available in the literature, such as convection drying, solar drying, dielectric drying, lyophilization, and natural air drying. Of these drying methods, convection drying is the method most used in industry, such as the agricultural and food industry, construction materials, paper industry, and textile industry, due to its simplicity and profitability. Convection drying of foods and vegetables is a slow process of high energy consumption and takes much time, up to 25 h, to complete the drying process, depending on drying conditions, given the high latent heat of water vaporization, low or limited rate of internal water transport to the product's surface, particularly in foods, and the efficiency of using hot air as drying medium. According to available energy consumption data, countries such as the United States, France, and the United Kingdom consume 10%–15% of the total national industrial energy in drying processes, and it is 20-25% for Denmark and Germany [6, 8, 14, 15].

Convection drying appears to be the most appropriate technique mainly due to its easy operation and faster drying rates. Drying is an energy-intensive process, and it is imperative to find optimal drying conditions for economic operation. Many works use empirical and semi-empirical methods, such as the Page and the Lewis models, logarithmic, etc., to fit to the experimental data. Given that drying implies simultaneous heat and mass transfer, the precision of the spatial and temporal profiles depends on the exactness of the effective diffusivity (D_{eff}) value. D_{eff} is the key variable to describe moisture diffusion through food products during drying. At the same time, these drying models not only permit predicting the best process but also offer tools to predict storage and packaging conditions, besides helping to establish the final moisture content of agricultural products and the requirements of the drying process [6, 10, 12, 14, 16].

The study of drying characteristics during a convection process is important for designing a dryer, selecting the appropriate operating conditions, and determining the effect of drying air rate and temperature on its efficiency, cost, and degradation of food quality attributes. Moisture diffusivity and activation energy are the two important parameters used in the design, modeling, and optimization of the convection drying process, with food moisture D_{eff} being an important parameter that governs the mass transport phenomenon in the drying process. The term "effective" is used because the diffusivity value determined experimentally involves the interaction of various external factors that influence the mass transfer process. Due to the complex nature of food systems and various factors, such as changes in moisture content, porosity, density, and shape involved during the drying process, it is quite difficult to determine the diffusivity value. Therefore, a set of experimental data is required to predict the internal moisture transfer characteristics [6, 8, 9, 12, 14, 16].

According to the aforementioned, it is important to study banana drying kinetics to evaluate variations of moisture content and drying rates as a function of time at different temperatures, using a forced convection dryer, to design a correct drying process that additionally permits obtaining a quality product and which can be considered a tool to prevent damage to the product, excessive energy consumption, equipment wear, or diminished yield in the drying processes and, thus, determine kinetic parameters in the convective drying of banana slices AAAea (*Musa sapientum* L.), due to the effect of air temperature, like the effective diffusivity (D_{eff}) of water during drying, and calculate the activation energy required to start moisture diffusion in the drying process.

1. Materials and Methods

Bananas in the green ripening state were purchased from the local market in Armenia, Quindío. These were peeled and cut into slices 2.7 cm in diameter, which mainly comprised the parenchymatous tissue, and 3 mm thick.

1.1. Moisture Content

The initial moisture content in the wet base was determined through stove heating at 105°C for 24 h until reaching a constant weight [17], which was carried out in triplicate from three different lots.

1.2. Drying

This was conducted in a Memmert natural convection stove (model UFB 500) at different temperatures and relative moisture of 40°C–28%, 50°C–17.8%, 60°C–11.4%, 70°C–4.1%, and 80°C–1.5%, respectively (thermo-hygrometer, Luton HT-3009) and air rate of 1.8 m/s (anemometer, Luton AM-4200). Three metal trays were used, in each of which nine banana slices were placed separately from each other, where the space occupied did not exceed 70% of the total area of the container, and moisture monitoring was conducted through the weight loss of the total mass in each metallic tray with respect to the initial weight. Weight measurements were made at 0, 5, 10, 15 min, then every 15 min, up to 180 min, and after that every 30 min until constant weights were obtained depending on the temperature used, which was carried out in triplicate for each of the temperatures from different lots.

1.3. The Process Modeling

To interpret the drying of green banana slices in the presence of hot air provided to the system through convection, the mass transfer mechanism is based on the loss of free moisture through mechanisms such as conduction and bound water and volatile compounds by diffusion in steady state, according to Fick's second law, which provides a connection between effective diffusivity, moisture, and moisture ratio and the mass transport mechanisms that describe this process [13, 18-21].

To solve Fick's law, mathematical analyses were used to determine the drying kinetics, k (drying constant), diffusivity coefficient (D_{eff}), and activation energy (E_a) from the Arrhenius equation, as described below.

