



Experimental and theoretical investigation of drying kinetics of banana slices

Muz dilimlerinin kurutma kinetiğinin deneysel ve teorik incelenmesi

Burak TÜRKAN¹ , Akın Burak ETEMOĞLU^{2*} 

^{1,2}Mechanical Engineering Department, Faculty of Engineering, Uludag University, Bursa, Turkey.
burakt@uludag.edu.tr, aetem@uludag.edu.tr

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Abstract

Modeling of the hot air dehydration period is very important to increase food property and reduce energy consumption. The objective of the study is to examine the drying behaviour of banana slices by using convective hot air drying method. Drying kinetics of the banana slices was investigated experimentally for different air temperatures (40, 50, and 60 °C). The drying models were fitted to the experimental data. The model which gives the nearest results to the experimental information was predicted as the Midilli model ($R^2=0.99$). It was determined that the L (brightness) colour parameter value declined as the moisture content of the food decreased. Effective diffusion coefficients (2.02×10^{-10} , 5.05×10^{-10} , and $8.08 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$), activation energy ($61.1 \text{ kJ (mol)}^{-1}$) and shrinkage coefficients (23%, 32% and 40%) were calculated and it was seen to be compatible with the data given in the literature on food drying. The temperature and moisture content obtained from the experimental study were compared with numerical analysis and found to be compatible.

Keywords: Convective drying; Shrinkage, Banana.

Öz

Sıcak hava ile kurutma modellenmesi, gıda kalitesini arttırmak ve enerji tüketimini azaltmak için çok önemlidir. Çalışmanın amacı, sıcak hava kurutma yöntemi ile muz dilimlerinin kurutma davranışlarını incelemektir. Muz dilimlerinin kurutma kinetiği, farklı hava sıcaklıkları (40, 50 ve 60 °C) için deneysel olarak incelenmiştir. Kurutma modelleri deneysel verilere uygulanmıştır. Deneysel verilere en yakın sonuçları veren model Midilli modeli ($R^2=0.99$) olarak tahmin edilmiştir. Ürünün nem içeriği azaldıkça L (parlaklık) renk değerinin azaldığı belirlenmiştir. Efektif difüzyon katsayıları (2.02×10^{-10} , 5.05×10^{-10} ve $8.08 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$), aktivasyon enerjisi ($61.1 \text{ kJ (mol)}^{-1}$) ve büzülme katsayıları (%23, %32 ve %40) hesaplanmış ve sonuçların gıda kurutulması üzerinde literatürde verilen bilgiler ile uyumlu olduğu görülmüştür. Deneysel çalışmadan elde edilen sıcaklık ve nem içeriği değerleri nümerik analiz sonuçları ile karşılaştırılmış ve uyumlu olduğu bulunmuştur.

Anahtar kelimeler: Konvektif kurutma, Büzülme, Muz.

1 Introduction

Bananas among food products are widely consumed in many countries. Banana has very nutritious due to containing protein, fiber, fat acid, minerals and vitamin E such as magnesium, copper, and iron [1]. Fruits and vegetables containing water cause spoilage. Therefore, the drying process is used in the conservation of agricultural products. This process provides long-term protection without losing the vitamin value of the product [2].

Sun drying is one of the habitual approaches utilized for dehydration of farming foods. However, convective dehydration is the most common industrial structure due to the homogeneous and fast dehydration procedure [3].

The air drying process usually consists of a term of constant rate, followed by a period of falling rate. In the constant rate term, the surface is covered with water. As the water evaporates, the mass transfer to air from the surface occurs. In the falling rate duration, humidity transfer is directed by interior mass transfer structures such as liquid, vapor diffusion, and capillary flow. Two falling rate periods occur in hygroscopic materials during drying. The wet surface area decreases as the moisture content of food vaporizes in the initial falling rate period. After the surface dries, the second

decreasing ratio term begins, and evaporation occurs inside of the product [4].

The drying of farm products containing high moisture usually creates a remarkable deformation effect. The shrinkage effect occurring in food products has a powerful impact on the drying ratio and on the structure of the dried food and is observable [5].

