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Mathematical modeling of the effects of thickness and temperature on thin-layer drying kinetics of oven-dried cooking bananas (Musa spp., sub. grp. ABB) slices

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Abstract

Cooking bananas is a major beneficial food in developing countries that is involved in improving human well-being and health. However, owing to its high moisture content, it quickly deteriorates. Understanding the dehydration mechanism of raw banana slices is important for subsequent processing, preservation, transportation, and product quality. Thus, this study investigates the influence of slice thickness (5, 10, and 15 mm) at varying temperatures (45, 55, and 65 °C) in a convective oven dryer on thin-layer drying kinetics and extrapolates their effect on the drying kinetics of cooking banana slices. As the temperature and slice thickness increased, the drying time also increased. Midilli's model was found to be the best for explaining the experimental data. The effective moisture diffusivity ranged from 1.393×10^{-8} to $8.889\ 10^{-8}$ m^2/s. The dependence of moisture diffusivity on temperature was described by an Arrhenius-type equation, and the activation energies were found to be 23.599, 24.804, and 24.223 kJ/mol for thicknesses of 5, 10, and 15 mm, respectively.

Highlights

- Cooking bananas (*Musa spp*., sub. grp. ABB) are undervalued, underutilized and are highly perishable.

- Mathematical modelling of drying characteristics using oven-dryer to improve functionality and storage.

- Midilli's model was found to be the best for explaining the experimental data.

Keywords Drying kinetics, Cooking banana, Mathematical modeling, Oven drying, Banana slices

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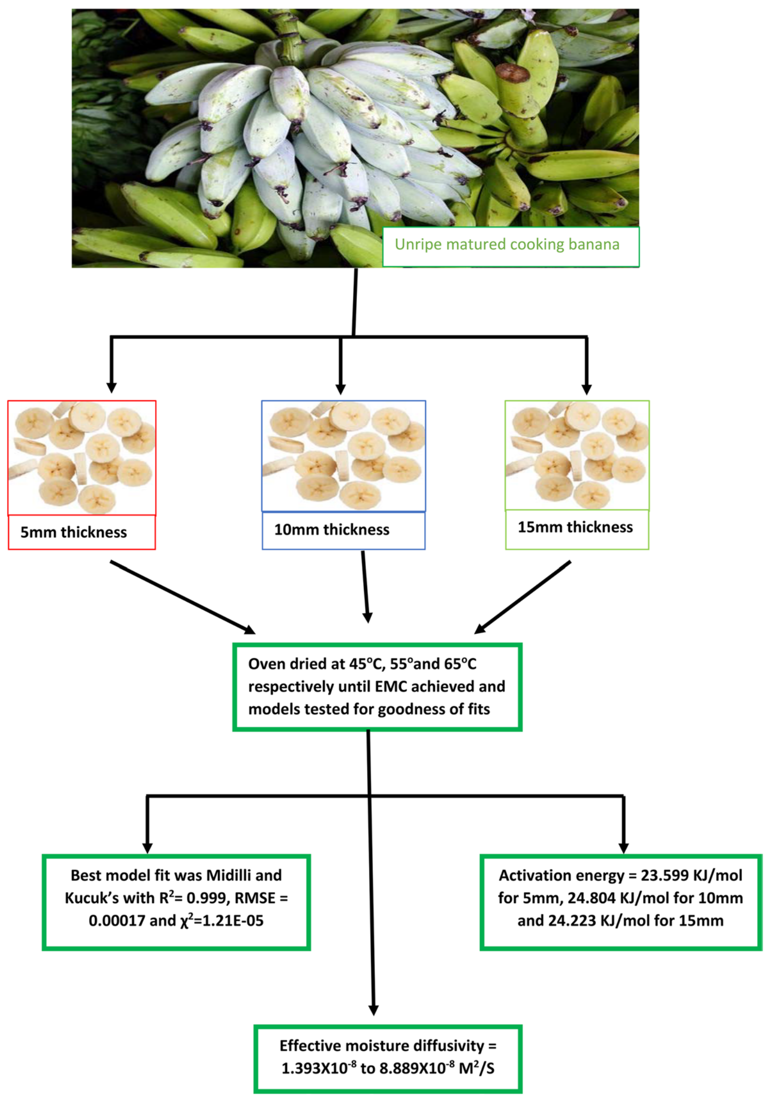
Graphical Abstract



Introduction

Bananas (*Musa* spp.) are herbaceous monocotyledonous plants belonging to the genus Musa and are the main staple food of over a million people. It is a significant crop for farmers in the humid forest agroecological zones of West and Central Africa, the Caribbean islands, and Central and Northern South America (Cenci et al. 2021). It is generally accepted to be native to the Indo-Malaysian region, domesticated in Southeast Asia, and spread throughout the tropical and subtropical regions of the Americas, Africa, Asia, and Australia, with the wild species *Musa acuminata* Colla (A genome) and *Musa balbisiana* Colla (B genome) contributing widely to the major varieties cultivated worldwide (Cenci et al. 2021; Janssens et al. 2016). The hybridization of *M. accumulata* and *M. balbisiana* gave rise to a series of genomic polypoid groups known as *Musa* × *paradisiaca*, including landraces of dessert bananas (AA, AAA, AAB), cooking bananas (AAA, AAB, ABB), and plantain-cooking bananas (AAB) (Gibert et al. 2009).

First introduced into southeastern Nigeria in the late 1980s (Ayo-Omogie et al. 2010; Annor et al. 2016; Ohizua et al., 2017), the cooking banana (ABB genome) cultivars Cardaba, Bluggoe, Fougamou, Nzizi, and Pelipita are used for a variety of traditional and industrial purposes and are typically gathered when mature yet unripe, with fruits resembling immature dessert bananas; however, when compared to other banana varieties, their outer looks frequently give the impression that they are larger (Falade & Oyeyinka 2015). In Nigeria, they are consumed boiled, fried, or roasted. As raw bananas lack sweetness and have an unpleasant texture that feels gritty and hard in the mouth, most cooking banana cultivars are traditionally grown for cooking at different stages of maturation as part of a staple diet. The remaining portion is then processed into stable and storable products, such as flour, fried chips, beer, and wine (Ayo-Omogie et al. 2010; Falade & Oyeyinka 2015; Gibert et al. 2009). Compared with dessert banana varieties, they are considered an excellent choice for making flour because they are inexpensive, have a high starch content, and are less prone to discoloration when dried (Ohizua et al., 2017). Additionally, they are abundant in vitamins (A, B_1, B_2, B_6, and C), minerals (iron, zinc, selenium, magnesium, calcium, phosphorus, and potassium), and proteins and are an essential source of antioxidants, polyphenols, and resistant starch (Ohizua et al., 2017; Tamiru Yazew 2022). According to estimates, between 30 and 33% of the world's banana production is lost because of the fruit's quick perishability upon ripening, its rapid rate of degeneration due to its high moisture content, inadequate storage, and a general lack of knowledge regarding the best post-harvest management techniques for the fruit (Falade & Ogunwolu 2012; Kamble et al. 2022). Less expensive procedures can be used to convert cooking bananas to intermediate moisture products to prevent postharvest losses, increase value, and keep commodities available year-round.

One approach to stopping postharvest losses is the drying process. As the most used food preservation method worldwide, drying attempts to reduce the moisture content and water activity of foods to prevent degradation by limiting microbial growth and moisture-mediated chemical reactions (Guiné & Barroca 2013). Additionally, it alters the final product's taste, flavor, and texture to boost its market value and cater to consumer preferences, although this may result in a product of lower quality. Drying is a complex process that involves the simultaneous transfer of matter and energy. The value chain of cooking bananas is highly dependent on how moisture can be removed from the product; hence, attaining theoretical information about the behavioural pattern and drying kinetics of critical moisture during drying is fundamental for controlling the drying process itself and is paramount to the development and improvement of the drying equipment and the final product (Demirel & Turhan 2003; Kamble et al. 2022). Bananas can be dried using a variety of methods, including sun drying, microwaves, osmotic dehydration, freeze drying, and convective hot air drying (Demirel & Turhan 2003; Guiné & Barroca 2013).