1.4. Drying Curve

To calculate this, the moisture percentage was determined in the wet base (X_{bh}) (Eq. 1).

$$X_{bh\,(t)} = \frac{Weight_{initial} - Weight_{final}}{Weight_{initial}} * 100 \quad (1)$$

Thereafter, the mass of solids M_s (gr of solids) was determined (Eq. 2).

$$M_s = M_{Total\ initial} * (1 - X_{bh}) \quad (2)$$

From the weight of the banana slices in the drying process for each of the temperatures, the dry base moisture content was calculated as a function of time ($X_{bs\,(t)}$) (Eq. 3), obtaining the drying curve [7, 9, 18-21].

$$X_{bs\,(t)} = \frac{M_t - M_s}{M_s} * 100 \quad (3)$$

where M_t is the sample mass (g) over time, t, and M_s is the total dry sample mass (g).

1.5. Drying Constant (k)

From the equation of the dimensionless parameter moisture ratio (R) (Eq. 4) and based on Newton's empirical model, the drying constant value was determined (Eq. 5) [7, 18-20].

$$MR = \frac{X_t - X_E}{X_0 - X_E} \quad (4)$$

where X_t is the moisture at each of the study times, X_E is the moisture in equilibrium, and X_0 is the banana's initial moisture at t = 0. All the moisture values are reported in dry base.

$$MR = e^{-Kt^n} \quad (5)$$

with k and n being constants of the process and t being the drying time in seconds; the experimental data obtained were fitted to Newton's model through a non-linear regression to calculate n and k for each test [12, 18].

From the linearization of Eq. 5, Ln (MR) is plotted versus time, and the slope is found to be equivalent to the drying constant k, hence Eq. 6.

$$Ln\left[\frac{X_t - X_E}{X_0 - X_E}\right] = -kt \quad (6)$$

1.6. Drying Rate (N_w) (gr of water/(m^2 min))

The ratio of the change in moisture with respect to the mass of solids and the contact surface area is described by Eq. 7.

$$N_w = -\frac{M_s}{A}\left(\frac{\partial X}{\partial t}\right) \quad (7)$$

Assuming that moisture transport occurs through diffusion, contraction is ignored, and the diffusion coefficient and temperature take constant values, the analytical solution of the second equation of Fick's law is developed by Crank [22] for the case of an infinite plate.

$$Ln\left[\frac{X_t - X_E}{X_o - X_E}\right] = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\frac{\pi^2 D_{eff} t}{4L^2}\right] \quad (8)$$

For a sufficiently long drying time, all the terms of the prior series are insignificant compared with the first term. Thus, Eq. 8 turns into Eq. 9.

$$\ln\left[\frac{X_t - X_E}{X_o - X_E}\right] = \frac{8}{\pi^2}\exp\left[-\frac{\pi^2 D_{eff} t}{4L^2}\right] \quad (9)$$

where L (m) is half the thickness of the samples used.

The moisture effective diffusivity can be deduced using the slope method. In fact, the equation transforms into Eq. 10.

$$Ln\left[\frac{X_t - X_E}{X_o - X_E}\right] = Ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{eff}}{4L^2}t \quad (10)$$

The D_{eff} coefficient can be calculated from the slope of Eq. (10) by adjusting the experimental data of the drying model [8, 10, 18, 21].

The analysis is simplified by establishing that moisture transfer during drying occurs from within an infinite homogeneous plate, with constant diffusivity and dimensions during the process. The solution of the equation, which is an expression of Fick's second law, is performed by the method of separation of variables defining boundary conditions [16, 21, 23].

The diffusivity coefficient (D_{eff}) allows Fick's law to be expressed mathematically, which is expressed as the flow of matter of a component per unit area, proportional to the concentration gradient of the banana in the dryer. This indicates that the diffusion between the gas (air) and the solid (banana), as described in Eq. 11, is appropriate for sliced products.

$$\frac{\partial X}{\partial t} = D_{eff}\left[\frac{\partial^2 X}{\partial x^2}\right] \quad (11)$$

where X is the banana's moisture content, and D_{eff} (m^2/s) can be given in radial coordinates for the dryer, according to Eq. 12.

$$D_{eff} = \frac{m\ 4L^2}{\pi^2} \quad (12)$$

where m is the slope of the graph of Ln (MR) vs. the banana's drying time when the curve passes through the origin, coordinates 0.0. It was kept in mind that the banana slice thickness was 2L, with L being the length of each face, hence (Eq. 13) [12, 16, 18, 20, 21, 23].