Fick's law of diffusion is used to describe the drying kinetics. The thin layer drying models obtained by using this law are frequently encountered in the literature. The Lewis model [6]; Henderson and Pabis model [7]; Two Term model [8]; Wang and Singh model [9]; Midilli model [10] can be given as examples. These models are classified as theoretical, semi-theoretical, and experimental. The drying process and kinetics of agricultural products have been investigated by many researchers in the literature [11]-[19]. The drying kinetics is important for determining the moisture content of the product and determining the drying time. At the same time, the quality of the dried products should be checked in order not to deteriorate. For this purpose, it is important to examine the quality parameters (colour, rehydration ratio, activation energy etc.) while determining the drying behavior of the products.

In the literature, it is possible to find many studies conducted separately on drying characteristic kinetic, colour analysis,

*Corresponding author/Yazışılan Yazar

drying models, activation energy, effective diffusion coefficient, and shrinkage effect. The studies conducted on the banana drying in the literature can be summarized as follows: Karim and Hawlader [11] improved a mathematical model working out the heat and mass transfer equalities during the drying of bananas with the forced convection in their study. With the data they obtained from the experiment, they confirmed the model they developed and conducted a parametric study for different drying conditions. They also calculated the effective diffusion coefficients of banana. Samadi et al. [12] examined the drying of banana of different thicknesses. Using mathematical models, they found the Midilli model to be the most suitable model for their study. Thuwanapicyanana et al. [13] explored the affect of temperature on banana drying. They also examined the drying rate, colour analysis, deformation, and product microstructure. Baini and Langrish [14] examined the effect of temperature and moisture content on the product diffusivity for the banana drying process. Nguyen and Price [15] examined the effects of test parameters such as temperature, moisture, and thickness on the drying of bananas. Fernando et al. [16] studied the impression of the thicknesses of different banana slices on the effective diffusion coefficient in the convective dryer. Silva et al. [17] used three different diffusion models to determine the drying. The researchers solved the diffusion equations analytically using boundary conditions and compared the results with the experimental study. Joardder et al. [18] used the IMCD (intermittent microwave convective) method to improve energy efficiency and drying quality. Multiphase porous media approach method has been developed describing heat and mass transfer mechanism. Finally, they discussed the change of evaporation and vapor pressure. Saha et al. [19] developed two diffusion models by adding the shrinkage effect. The authors recommended that the shrinkage effect should be added to the thin-layer dehydrate models for better drying results. And, they also examined the quality of the food during dehydration. In this study, the effect of drying air temperature in the drying process was investigated. Therefore, while choosing the air temperaure (40, 50 and 60 °C) and air velocity (0.5 ms^{-1}) it was preferred to be over the values used in the some studies in the literature [11],[20].

In the literature, colour measurement, effective diffusion coefficient calculation, application of drying models, activation energy, shrinkage calculation and numerical verification studies are discussed. In this study, it is aimed to contribute to academic and industrial users by calculating these values besides drying kinetics of the product experimentally. Moisture content and drying ratio of food were obtained during convective drying process for different air temperatures (40, 50 and 60 °C). Our study provides an approach to estimate colour due to moisture content during drying. The numerical model was proposed to estimate simultaneous moisture and temperature distribution inside the food product. Five drying models were also used to find the best fit to experimental data. Finally, it was determined effective diffusion coefficients, shrinkage coefficient and activation energy at the end of the six hour drying processes.

2 Material and methods

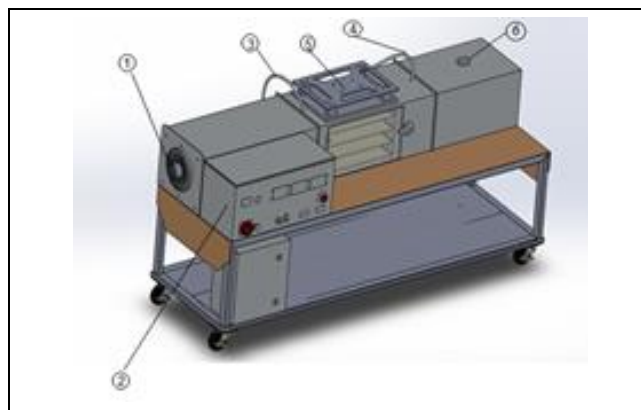
2.1 Material

In the experiments, bananas sold in a local market in Bursa (imported from Ecuador) were used. The purchased bananas were first held in the refrigerator at 4 °C for 24 hours. Then, they were left in the laboratory for 3 hours until they reached