Drying kinetics, when used with chemical analysis, helps predict an effective drying time–temperature combination, involving less degradation of nutritional parameters within a crop. The drying kinetics of food materials can be completely described using the drying constant (k), together with the drying medium. Food products are usually dried in a single layer of slices or particles, a process known as "thin layer drying" (Falade & Ogunwolu 2012). Effective modelling of the drying behaviour using thin-layer modelling is necessary to effectively study the drying kinetics of agricultural commodities. The thin-layer equation, which unifies the drying phenomena and characterizes them in a manner independent of the governing mechanism, can be used to construct the drying constant, which incorporates all transport features (Guiné & Barroca 2013). Thin-layer equations are generated using mathematical modelling and a drying curve simulation under different conditions, which is essential to obtain better control of the unit operation and an overall improvement in the quality of the final product. Many mathematical models have been used to describe the drying process of agricultural products (Demirel & Turhan 2003; Falade & Ogunwolu 2012). Previous works focused on other varieties of banana and plantains including fresh and osmotically pretreated cooking banana and plantain slices (Falade & Ogunwolu 2012), air-drying behavior of Dwarf Cavendish and Gros Michel banana slices (Demirel & Turhan 2003), convective drying of banana var Monthan (Kumar et al., 2019), heat pump drying analysis of Cavendish bananas (Tunckal & Doymaz 2020), hot air convective drying of plantain slices (Kamble Kamble et al. 2022), heat-pump assisted drying of Cavendish banan (Kushwah et al., 2022), and geometric and thermogravimetric analysis on convective air dried local bananas from Brazil (Farias et al. 2022), air-drying of low-fat banana slices (Prachayawarakorn et al. 2008), air drying of fresh and osmotically dehydrated banana (Ehabe et al. 2007), and microwave-drying of osmotically pretreated banana slices (Pereira et al. 2007). However, data on the proper modelling of this indigenous variety cooking banana drying kinetics when using a convective oven dryer, which is the most easily accessible form of drying in developing regions is still lacking. Also, the convective oven drying method is explicitly available and less expensive for large quantity of drying when compared with other modern drying methods. Hence the present work investigated the effects of slice thickness and temperature on the drying kinetics of oven-dried cooking banana slices to determine the best drying state without distorting the samples. Also, we aim to analyse the applicability of several thin-layer models described in the literature for fitting convective oven-drying data into the most suitable model through statistical analysis procedures.

Materials and methods

Materials

Fresh mature and unripe cooking banana (var. *Bluggoe*), locally known as "une," at the second stage of ripening (Aurore et al. 2009), was purchased from the Ndoru market in Umuahia, Abia State, Nigeria. This variety was selected because of its availability and its medicinal and nutritional properties. The banana fingers were sorted according to their appearance and size with no evidence of mechanical damage. All the methods were carried out following institutional guidelines set out by the Department of Agricultural and Bioresources Engineering and the Department of Food Science and Technology, Michael Okpara University of Agriculture, Umudike, Abia State.

Experimental setup and design

Experimental design

A 3^2 factorial design consisting of two factors, each at three levels. Temperature and thickness were considered as independent parameters for the practical study. The experiments were repeated three times, and the average value was used for further calculations, as shown in Table 1.

Drying experiments

The selected cooking banana fingers were detached, washed, peeled, and sliced into different thicknesses (5 mm,10 mm, and 15 mm) using a vegetable cutter and slicer (Qualheim-Electro-cut, model 101, Qualheim Inc., USA). Slice thickness was determined using a GVC-15Kd SK Niigata Seiki digital Vernier caliper (Niigata-ken 955–0061, Japan of 0.01 mm sensitivity. Hot-air drying was performed using a convective oven dryer (Thermo-scientific Heratherm OMS100, USA) at temperatures of 50 °C, 60 °C, and 70 °C. Before starting the experiments, the dryer was switched on for at least 30 min, until the drying air reached the desired temperature. When the system reached a stable temperature, the freshly sliced banana fruits were placed in a drying cabinet without any pretreatment. Samples were placed on the tray in a single layer inside the forced-air oven dryer, where only one side of the slices was in contact with the drying air and the other side was in contact with the support. During the drying process, the tray was removed at 30-min intervals to measure the weight loss for the determination of drying curves using a digital weighing balance. The drying process was continued and stopped when equilibrium moisture content (EMC) was reached. All experiments were conducted in triplicate, and the average values were obtained.

Table 1 Factorial design of the experiments (Oven drying)

Thickness (mm)	Drying temperature(°C)		
	50°C	60°C	70°C
5	EXP 1,2,3	EXP 10,11,12	EXP 19,20,21
10	EXP 4,5,6	EXP 13,14,15	EXP 22,23,24
15	EXP 7,8,9	EXP 16,17,18	EXP 25,26,27

Drying kinetics

Moisture content determination

The initial moisture content of the banana slices (wet basis) was determined by desiccating the samples in a hot air oven (MEM_6001, Memmert, Germany) at 105 °C for 24 h until a constant weight was achieved. The experiment was replicated and calculated using equation (Eq.) 1, according to AOAC (2006).

$$\mathrm{Mc(w.b)\%} = \frac{W_w - W_d}{W_w} x100 \tag{1}$$

where Mc (W. b.) is the moisture content on a wet basis, W_w is the weight of the wet sample (g), and *Wd is the* weight of the dried sample (g).

Determination of moisture ratio (MR) and drying rate (DR)

After drying to equilibrium moisture content without any net moisture exchange between the sample and drying air, the "MR" of bananas was determined according to Kamble et al., (2022) using Eq. 2.

$$\boldsymbol{MR} = \frac{\boldsymbol{Mt} - \boldsymbol{Me}}{\boldsymbol{Mo} - \boldsymbol{Me}} \tag{2}$$

where *Mt*, *Mo*, and *Me* represent the moisture content at time t, initial moisture content, and equilibrium moisture content (g water/g dry matter), respectively.

The *Me* value was determined as the moisture content at which the sample stopped losing mass at the end of drying. During a long drying time, the *Mo* and *Mt* values were always greater than the *Me* value of the cooked banana slices. Thus, the equation can be simplified as shown in Eq. 3 according to Tunckal and Doymaz (2020).

$$\boldsymbol{MR} = \frac{\boldsymbol{Mt}}{\boldsymbol{Mo}} \tag{3}$$

The *DR* was calculated using Eq. 4 as expressed by Kumar et al., (2019)

$$\boldsymbol{DR} = \frac{\boldsymbol{M_{t+dt}} - \boldsymbol{M_t}}{\boldsymbol{dt}} \tag{4}$$

where, M_t and M_{t+dt} moisture content at a specific time and moisture content at t+dt (g water/g dry base) respectively, *t* is drying time (mins).

Fitting of thin-layer mathematical models for drying kinetics

Thin-layer drying models are classified into three types to describe thin-layer drying of food products: theoretical, semi-theoretical, and empirical (Falade & Ogunwolu 2012; Kumar et al. 2019; Midilli et al. 2002; Tunckal & Doymaz 2020). As shown in Table 2, 15 mathematical models for thin-layer drying were used to fit the results of drying experiments conducted at different temperatures and thicknesses.

Determination of effective moisture diffusivity

During the drying process, the drying mechanism changed as the moisture content of the material decreased. Biological materials typically dry during the falling rate period, and moisture transfer during drying is controlled by internal mass transfer and diffusion. Fick's second law of unsteady state of diffusion as shown in Eq. (5), has been widely used to describe moisture transfer during the falling-rate drying period of cylindrical-shaped samples in Eq. 6 (Tunckal & Doymaz 2020).

$$\frac{\partial \boldsymbol{M}}{\partial \boldsymbol{t}} = \nabla\left[\boldsymbol{D_{eff}}(\nabla \boldsymbol{M})\right] \tag{5}$$

$$MR = \frac{\boldsymbol{Mt} - \boldsymbol{Me}}{\boldsymbol{Mo} - \boldsymbol{Me}} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\left(\frac{1}{2n+1}\right)\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}t}{4L^2}\right) \tag{6}$$

where D_{eff} is the effective moisture diffusivity (m^2/s), n is a positive integer ($n = 0$), t is the drying time in seconds, and l is the half thickness of the slice (m).