$$L = \frac{Slice\ thickness}{2} \quad (13)$$

1.7. Arrhenius Equation

The activation energy, E_a, in a drying process is the minimum amount of energy that must be exceeded for this process to be feasible. The E_a value is closely related to the D_{eff} coefficient, and its dependence on temperature can be expressed through the Arrhenius model. Based on the drying constants obtained at each temperature, the activation energy is determined, as shown in Eq. 14.

$$k_t = k_0 * e^{\frac{-E_a}{RT}} \quad (14)$$

where k_t is the reaction rate, K_0 is the drying constant, E_a is the activation energy, R is the gas constant (8.314 J/mol ºK), and T is the air temperature expressed °K, from Eq. 11, where plotting Ln (D_{eff}) vs. (1/T) gives a straight line whose slope is ($-E_a$/R), which permits obtaining the activation energy [6, 7, 8, 12, 16, 18, 20, 23].

2. Results and Discussion

Fig. 1a and 1b show the weight of the banana slices and the moisture content in the dry base against the drying time of the slices for all temperatures evaluated. For all the drying temperatures evaluated, the weight of the slices and the moisture content diminishes when the drying period is increased. Therefore, the slopes of the weight and moisture lines are steeper at the beginning of the drying process, diminishing their intensity during the drying process. The reason is that banana slices contain an important amount of moisture, and thereby, the moisture diffusion rate is high at the start of the process. However, during the process, the moisture content of the samples decreases, moisture diffusion from the internal parts of the slices to their surfaces and to the environment slows down, and consequently, the moisture transport rate diminishes. In fact, the downward trend in the moisture diffusion rate was due to the decreased moisture content of the slices, where samples with higher drying rates reached a constant weight in less time. The drying time required to reach constant moisture content in the banana slices diminished as the drying temperature increased (Fig. 1a and 1b). This managed to reduce the drying time by 68.75% at 80°C, 50% at 70°C, 31.25% at 60°C, and 12.5% at 50°C, with respect to the drying time at 40°C. This phenomenon is produced by increased surface temperature, subsequent growth of water vapor pressure over the slice, and, consequently, a higher evaporation rate [12].

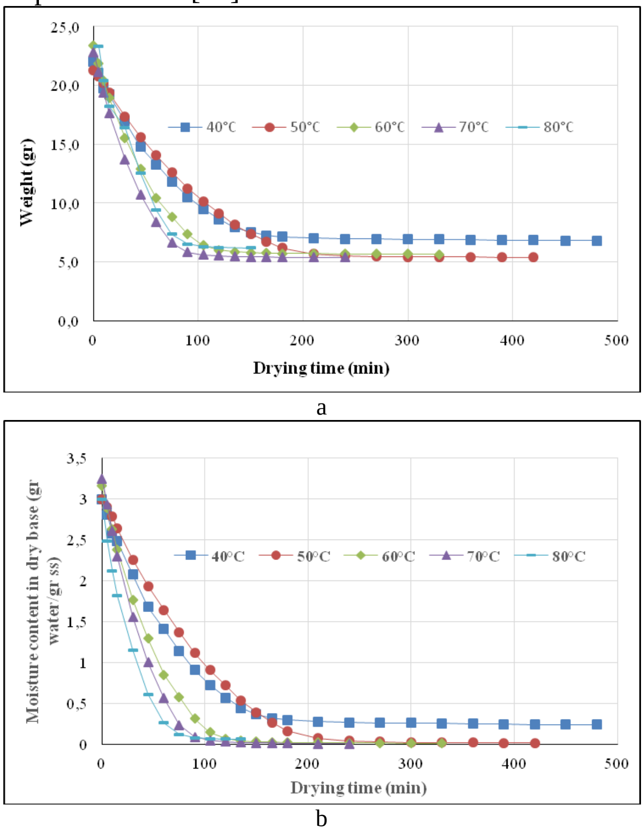

Fig. 1 Variations of a) weight of banana slices vs. drying time and b) moisture content (bs) of banana slices vs. drying time (The author's elaboration)

The results observed are consistent with those by Nadery-Dehsheikh et al. [7], who applied a coating process using carboxymethylcellulose (CMC), with an ultrasonic system as a pretreatment technique to dry banana slices through convection; Roman et al. [12] in convective drying of yellow onion, Singh and Talukdar [8] in convective drying of potato, Flórez-Marín and Lucas-Aguirre [9] in drying kinetics of Cassava slice (*Manihot esculenta* Crantz) variety Ica Catumare.