the room temperature. First of all, bananas were sliced to 1 cm thickness as a disc shape. The diameter of the banana ranges from 2.5 cm to 3.5 cm.

2.2 Drying equipment and method

Drying processes were carried out by a convective tunnel type drier found in Uludag University Heat Engineering Laboratory. The experimental setup is illustrated in Figure 1.



(1): Fan (air inlet). (2): Automatic control unit (velocity, temperature, humidity, and weight). (3)-(4): Temperature, humidity and velocity sensors, (5): Balance.

Figure 1. Experimental set up of tunnel type convective dryer.

2.3 Determination of the initial moisture

For determination of the initial moisture content, banana slices weighing $351 \pm 0.05 \text{ g}$ were located in a dryer (Ogen, Turkey) and dehydrated at an air temperature of $75 \pm 0.3 \text{ °C}$. Drying was performed until the difference between the last two measurements became 1%. The average primary moisture content (on wet basis) of the product was obtained to be as 72%.

2.4 Drying of banana

The air temperatures ($40 \pm 0.3 \text{ °C}$, $50 \pm 0.3 \text{ °C}$ and $60 \pm 0.3 \text{ °C}$) and 0.5 m s^{-1} air velocity were used during experiments. In the meantime, the tunnel-type dryer was started until the steady regime was reached. The weight of empty tray ($33 \times 38 \text{ cm}$) was measured and recorded. When the required provisions were ensured, the tray was placed in the dryer chamber. The drying chamber was constructed as a rectangular tunnel in 34.5 cm height, 228 cm lenght, 40 cm width. During the experiment, the change in the weight of the product was registered periodically with a digital scale (Kern, Germany) with a sensitivity of 0.05 g. The experimental results were repeated three times. One side of the food was dried on the tray. Moisture is transferred from the surface of the product to the air while liquid diffusion reaches the surface from the inside product. Colour values (L, a and b) were measured in a colorimeter (PCE CSM 1-Germany with ± 0.08 sensitivity), while temperature measurement (± 0.5) was performed with temperature sensor (PCE 228-Germany). T-type thermocouple was used for center temperature measurement of the food. Center temperature was measured at the correct depth with a marker on the thermocouple and the measurement results were transferred to the data collector. and temperature value and colorimeter values (L, a, b) were recorded every half hour. For this, the average values of each colour parameter (L, a, b) were calculated by performing measurements from 5 different slices. Two trays of equal weight were prepared for each

experiment at different temperatures. One tray was used only for weighing and colour measurement while the other was for the temperature measurement.

2.5 Calculation of moisture content

In order to determine the moisture content of the food material on dry and wet basis, Eq. 1 and Eq. 2 expressions are defined as:

$$M_{DB} = \left(\frac{W_w}{W_{dr}} \right) = \left(\frac{W_w - W_{dr}}{W_{dr}} \right) \quad (1)$$

$$\%M_{WB} = \left(\frac{W_w}{W_w + W_{dr}} \right) \times 100 \quad (2)$$

Where W is initial weight (g) of the food, W_w is the water mass (g) in the food, and W_{dr} is the mass (g) of the dry product [21]. The drying ratio (DR), which is the change in the moisture of the dried food per unit of time, can be expressed as follows:

$$DR = \left(\frac{M_t - M_{t+\Delta t}}{\Delta t} \right) \quad (3)$$

Where M_t is the moisture content of the food according to the dry basis [g water (g dry matter)⁻¹] at t time, and $M_{t+\Delta t}$ is the moisture content of the food according to the dry basis at the $t + \Delta t$ time [21]. Dimensionless moisture ratios (MR) is related to moisture content as:

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad (4)$$

Where M_e [g water (g dry matter)⁻¹] is the equilibrium moisture content at the end of drying, and M_i [g water (g dry matter)⁻¹] is the initial moisture content. In the study, the dimensionless moisture ratio was simplified, and $MR = M_t/M_i$ was used [19]-[21].