The effective moisture diffusivity (D_{eff}) for the lumped parameter approach considers all possible resistances to moisture transport. When interpreted for an infinite one-dimensional slab with a negligible temperature gradient, constant temperature, diffusivity, and no significant external resistance, Eq. (6) is suitable for determining D_{eff} (Chen et al. 2012; Kamble et al. 2022; Tunckal & Doymaz 2020). For longer drying periods, Eqs. (6) can be further simplified to Eq. (7) by taking the first term of a series solution without significantly disturbing the precision of the calculation as follows:

$$MR = \frac{8}{\pi^2}\exp[-\frac{\pi^2 D_{eff}t}{4L^2}] \tag{7}$$

Equation 7 can also be expressed in natural logarithmic form (Eq. 8), the slope (K) can be obtained from the linear regression of ln(MR) versus time curves, and D_{eff} can be calculated using Eq. 9

$$\ln MR = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}t}{4L^2}\right) \tag{8}$$

$$\mathrm{K} = \frac{\pi^2 D_{eff}}{4l^2} \tag{9}$$

Determination of the activation energy

Temperature has the greatest effect on diffusivity, and many studies have quantified this effect. The activation energy (E_a) indicates how the effective moisture diffusivity varies with the temperature of the air in the dryer. This correlation is typically depicted under Arrhenius-type conditions (Tunckal & Doymaz 2020; Kushwah et al., 2022) and can be calculated using Eq. 10

Table 2 Thin-layer mathematical models used

No	Model name	Model Equation	Reference
1	Newton	$MR = exp\ (-kt)$	Ertekin & Yaldyz (2004)
2	Page	$MR = exp\ (-kt^n)$	Ertekin & Yaldyz (2004)
3	Modified Page	$MR = exp[-(kt)^n]$	Demir et al., (2007)
4	Henderson and Pabis	$MR = a\ exp\ (-kt^n)$	Ertekin & Yaldyz (2004)
5	Modified Henderson and Pabis	$MR = a\ exp(-kt) + b\ exp(-gt) + c\ exp(-ht)$	Ertekin & Yaldyz (2004)
6	Midilli	$MR = a\ exp(-kt^n) + bt$	Midilli et al., (2002)
7	Modified Midilli	$MR = a\ exp(-kt) + b$	Gan and Poh (2014)
8	Logarithmic	$MR = a\ exp\ (-kt) + c$	Ertekin & Yaldyz (2004)
9	Two-term	$MR = a\ exp(-K_1 t) + b\ exp\ (-K_2 t)$	Ertekin & Yaldyz (2004)
10	Two-term exponential	$MR = a\ exp(-k_0 t) + (1-a)exp\ (-k_1 at)$	Ertekin & Yaldyz (2004)
11	Demir et al	$MR = a\ exp\ (-K\ t)^n + b$	Demir et al., (2007)
12	Verma et al	$MR = a\ exp(-kt) + (1-a)exp\ (-gt)$	Ertekin & Yaldyz (2004)
13	Diffusion approximation	$MR = a\ exp(-kt) + (1-a)\ exp\ (-kbt)$	Ertekin & Yaldyz (2004)
14	Hii et al	$MR = a\ exp(-K_1 t^n) + b\ exp(-K_2 t^n)$	Kumar and Sagar (2014)
15	Wang and Singh	$MR = 1 + at + bt^2$	Ertekin & Yaldyz (2004)

Where MR = (M – Me)/ (Mo – Me) is the moisture ratio (dimensionless); a, b, c, g, h, k, k_0, k_1, k_2, and n are drying constants; and t is the drying time (min)

$$D_{eff} = \boldsymbol{D_o}\mathbf{exp}(\frac{-\boldsymbol{Ea}}{\boldsymbol{R}(\boldsymbol{T} + 273.15)}) \tag{10}$$

where, E_a energy of activation (kJ/mol), R the universal gas constant (8.3143 J/ (mol.K)), T absolute temperature of the drying medium (K), D_o is a pre-exponential factor of the Arrhenius equation (m^2/s). The temperatures used in Eq. 10 is the temperature of the dryer.

The activation energy was calculated by plotting the linear form of the equation obtained using the logarithmic operation as shown in Eq. 11

$$\mathbf{ln}\boldsymbol{D_{eff}} = \mathbf{ln}\boldsymbol{D_o}\mathbf{exp}(\frac{-\boldsymbol{E_a}}{\boldsymbol{R}(\boldsymbol{T} + 273.15)}) \tag{11}$$

Statistical evaluation of drying models

The least-squares method of parameter estimation was used to determine the missing parameters of the drying models. Curve fitting was performed using the Microsoft Excel 2016 solver add-ins. The coefficient of determination (R^2), reduced chi-square value (x^2), and root mean square error (RMSE) as shown in Eqs. 12 – 14 were used to select the best equation representing the sample drying curve based on the goodness of fit. The highest values of R^2 and the lowest values of x^2 and RMSE were used to determine the best goodness of fit (Demir et al. 2004). After the unknown parameters were established, the model was validated by comparing the experimental data with the predicted data to ensure consistency.

$$R^2 = \frac{\sum_{i=1}^{N} MR_{Pre,i}MR_{exp,i} - \sum_{i=1}^{N} MR_{pre,i} \sum_{i=1}^{N} MR_{exp,i}}{\sqrt{}(\sum_{i=1}^{N}(MR_{pre,i})^2 - (\sum_{i=1}^{N} MR_{pre,i})^2)(N\sum_{i=1}^{N} MR_{exp,i} - (\sum_{i=1}^{N} MR_{exp,i})^2)} \tag{12}$$

$$X^2 = \frac{\sum_{i=1}^{n}(MR_{exp,i-}MR_{pre,i})^2}{N-n} \tag{13}$$

$$\mathrm{RMSE} = [\sum_{i=1}^{N}\frac{1}{N}(MR_{exp,i-}MR_{pre,i})^2]^{\frac{1}{2}} \tag{14}$$

where $MR_{exp,I}$ is the experimental moisture ratio, $MR_{pre,i}$ is the predicted moisture ratio, n is the number of constants and N is the number of observations.

Results and discussion

Drying characteristics of cooking banana

During the drying experiments, as shown in Fig. 1, the initial moisture content decreased to a final moisture content of 5.6% on a wet basis, which is an appropriate range to avoid microbial attack and subsequent deterioration during storage. On a wet basis, the initial and final moisture contents of the cooking bananas were 74.6% and 5.6%, respectively. The moisture contents of the dry basis and dry matter were found to be 293.7% and 25.43%, respectively.

As drying progressed, the rate of moisture released into the drying air tended to decrease. Drying was continued until equilibrium moisture content was attained. Generally, it can be observed that the moisture content decreases continuously with the drying time. Irrespective of the slice thickness and temperature difference, the drying process of the samples ended in the range of the falling rate phase. These curves show the two phases of drying rate, which is consistent with the results of other studies on bananas and plantains (Saeed et al. 2006). This means that diffusion is the main physical mechanism controlling the movement of moisture in the material and is dependent on the moisture content of the samples (Srikanth et al. 2019; Ojediran 2020).

Drying curves

As the initial moisture composition of the samples varied from one set to the next, the experimental data on moisture content (drying curves) were transformed into a more useful form, namely, the dimensionless moisture ratio (MR) expression. The variations in the moisture ratio (MR) and drying rate (DR) with drying time for cooking bananas are shown at three different drying temperatures (50, 60, and 70 °C) and thicknesses (5, 10, and 15 mm).