Fig. 2 does not show a constant drying period rate during the drying of the banana samples; in whose period at constant rate, the surface moisture remains constant as the rate of moisture evaporation from the surface is offset by the rate of moisture diffused through the solid. However, in this study, it is observed that the surface moisture is depleted as soon as drying begins, which demonstrates that moisture diffusion through the solid cannot compensate for moisture evaporation on the surface. During this period, the temperature of the banana remains close to the wet bulb temperature due to evaporative cooling, indicating that diffusion is the dominant physical mechanism that governs moisture movement during drying of banana samples. The same behavior was reported by Agrawal and Methekar [10], Rojas and Augusto [24], Singh and Talukdar [8] in the convective drying of pumpkin and potato, respectively. The moisture elimination is quick at the start of the drying process, varying between 28.14 and 40°C, 36.8 and 50°C, 55.01 and 60°C, 80.44 and 70°C, and 127.88 and 80°C (gr H_2O/m^2min), and the drying rate diminished gradually as drying advanced. Furthermore, the minimum drying rate was quite low, 0.010, 0.0062, 0.0059, 0.0040, and 0.006 (gr H_2O/m^2 min) for each temperature, respectively, where, with constant moisture content, the drying rate increased with increased drying air temperature, given that as air temperature increased, the temperature gradient between the food sample and drying air became higher, which accelerated moisture elimination [14].

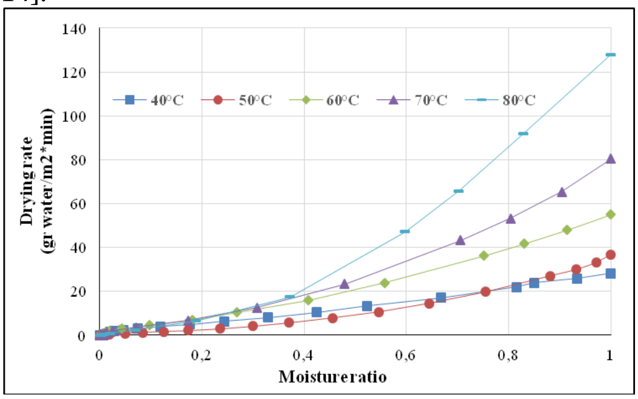

Fig. 2 Drying rate versus moisture ratio at different drying temperatures (The author's elaboration)

During drying, the banana exhibited two distinct drying periods at a decreasing rate without a drying phase at a constant rate [8, 9, 10, 12]. These curves follow an exponential reduction of moisture, showing two stages: in the first, the MR falls linearly over time at a higher rate and in the second phase, this weight loss is produced at a lower rate (Fig. 2). This phenomenon occurs because of the accessibility of the surface water and its subsequent diffusion to maintain the drying rate constant at the beginning, which results in greater moisture diffusion and, consequently, in high drying rates. This phenomenon has been observed by other researchers and indicates that the fall rate is a principal drying mechanism to control the water evaporation rate. When moisture diffusion from the inner core to the surface slows down, the drying rate of the later stage also diminishes. Besides, and bearing in mind that water is present in a solid as free and bound water, at a moderately low drying temperature, the moisture eliminated is usually considered the free moisture weakly bound to the solid [8, 12].

To model the decreasing rate period in banana drying, the diffusion model was used, a method used in the study of mass transfer of agricultural products [8, 10, 18, 21]. The integrated equation of Fick's second law was used (Eq. 10), where the diffusion coefficient (D_{eff}) for each temperature was calculated from the slope of the straight line obtained by plotting Ln (MR) as a function of drying time in minutes (Fig. 3).

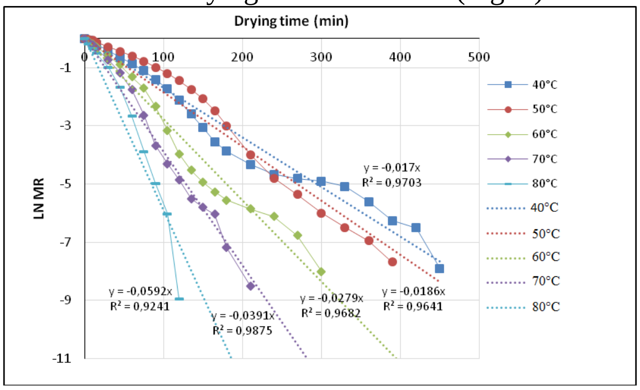

Fig. 3 Drying constants (k) at 40, 50, 60, 70, and 80°C and fitted linear trend line of each data series (The author's elaboration)

In Fig. 3, for the five drying air temperatures, the linearity of the curves shows that D_{eff} is independent of the moisture content, where R^2 varied between 0.924 and 0.970 for the temperatures tested and all the experimental runs conducted, but is dependent on temperature. At the same time, the drying constant (k) obtained from Newton's empirical model serves to determine that the mathematical modeling of the process is a useful method to describe the relationship between the parameters of the process and the results of banana convective drying [19].