2.6 Total colour change

The colour measurement help determine the freshness and quality of the product, the total colour deviation can be calculated using Eq. 5 [22].

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta b)^2 + (\Delta a)^2} \quad (5)$$

$$\Delta L = L_{fresh} - L_{dried}$$

$$\Delta a = a_{fresh} - a_{dried}$$

$$\Delta b = b_{fresh} - b_{dried}$$

2.7 Mathematical modelling for the numerical analysis

Fourier's and Fick's laws can be used to define the energy and mass balance in solids mathematically. While the heat from the air is conveyed to the food surface by convection, liquid in the product is transported to the surface by diffusion, and evaporation is observed. The energy conservation equation in solids based on Fourier's law can be given as follows;

$$\rho c_p \left(\frac{\partial T}{\partial t} \right) + \nabla(-k\nabla T) = 0 \quad (6)$$

Where c_p is specific heat of food [J (kg K)⁻¹], k is the thermal conductivity of food [W (mK)⁻¹], ρ is density of food [kg (m³)⁻¹] and the mass conservation equation in solids based on Fick's law can be given as follows [23]:

$$\frac{\partial C}{\partial t} + \nabla(-D_{eff}\nabla M) = 0 \quad (7)$$

Where D_{eff} is effective diffusion coefficient (m² s⁻¹) and M is the moisture content [g water (g dry matter)⁻¹].

2.7.1 Initial and boundary conditions

Beginning the first temperature and moisture content of food is 21 °C and 72%.

2.7.2 Heat transfer boundary conditions

The surface boundary condition for heat transfer is given by:

$$-n(-k\nabla T) = \lambda h_m(M - M_s) + h_t(T - T_s) \quad (8)$$

Where h_m is mass transfer coefficient (m s⁻¹), h_t is heat transfer coefficient [W (m²K)⁻¹], T_s is the drying air temperature (°C) and M_s is the moisture content of air [g water (g dry matter)⁻¹]. Symmetry boundary condition for heat transfer is given by:

$$n(k\nabla T) = 0 \quad (9)$$

2.7.3 Mass transfer boundary conditions

The surface boundary condition for mass transfer is written for balance between the liquid transfer from inside the food to the surface with diffusion and the vapour transfer from the food surface to the drying air.

$$-n(D\nabla M) = h_m(M - M_s) \quad (10)$$

Symmetry boundary condition for mass transfer is given by:

$$n(D\nabla M) = 0 \quad (11)$$

2.8 Shrinkage dependent effective diffusivity

The shrinkage effect was considered in the numerical model during drying. It is significant to examine the effect of the change in the product volume to calculate the diffusion coefficient. Shrinkage-dependent diffusivity is obtained by the following equation:

$$\frac{D_{ref}}{D_{eff}} = \left(\frac{b_0}{b} \right)^2 \quad (12)$$

Where D_{ref} is the reference diffusion coefficient (m² s⁻¹) which is determined experimentally, and b_0 and b are the half-thickness of the product at the beginning and t time [11],[20]. In order to find the D_{eff} coefficient depending on the shrinkage effect given in Eq.12, the thickness-ratio variation must be calculated from Eq. 13 [24].

$$b = b_0 \left[\frac{\rho_w + M\rho_s}{\rho_w + M_0\rho_s} \right] \quad (13)$$

Where M is the moisture content of food [g water (g dry matter)⁻¹] and M_0 is the initial moisture content of food [g water (g dry matter)⁻¹].