Effect of temperature on drying curve

The effect of the drying temperature on the moisture ratio as a function of the drying time is shown in Fig. 2a – c. The results showed that an increase in drying temperature led to an increase in the drying rate, and hence a reduction in drying time. As expected, drying temperature had a significant effect on the moisture ratio of banana slices. This is because drying at a higher temperature result in a greater driving force for the heat transfer. The drying curves are typical for similar fruits and vegetables. Srikanth et al., (2019) reported that higher drying temperatures provide a larger water vapor pressure deficit, or the difference between the saturated water vapor pressure and partial pressure of water vapor in air at a given temperature, which is one of the driving forces for drying. Similar behavior was observed by Demirel and Turhan (2003), Ertekin and Yaldiz (2004), Kumar et al., (2019), Tunckal and Doymaz (2020), Kushwah et al. (2022),

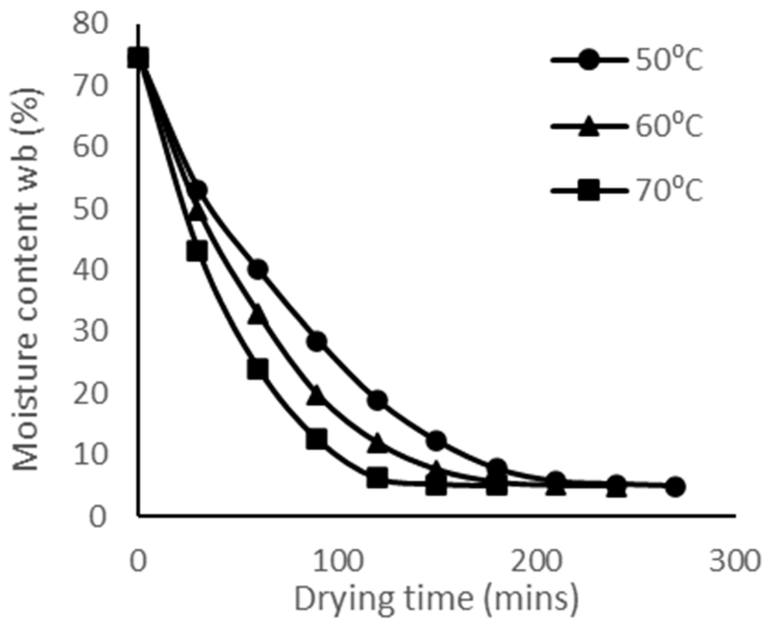


Fig. 1 Drying curve of moisture content vs drying time for cooking banana

and Kamble et al., (2022). Thus, the drying time required to reduce the initial moisture content to any given level depends on the drying conditions, mainly the temperature (with the longest drying time at 50 °C and the shortest at 70 °C) and thickness (with the longest drying time at 15 mm and the shortest drying time at 5 mm).

Effect of slice thickness on drying curves

As shown in Fig. 3a-c, the drying time increased with increasing slice thickness and decreased continuously with decreasing moisture content. This means that the drying time decreased drastically as it approached the final moisture content, the higher the sample thickness, the longer the drying time. A thinly sliced sample dehydrates more rapidly because moisture travels shorter distances, and more surface area is exposed for a given sample volume. Previous studies have found similar results for foodstuffs and vegetables (Demirel & Turhan 2003; Ertekin & Yaldiz 2004; Kumar et al. 2019, Tunckal & Doymaz 2020, Kushwah et al. 2022, Kamble et al. 2022).

Effect of temperature and slice thickness on drying time (t)

A chart of drying temperature versus duration (drying time) is presented in Fig. 4. The drying time was shown to vary with slice thickness and drying temperature. The combination of 5 mm-thick banana slices and a high temperature of 70 °C resulted in the shortest drying duration (180 min), while the thickest banana slices (15 mm) and lowest temperature (50 °C) combination gave the longest duration of 690 min. In summary, this means that drying time has a direct relationship with temperature, whereas it has an inverse relationship with slice thickness.

Effect of temperature and slice thickness on drying rate (DR)

The drying rate was obtained by calculating the time required to remove a given quantity of moisture from the dried samples. The curves of the drying rate versus time at different thicknesses and temperature levels are shown in Fig. 5a-c. As the slice thickness increased, the drying rate decreased as the drying time increased and vice versa. It was observed that slice thickness and temperature had the greatest influence on the drying rate, as increasing the temperature resulted in an increased drying rate while simultaneously decreasing the drying time.

During this time, a reduction in moisture migration from the interior to the surface of the product occurs. The drying rate was observed in both constant- and falling-rate phases. Initially, it was high because the moisture content was too high. As the drying approached the falling rate period, the drying rate decreased until it became constant, signalling the equilibrium moisture content stage. In addition, Srikanth et al., (2019), D_R slowed as the sample slice thickness increased owing to the decreasing kinetic energy of the water molecules. The ambient availability of surface moisture and its subsequent diffusion to maintain a constant D_R during drying at various temperatures and product thicknesses may be responsible for the rapid decline in moisture content during the first drying phase (Workneh & Oke

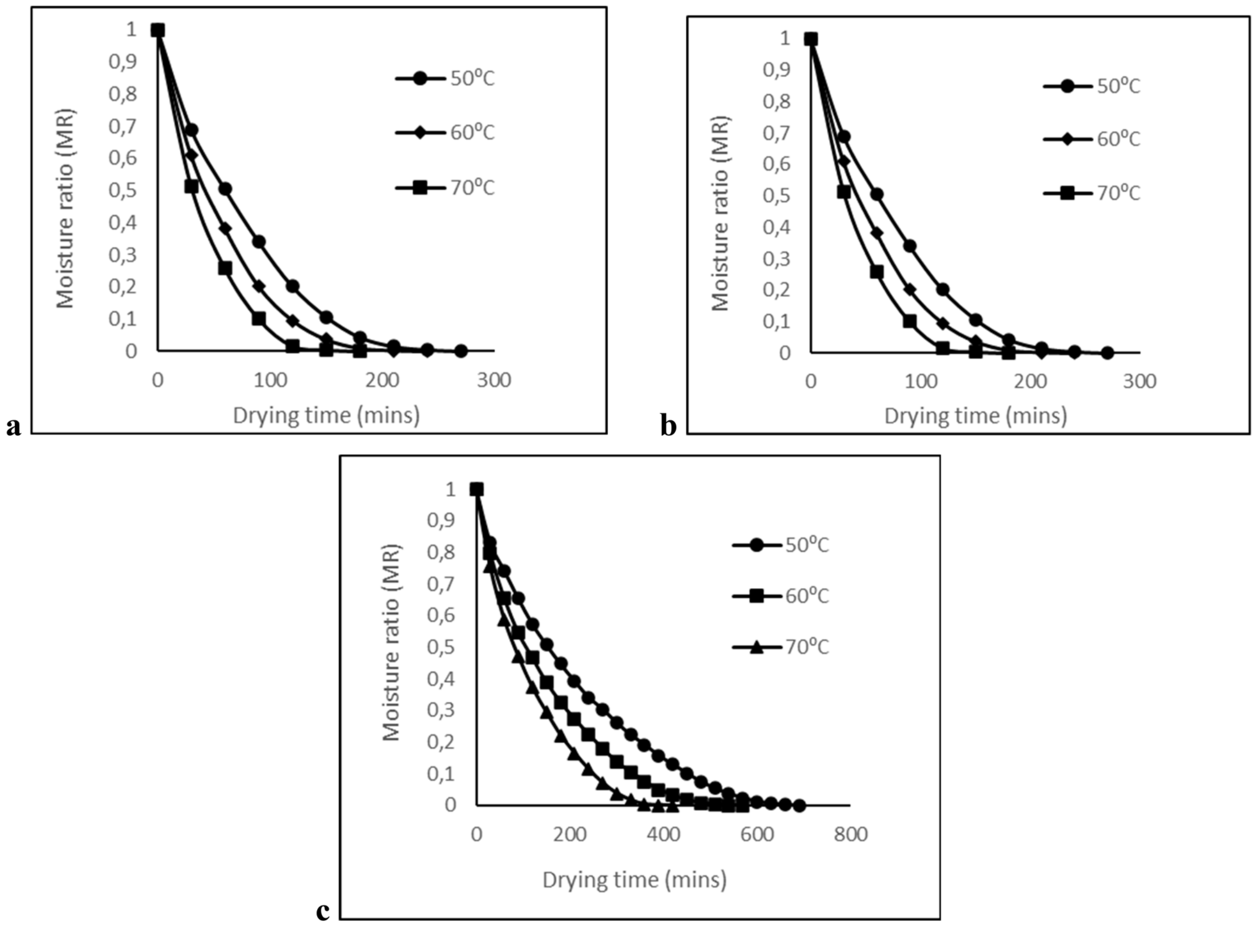


Fig. 2 Effect of temperature on the variation in moisture ratio (MR) versus drying time (**a**) at a slice thickness of 5 mm, (**b**) at a slice thickness of 10 mm, and **c** at a slice thickness of 15 mm

2012). According to Ojediran et al., (2020), the bound water in the samples significantly decreased the D_R value as drying advanced, and moisture was able to diffuse from the centre of each particle to its surface. The mass-transfer-controlled technique eventually led to a falling rate period for the entire drying process.