Furthermore, it is observed that no significant change exists between the values of k obtained at 40°C (0.017 min^{-1}) and 50°C (0.0186 min^{-1}), unlike the values reached above 60°C, indicating that in this temperature range the drying process is much slower; contrary to that registered for 60°C (0.0279 min^{-1}), 70°C (0.0391 min^{-1}), 80°C (0.0592 min^{-1}) which was the fastest. This behavior directly affects the drying rate behavior, as shown in Fig. 3.

Using Fick's diffusion model to determine the D_{eff} from experimental drying data, it is important to keep in mind that this parameter represents the intrinsic characteristics of the mass transfer of moisture from the banana that imply liquid and molecular diffusion, hydrodynamic flow, vapor diffusion, and other mass transport mechanisms [12, 21, 25]. Thereby, the D_{eff} values obtained for the banana slices were $1.155x10^{-8}$ at 40°C, $1.67x10^{-8}$ at 50°C, $2.54x10^{-8}$ at 60°C, $3.57x10^{-8}$ at 70°C, and $5.40x10^{-8}$ at 80°C m^2/s. The fit was satisfactory because the regression coefficients were > 0.98. The values obtained are within the adequate range of various food products, 10^{-8} to 10^{-11} m^2/s, reported in the literature, and the values can vary in the same species, depending on the variety, slice thickness, drying process conditions, geometry, the product's thermophysical properties, and drying conditions, such as temperature, relative humidity, and air flow rate [8, 12, 21, 25, 26].

D_{eff} increases gradually with increasing temperature, reducing drying time significantly. This behavior may be explained by the fact that the temperature increase produces rapid heating of the banana particles, increasing the kinetic energy and activity between the water molecules, vapor pressure in these particles, and rate of moisture diffusion to the sample surface [8, 27]. This D_{eff} behavior is expected because it is a strong function of temperature, as can be seen in the Arrhenius equation (Eq. 14). Higher air temperature means higher temperature of the sample surface, and hence, D_{eff} increases [8, 9, 21]. Fick's diffusion model assumes that diffusion occurs from a single direction, that is, from within to the surface of the slices; this assumption is valid for thin slices, where lateral diffusion is insignificant [25]. Similar results were reported by Srikanth et al. [27] in convective drying of elephant foot yam (*Amorphophallus paeoniifolius*) for D_{eff}, where diffusivity depends largely on the drying temperature and sample size, where upon increasing the drying air temperature, heat transfer increases and improves the moisture movement and the sample size reduction, yielding as a result greater moisture diffusivity.

The highest D_{eff} value observed in this study may be due to a higher drying temperature that improved the activation energy, where activation energy is the energy required for moisture diffusion and indicates the product's temperature sensitivity. The activation energy value for moisture diffusion in most agricultural food products is between 12 and 110 kJ/mol, which is also the case for banana, where the estimated values of the pre-exponential factor and activation energy were 1288.32 m^2/s and 29.59 Kj/mol, respectively, which are similar to those reported by Singh and Talukdar [8] in convective drying of potato with maximum and minimum activation energy values of 36.17 and 25.35 kJ/mol obtained at air rates of 6 and 2 m/s, respectively; and by Srikanth et al. [27] in convective drying of elephant foot yam, which varied from 25.18 to 32.46 kJ/mol.

3. Conclusions

The prediction of drying kinetics in raw materials under different conditions allows sufficient tools for mathematical modeling and simulation that are important to understand the complexity of drying and obtain the appropriate operating conditions through the optimization of the process.

The drying air temperature had a strong influence on drying time decreasing with its increase. During drying, banana exhibited two distinct periods of decreasing drying rate, without a drying phase at a constant rate.

Diffusion is a physical mechanism that governs moisture migration in banana drying; hence, the experimental data fit Fick's second law. The D_{eff} values obtained for the banana slices were 1.155x10^{-8} at 40°C, 1.67x10^{-8} at 50°C, 2.54x10^{-8} at 60°C, 3.57x10^{-8} at 70°C, and 5.40x10^{-8} at 80°C m^2/s, and the activation energy required for the moisture diffusion obtained was 29.59 Kj/mol.

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