2.9 Determining of the heat and mass transfer coefficients

The heat and mass transfer coefficients are estimated with well-known correlations in the literature. While the heat convection coefficient is obtained with the Nusselt (Nu) number depending on the Reynolds (Re) and Prandtl (Pr) dimensionless numbers, the mass transport coefficient is calculated with the Sherwood (Sh) number depending on the Reynolds and Schmidt (Sc) dimensionless numbers [11],[20],[25].

$$Nu = \frac{h_T L}{k} = 0.664 Re^{0.5} Pr^{0.33} \quad (14)$$

$$Sh = \frac{h_M L}{D_{AB}} = 0.664 Re^{0.5} Sc^{0.33} \quad (15)$$

Where h_T is the heat transfer coefficient [W (m²K)⁻¹], L characteristic length (m) and k is the thermal coefficient [W/mK].

2.10 Data analysis

In the experiment, the comparison was made with different drying models for the verification of the data obtained for different temperatures. Different empirical (Wang and Singh), and semi-theoretical (Lewis, Henderson and Pabis, Two Term, Midilli) models widely used in the literature were applied [26],[27]. These equations are presented in Table 1. Statistical calculations were made with the Sigma Plot program. The drying coefficients (a, b, k, k₀, k₁, n) and the coefficients of determination (R²), standard error of estimate (SEE) and chi-square (x²) expressions, which are statistical parameters are calculated as [28]:

$$SEE = \sqrt{\frac{\sum_{i=1}^N (MR_{exp} - MR_{pred})^2}{N - z}} \quad (16)$$

$$x^2 = \frac{\sum_{i=1}^N (MR_{exp} - MR_{pred})^2}{N - z} \quad (17)$$

where MR_{exp} is experimental moisture ratio, MR_{pred} is the predicted moisture ratio, N is the number of experimental data points and z is the number of parameters in the model. To describe the most appropriate model, the R² value should be close to 1 and SEE and x² values should be close to 0 [29].

Mean differences for colour parameter were tested by using an JMP programme (Tukey HSD test) at 1% levels of significance.

2.11 Calculation of the effective diffusion coefficient and activation energy

Fick's law of diffusion is widely used in drying processes. Eq. 18 is used to determine the diffusion coefficient [30]:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L^2}\right) \quad (18)$$

Where, D_{eff} is the effective diffusion coefficient (m² s⁻¹), and L is the half-thickness (m) of the product. It can be explained by taking the initial term of the series given in Eq. 18 for different time periods [29].

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (19)$$

The inclination (i) is arranged by plotting of ln(MR) against drying time from Eq. 19.

$$i = \left(\frac{\pi^2 D_{eff}}{4L^2}\right) \quad (20)$$

Moisture bonding potential is used to define the drying characteristics of the product. This value is measured by the activation energy, which is the energy required to remove 1 mol moisture from the product [30]. The activation energy, E_0 , which is the starting energy of chemical reactions, can be arranged by the following equation;

$$D_{eff} = D_0 \exp\left(-\frac{E_0}{RT}\right) \quad (21)$$

Here R is universal gas constant [8.314×10⁻³ kJ (mol.K)⁻¹], T is temperature (K).

2.12 Calculation of food shrinkage

The shrinkage effect is widely observed in foods during the drying process. It affects the product property adversely. Therefore, it is important to consider this effect in the drying process.

The shrinkage coefficient (S_b) can be obtained using the following equation [31].

$$S_b = \left(1 - \frac{V_t}{V_0}\right) \times 100 \quad (22)$$

2.13 Uncertainty analysis of moisture content

An error may occur in the experimental work due to the measuring devices. Therefore, it is necessary to determine the total error value by performing the uncertainty analysis of the measurement results. Overall uncertainty can be calculated using the next phrase;

$$W_r = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2 \right]^{\frac{1}{2}} \quad (23)$$

$$e = \frac{W_r}{R} \quad (24)$$

Where, $R(x_1, x_2, x_3, \dots, x_n)$ is a function of independent variables, W_r overall uncertainty, $w_1, w_2, w_3, \dots, w_n$ are error values of independent variables and e relative uncertainty [20],[32].