Drying rate constant (k)

The drying rate constant was estimated by plotting the log of the moisture ratio against time (t). Plots of the natural log of MR (ln MR) against time (t) to show the drying rate constant are presented in Fig. 6a-c. The logarithm of the moisture ratio was plotted against the drying time to get a straight line whose slope is the drying rate constant (k) for the product at the prevailing conditions (temperature 50, 60, and 70 °C and thickness 5, 10, and 15 mm).

Effect of drying temperature and slice thickness on drying rate constant (k) Table 3 shows the drying rate constant used in calculating moisture diffusivity. For models derived from Newton's law of cooling (Newton and Page models), the k values increased with an increase in drying temperature. For models derived from Fick's second law of diffusion (Henderson and Pabis, Midilli, logarithmic, etc.), the drying constant (k) also increases linearly with increasing drying air temperature and has an inverse relationship with sample thickness; hence, k is a function of the drying temperature. In concurrence with Mdilli's model, an increase in the drying constant (k) coincided with a decrease in drying temperature and an increase in slice thickness, indicating that a lower temperature and higher thickness enhanced the driving forces for heat and mass transfer. However, the remaining estimated coefficient values for the other models did not exhibit temperature dependence, nor did they show any clear patterns.

Effect of temperature on effective moisture diffusivity (D_{eff})

To characterize the distinctive movement of a food's intrinsic moisture, effective moisture diffusivity is usually used during drying, which is a complicated process

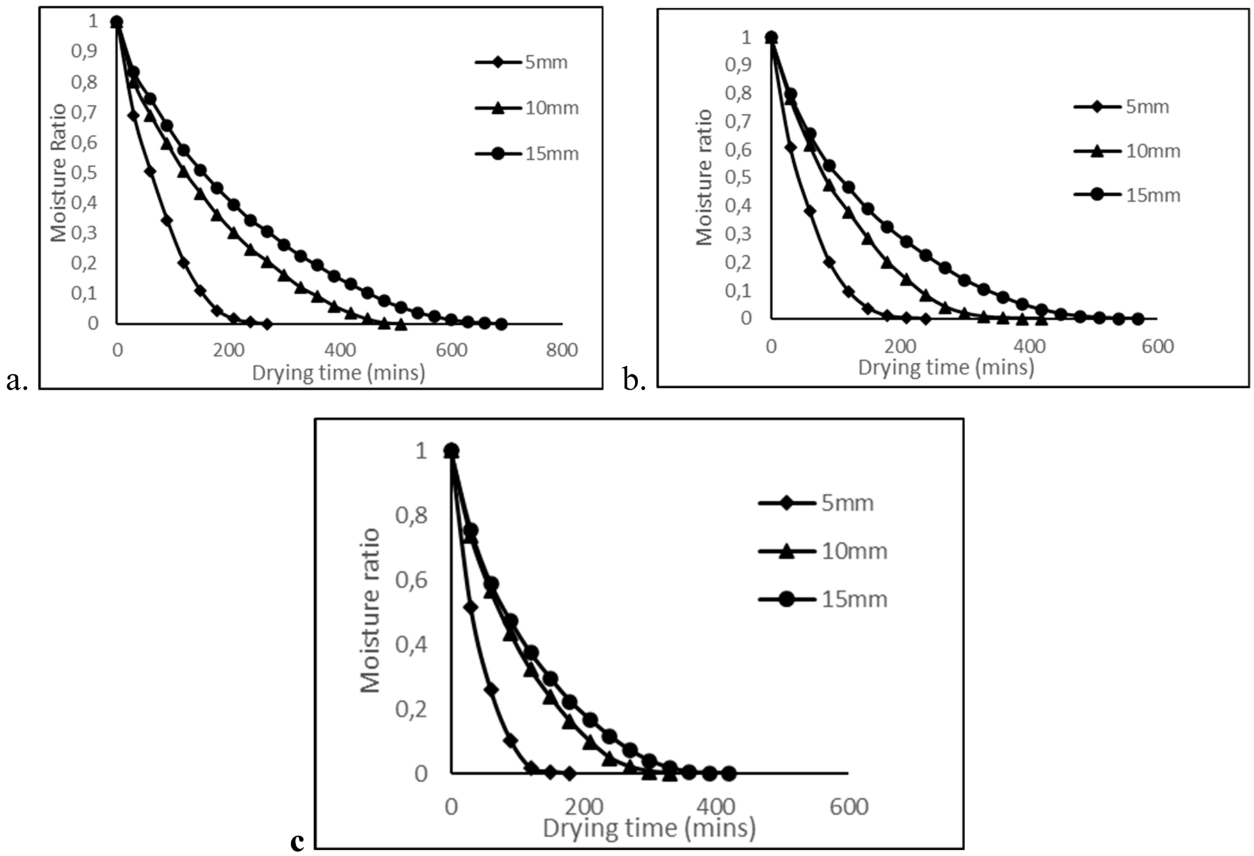


Fig. 3 Effect of slice thickness on the variation of moisture ratio (MR) vs drying time at **a** 50 °C **b** 60 °C **c** 70 °C temperatures

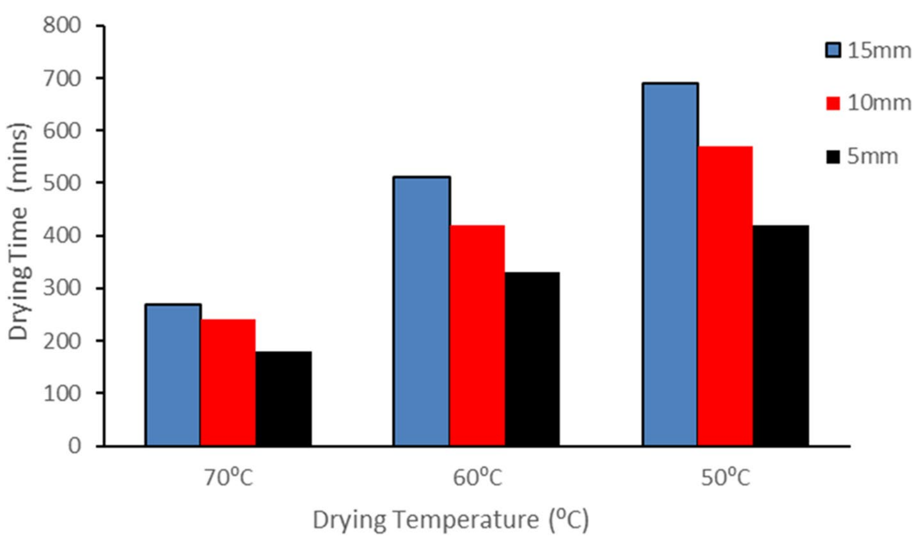


Fig. 4 Effect of temperature of the drying medium and slice thickness against drying time

that incorporates different diffusion factors, such as liquid, molecular, vapor, and hydrodynamic diffusion (Kamble et al. 2022; Nachaisin et al. 2016). The drying data of unripened cooked banana slices were analyzed to obtain the values of effective moisture diffusivity during the falling drying rate phase. The effective moisture diffusivity

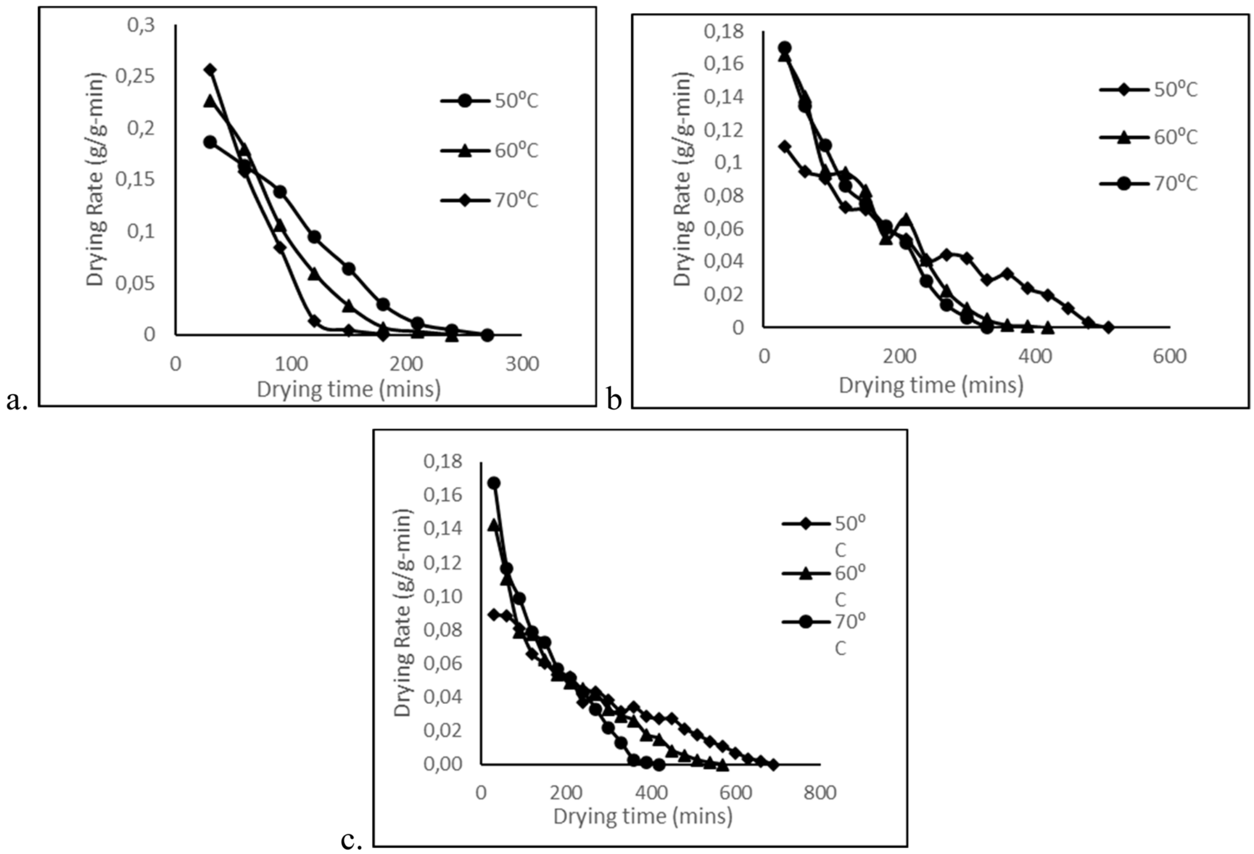


Fig. 5 Effect of drying rate on drying time at (**a**) slice thickness of 5 mm, (**b**) slice thickness of 10 mm, and (**c**) slice thickness of 15 mm at different temperatures (50, 60, and 70 °C)

was calculated using the slope derived from the natural logarithm of the moisture ratio against drying time (min) (Eq. 9). The calculated effective diffusion coefficient values of unripe cooked banana slices are shown in Table 4 and show that the effective diffusivity increases with an increase in drying air temperature and slice thickness. This is due to the increase in vapor pressure inside the food samples, which causes an increase in heat energy and water molecule activity, leading to an improvement in the effective moisture diffusivity toward the exterior surface. The D_{eff} values obtained from the experimental data fall within the general range of 10^{-12} to 10^{-8} m^2/s reported for food products (Zogzas & Maroulis 2007). The results obtained were comparable to the 1.61×10^{-8} m^2/s to 8.89×10^{-9} m^2/s gotten by Kumar et al., (2019) and higher than the values of banana slices 1.12×10^{-10} m^2/s to 1.64×10^{-10} m^2/s, respectively) gotten by Tunckal and Doymaz (2020), 1.05×10^{-10} m^2/s to 1.56×10^{-10} m^2/s reported by Kushwah et al., (2022), and 1.11×10^{-10} to 1.79×10^{-9} m^2/s obtained by Kamble et al., (2022). Differences in composition, shape, size, drying temperature, pre-treatment method, initial moisture content, equipment, and experimental setup may account for the minor differences between the current findings and those of previous researchers.

Activation energy (Ea)

Cooking banana slices require energy to initiate a reaction from intrinsic to extrinsic (moisture diffusion), which is expressed as the activation energy (E_a). E_a and the constant D_0 were determined by plotting ln (D_{eff}) versus 1/T + 273.15, yielding a straight-line graph with a slope equal to (-E_a/R) (Fig. 7). The activation energy increased as the slice thickness increased. According to the slope of the straight line described by the Arrhenius equation, the values of the activation energies were calculated to be 23.599, 24.804, and 24.223 kJ/mol for thicknesses of 5, 10, and 15 mm, respectively. This observation agrees with the value of 22.035 kJ/mol reported by Kumar et al., (2019). The value obtained is higher when compared with the value reported by Kamble et al., (2022) ranging from 13.70 to 18.23 kJ/mol for banana slices dried at four different temperatures (50, 60, 70, and 80 °C) and thicknesses (2, 4, 6 and

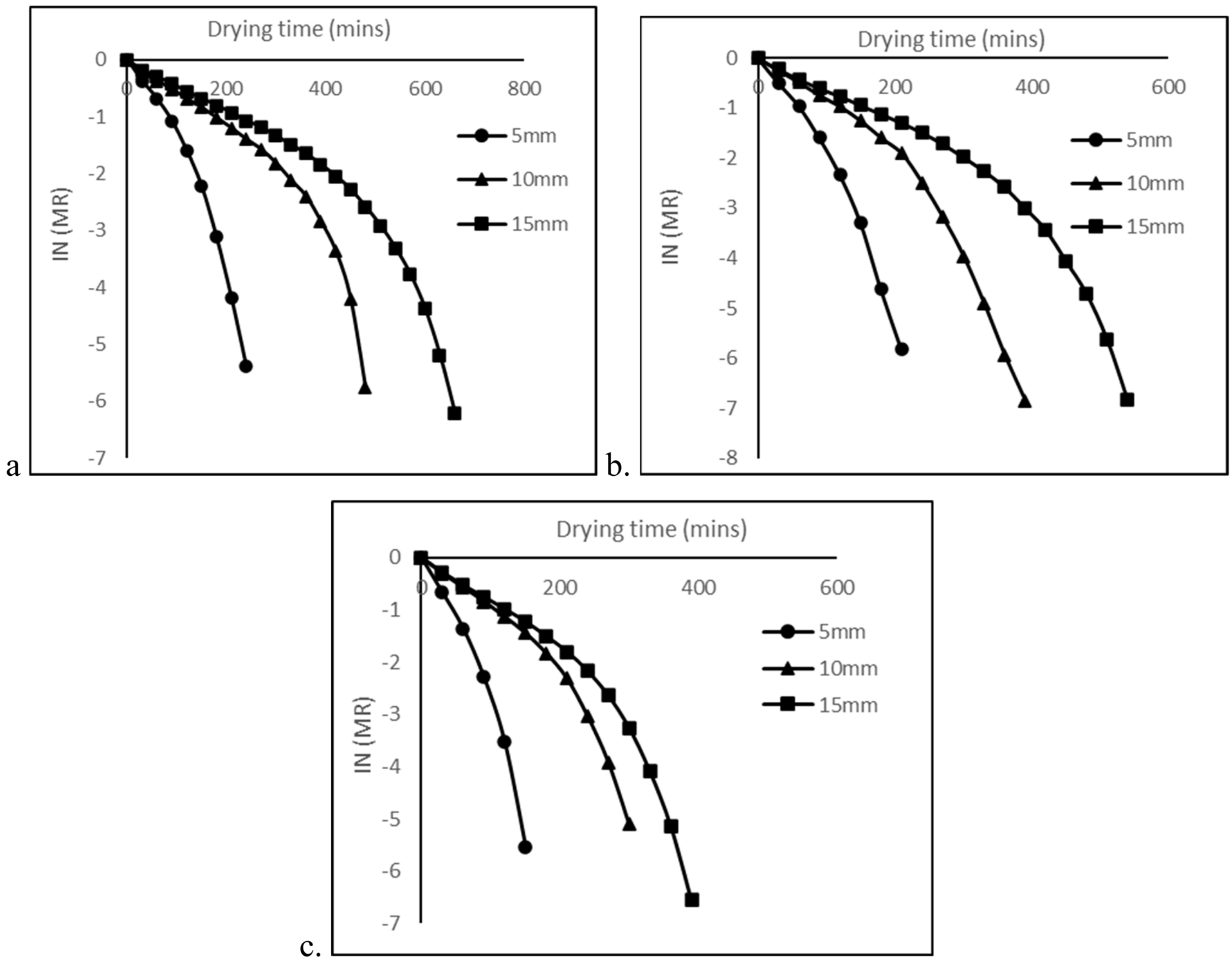


Fig. 6 Log of moisture ratio (MR) against time at (**a**) drying temperature of 50 °C, (**b**) drying temperature of 60 °C, and (**c**) drying temperature of 70 C, vs. thickness (5, 10, and 15 mm)