To calculate the moisture content of the food on a dry basis, the dry product and initial weight must be measured on a precision balance. Therefore, relative uncertainty that take place in the calculation of the moisture content will only depend on the weight. The uncertainty analysis equation associated with moisture content (Eq. 1) of the food product using Eq. 23-24 is expressed as;

Table 1. Constants and coefficients.

Model No	Name of Model	Model	Reference
1	Lewis	MR=exp(-kt)	[6]
2	Henderson and Pabis	MR=aexp(-kt)	[7]
3	Two Term	MR=aexp(-k ₀ t)+bexp(-k ₁ t)	[8]
4	Wang and Singh	MR=1+at+bt ²	[9]
5	Midilli	MR=aexp(-kt ⁿ)+bt	[10]

MR: Moisture ratio. k, k₀, k₁: Drying constant (min⁻¹). a, b: Coefficient, n: drying constant.

$$e_m = \left\{ \left(\frac{\delta W}{W - W_{dr}} \right)^2 + \left(\frac{W \delta W_{dr}}{(W - W_{dr})W_{dr}} \right)^2 \right\}^{\frac{1}{2}} \quad (25)$$

Where δW and δW_{dr} is percentage error of weighing, W_{dr} is dry weight of the food, W is initial weight of the food. Using Eq. 25, the relative uncertainties for moisture content at 40-50 and 60 °C were obtained as $\pm 0.08\%$, $\pm 0.09\%$ and $\pm 0.12\%$, respectively.

Sensitivity values and total uncertainty values of the measuring devices are given in Table 2. While the uncertainty arising from the device is specified by the manufacturer among the characteristics of the device, the uncertainty arising from the incorrect reading of the person making the measurement is taken as experience [33].

2.14 Numerical study

The shape of the dried product is cylindrical. The two-dimensional axisymmetric model approach, which is used to facilitate the solution of cylindrical models in a short time, was used in this study. A two-dimensional axisymmetric model was used to identify the simultaneous heat and mass transfer equations in the hot air convection drying process. Due to the axisymmetry of the food slabs, only one quarter of planer intersection was taken into consideration in the numerical method. It is observed in the literature that this model approach has been used in some numerical drying studies [20], [23],[38]. This model is established on the following hypotheses:

- Initially, the moisture content and the temperature value inside of the food were accepted to be homogeneous,
- The heat transfer in the food was considered by conduction, and mass transfer occurred with diffusion,
- The heat transfer occurred with convection from air to food and conduction inside the food, and the mass transfer took place with diffusion and convection from solid to air,
- The shrinkage effect was considered during the drying process,
- The radiation effect was neglected,
- The thermophysical properties of the air and food density were taken to be constant during the drying period.

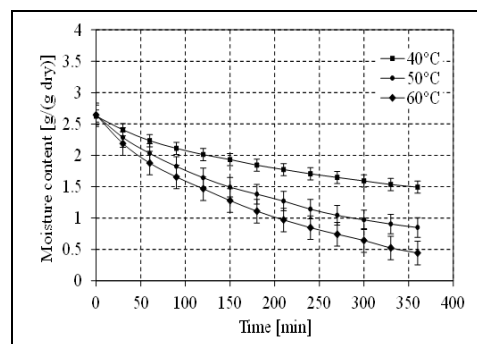
First of all, to find the optimal mesh structure of the model, the mesh independence study was performed with a sensitivity of 0.001. 1256 triangular mesh structure was found to be the most appropriate. Non-linear equations were solved using the finite element method (Comsol Multiphysics™ 5.3, Comsol AB, Stockholm, Sweden [39] with boundary and initial conditions for the drying air. The equations were calculated with a tolerance value of 0.001 for 30-minute time steps. The initial inlet conditions used in the analysis and the thermophysical characteristics of the food are demonstrated in Table 3.