Table 3 The drying rate constant (k) $(\text{min})^{-1}$ values

Temp (°C)	Slice thickness (mm)		
	5	**10**	**15**
50	-0.00550	-0.00280	-0.00230
60	-0.00690	-0.00390	-0.00290
70	-0.00920	-0.00480	-0.00390

Table 4 Effective moisture diffusivity (m^2/s) values

Temperature (°C)	Slice thickness (mm)/		
	5	10	15
50	1.393E-08	2.836E-08	5.242E-08
60	1.747E-08	3.951E-08	6.609E-08
70	2.33E-08	4.862E-08	8.889E-08

8 mm). However, they were lower than the 51.45 kJ/mol for 3-mm-thick banana samples by Tunckal and Doymaz (2020), and 42.58 kJ/mol for 2.5 mm thick samples by Kushwah et al., (2022). The effects of the banana type, slice thickness, content, and tissue properties can be used to explain the variations in the results. The activation energy levels of the samples fell within the overall range of 12.7 to 110 kJ/mol for foodstuffs (Zogzas & Maroulis 2007).

Generally, the greater the activation energy, the more sensitive D_{eff} is to the temperature (Kaymak-Ertekin 2002). In addition, it has been shown that the effective diffusivity changes with temperature based on an Arrhenius relationship. Thus, plotting ln (D_{eff}) versus 1/T + 273.15, the values of the energy activation (E_a) and the pre-exponential factor of Arrhenius (D_o) were calculated from the slope and intercept of the linear regression, respectively. The dependence of the effective

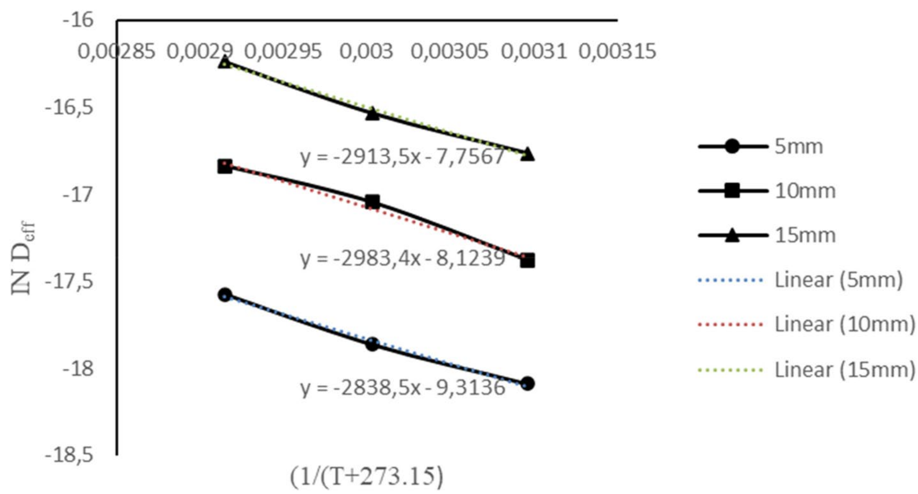


Fig. 7 Log of (D_{eff}) versus 1/(T + 273.15) of different levels of slice thicknesses showing Arrhenius-type relationship between effective diffusivity and temperature

diffusivity of banana samples on the drying temperature can be represented by the following equations for 5, 10, and 15 mm.

$$\boldsymbol{D_{eff}} = 111\mathbf{exp}\left(\frac{-23.599}{\boldsymbol{RT}}\right) \tag{15}$$

$$\boldsymbol{D_{eff}} = 337\mathbf{exp}\left(\frac{-24.804}{\boldsymbol{RT}}\right) \tag{16}$$

$$\boldsymbol{D_{eff}} = 243\mathbf{exp}\left(\frac{-24.223}{\boldsymbol{RT}}\right) \tag{17}$$

Evaluation and selection of the drying model for oven-drying kinetics

The moisture content of cooking bananas at different drying temperatures (50, 60, and 70 °C) and sample thicknesses (5, 10, and 15 mm) were converted to the moisture ratio (MR) and fitted to the 15 selected thin-layer drying models listed in Table 2 to determine the drying behavior. The values of the coefficient of determination (R^2), reduced chi-square (X^2), root mean square error (*RMSE*), and model constants and coefficients were determined by non-linear regression analysis using Microsoft Excel (2016) solver add-in. The estimated parameters and statistical analysis of the model for a given set of drying conditions are listed in Table 5. The average values of the statistical parameters were considered when selecting the best model for describing drying. In all cases, the R^2 values for the models were greater than the acceptable R^2 value of 0.90, indicating a good fit (Doymaz, 2008). Based on the criteria of the highest R^2, lowest RMSE, and reduced chi-square X^2, the model of Midilli (Midilli et al. 2002) was selected as the most suitable model to represent the single-layer drying behavior of unripened cooking banana slices for oven-drying. The coefficients and constants of the best drying model for different drying conditions obtained using the Midilli equation are listed in Table 6.

The best-fit model was validated graphically by plotting the experimental and predicted moisture ratio values against drying time, as shown in Fig. 8a–i. There is good agreement between the experimental and predicted variables when considering the constants and factors of the Midilli drying models for oven drying. The moisture ratio of cooking banana slices of 5, 10, and 15 mm at different stages (t) of drying within a temperature range of 50–70 °C can be successfully predicted using the empirical equations below;

$$5\mathbf{mm};\ \boldsymbol{MR} = 0.994\mathbf{Exp}(-1.10\mathbf{E}^{-2}\mathbf{xt}^{1.039}) + 9.62\mathbf{E}^{-4}\mathbf{t} \tag{18}$$

$$10\mathbf{mm};\ \boldsymbol{MR} = 1.009\mathbf{Exp}(-1.16\mathbf{E}^{-2}\mathbf{xt}^{0.918}) + 3.16\mathbf{E}^{-4}\mathbf{t} \tag{19}$$

$$15\mathbf{mm};\ \boldsymbol{MR} = 0.996\mathbf{Exp}(-8.63\mathbf{E}^{-3}\mathbf{xt}^{0.864}) + 1.92\mathbf{E}^{-4}\mathbf{t} \tag{20}$$

Thus, the Midilli model is expected to perform satisfactorily in addressing the drying behavior of cooking banana slices at different temperatures and slice thicknesses. This assessment agrees with a study conducted by Tunckal and Doymaz (2020), who showed that the Midilli model was the best fit for the experimental moisture ratio (MR) in their study of the modeling of banana slices in a heat-pump drying system. Kamble et al., (2022)

Table 5 Average Statistical results obtained from the selected models

No	Model Name	R^2	X^2	RMSE
1	Newton	0.969	0.00501	0.0633
2	Page	0.99	0.00063	0.0215
3	Modified Page	0.99	0.00063	0.0215
4	Henderson and Pabis	0.988	0.00018	0.0098
5	Modified Henderson and Pabis	0.997	0.000371	0.0117
6	Midilli	0.999	1.21E-05	0.00017
7	Modified Midilli	0.999	6.55E-05	0.0038
8	Logarithmic	0.999	3.42E-05	0.0033
9	Two-term	0.975	0.002215	0.0362
10	Two-term Exponential	0.998	0.000338	0.0128
11	Demir et al	0.998	3.70E-05	0.0034
12	Verma et al	0.998	0.00029	0.0116
13	Approximation of Diffusion	0.975	0.002001	0.0362
14	Hii et al	0.988	0.000592	0.0169
15	Wang and Singh	0.907	0.0901	0.2662

found the diffusion approach model to be the best fit for experimental MR in their analysis of convectively dried cooking banana slices. From the results, it was assumed that in banana drying, the least suitable models were the two-term model, approximation diffusion, and the Wang and Singh model, which agreed with the results of Kumar et al., (2019). Nonetheless, these models may be better suited for drying products with different dehydration properties.

Conclusion

The convective oven-drying characteristics of cooking banana slices were investigated at three different drying temperatures and slice thicknesses. The experimental study revealed that the drying rate, moisture content, and drying duration were all strongly influenced by the increasing temperature and decreasing thickness. The fact that the entire drying experiment occurred during a period of declining rate suggests that internal diffusion caused the water molecules to move from the interior of the material to its outer surface. To explain the drying kinetics of banana slices, 15 thin-layer drying models were used. Statistical analysis showed that the model found by Midilli had the best fit. The effective moisture diffusivity values, computed using Fick's second law, varied from 1.393×10^{-8} to $8.889\ 10^{-8}$ m^2/s over the temperature range. With an increase in drying temperature, the effective moisture diffusivity increased. The activation energy was estimated by an Arrhenius-type

Table 6 Statistical results of Midilli model (oven drying)

No	t(mm),T(°C)	n	a	k	b	R^2	X^2	RMSE
1	05,50	1.102	0.987	0.00553	0.000822	0.99822	6.35E-07	0.00062
2	05,60	1.006	0.998	0.01182	0.000894	0.9996	5.72E-08	0.00018
3	05,70	1.009	0.997	0.01566	0.001171	0.99963	1.31E-07	0.00024
	Mean	**1.039**	**0.994**	**0.0110**	**0.000962**			
1	10,50	0.856	0.994	0.00748	0.000122	0.99921	6.08E-05	0.00688
2	10,60	0.89	1.045	0.01102	0.000377	0.99582	6.90E-07	0.00071
3	10,70	1.008	0.987	0.0165	0.000449	0.99887	3.81E-07	0.0005
	Mean	**0.918**	**1.0087**	**0.0117**	**0.000316**			
1	15,50	0.811	0.998	0.00748	0.000048	0.99793	6.33E-05	0.00230
2	15,60	0.833	0.999	0.00887	0.000158	0.99851	3.92E-05	0.00177
3	15,70	0.948	0.991	0.00954	0.00037	0.99898	3.06E-06	0.00150
	Mean	**0.864**	**0.996**	**0.00863**	**0.000192**			
						0.99853	**1.21E-06**	**0.00057**

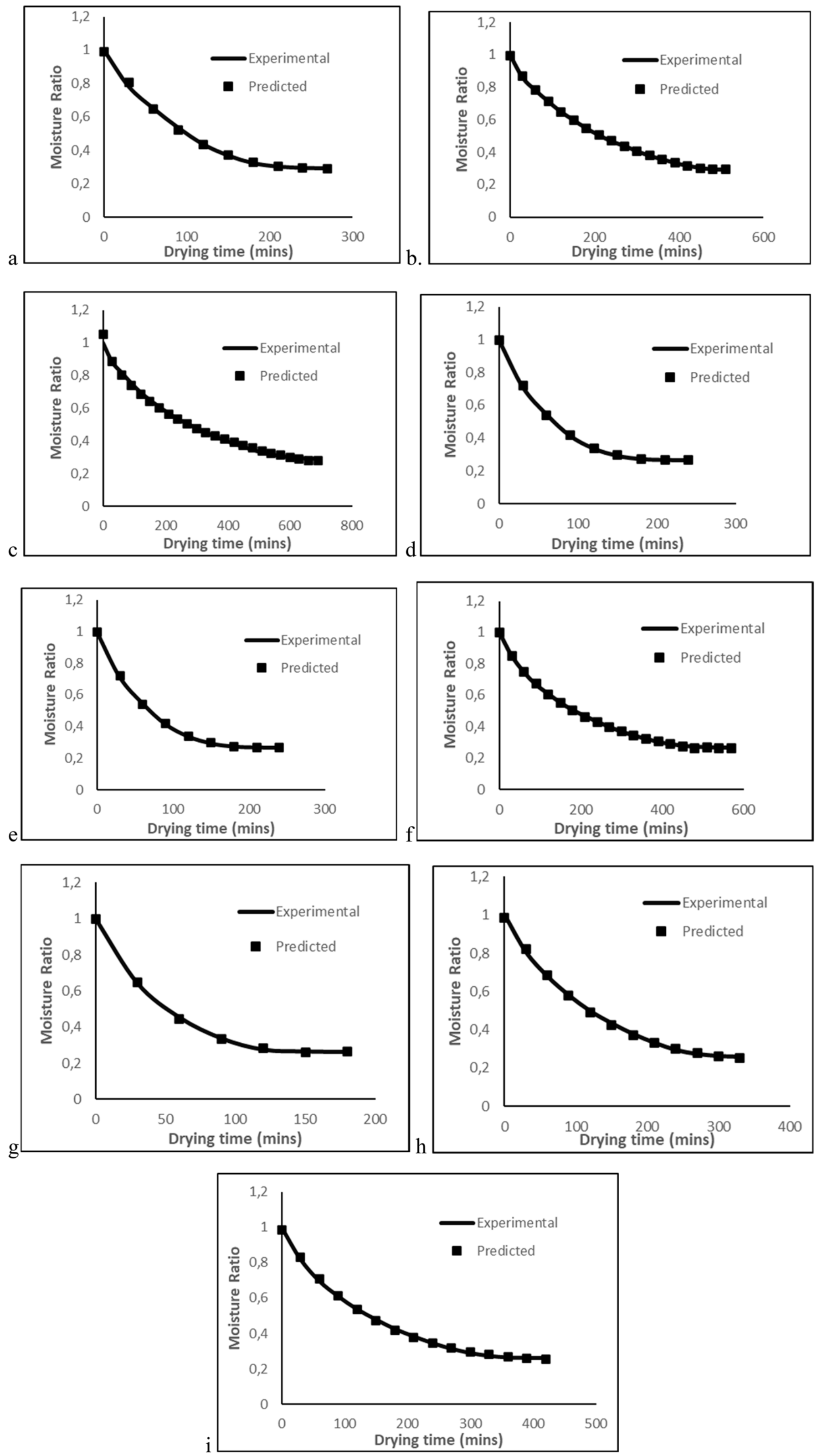


Fig. 8 Comparison of experimental and predicted moisture ratio values by Midilli model at different drying temperatures and thicknesses (**a**-**c**) 5, 10, and 15 mm at 50 °C; **d**-**f** 5, 10, and 15 mm at 60 °C; and (**g**-**i**) 5, 10, and 15 mm at 70 °C for cooking banana slices

equation and found to be 23.599, 24.804, and 24.223 kJ/mol for thicknesses of 5, 10, and 15 mm, respectively. The sample thickness and drying temperature have a direct impact on the energy consumption of the process. Before using them, it is vital to understand how the drying temperature and thickness affect the physicochemical composition, nutritional profile, sensory attributes, and microbial contamination. These are key research questions and areas for future research.

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Authors' contributions
KSC—Conceptualization, methodology, data curation, formal analysis, and writing – original draft; AL-C – Conceptualization, methodology, supervision and writing – reviewing and editing; FUM – Conceptualization, methodology, data curation, formal analysis, and writing – original draft; COA-L—Methodology, data curation, formal analysis; FOA—Writing – reviewing and editing; ABE – Conceptualization, supervision, investigation and writing – original draft; QNO – Investigation, writing – reviewing and editing.

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Availability of data and materials
The datasets generated and/or analyzed during the current study are available from the corresponding authors upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
The authors hereby give their consent for the publication of this work/material/image, etc. in any form or medium, with due acknowledgment.

Competing interests
The authors declare no conflict of interest.

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