3 Results and discussion

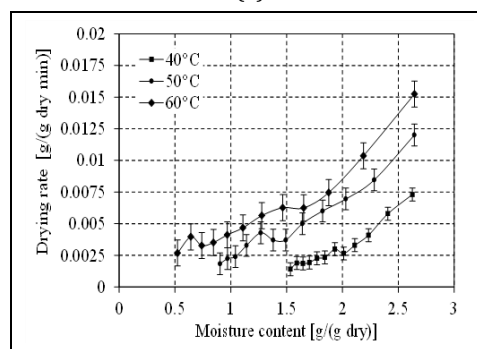
The moisture content (dry basis) under convective drying conditions is presented in Figure 2(a) at an drying air temperature 40, 50 and 60 °C and 0.5 m/s air velocity. It is clearly showed that drying at higher air temperatures results in lower moisture content. The moisture content values are found

to be 1.49, 0.84 and 0.44 [g (g dry)⁻¹] at the drying air temperature of 40, 50 and 60 °C at the end of the drying process.

The drying rates of banana slices as a function of moisture content are presented in Figure 2(b). The average drying rates for 40, 50, and 60 °C were calculated to be as 0.0031, 0.0049 and 0.0061 [g (g dry min)⁻¹], respectively.



(a)



(b)

Figure 2. (a): Moisture profile against drying time. (b): Drying rate-moisture content relationship of banana for different drying temperatures (40, 50 and 60 °C) and at constant air velocity 0.5 m s⁻¹.

It is clear that increasing drying air temperature rised drying rate.

From these figures, it can be stated that air temperature has a considerable effect on drying rates. Initial drying rate increased from 0.00730 [g (g dry min)⁻¹] to 0.01524 [g (g dry min)⁻¹] for increasing temperature from 40 to 60°C at 0.5 m s⁻¹.

As it can be seen in Figure 2, the invariable rate interval was not discovered in the drying curved but moisture content decreased substantially during the initial stages of drying because the liquid on the surface of the food has evaporated quickly. It was observed that an increase occurred in the drying rate at a higher temperature.

The temperature increase of 10 °C increased the drying rate by an average of 1.3 times. It is observed that drying occurs in the falling rate period for 3 temperature values. This region cannot be observed since the drying phase is very short at the constant rate in the drying of bananas. The actual drying process occurs in the falling rate period when the diffusion effect is observed [13]. Since the moisture content in the product decreases throughout the drying process at different temperatures, the drying rate also decreases in time. The decreased drying rate trend is also compatible with the results of some studies in the literature [11],[35]-[37].

Table 2. Total uncertainty values of the measuring devices used in the drying test.

Device	Parameter	Accuracy (\pm)	Uncertainty (\pm)	Overall uncertainty (\pm)
Dryer	Air temperature	0.3 °C	0.1	0.3162
	Air velocity	0.1 m s ⁻¹	0.1	0.1414
	Air relative humidity	%1.8 (RH)	0.01	0.0205
Temperature sensor	Food temperature	0.5 °C	0.1	0.5099
Digital scale	Food weight	0.05 g	0.01	0.0509
Colorimeter	Food colour change	0.08	0.1	0.1281

Table 3. Thermophysical properties and experimental drying conditions of the banana [11],[25],[34].

Parameter	Value
Air velocity [m(s) ⁻¹]	0.5
Food temperature (°C)	21
Food density [kg (m) ⁻³]	980
Air temperature (°C)	40-50-60
Food moisture content (% w.b.)	72
Air moisture content (%)	16.1(40 °C)-10.7(50 °C)-8.2(60 °C)
Thermal conductivity of food [W (mK) ⁻¹]	0.006M+0.120
Specific heat [J (kgK) ⁻¹]	0.811M ² -24.75M+1742
Heat of vaporization [kJ (kg) ⁻¹]	2454
Water density [kg (m) ⁻³]	998

M, Moisture content g (g dry)⁻¹.

Figure 2 also demonstrates that drying occurs in the falling rate period for different air temperatures. In the falling rate period, the drying rate of banana is appeared a sharp decline at the early stage of the drying process. It is appeared diffusion effect in this period. As soon as the water has been transported, the drying rate tends progressively to decrease [13],[17].

3.1 Validation study

The numerical model was verified by comparing the moisture content (on wet basis) and temperature values obtained from experiments. Figure 3 presents the variation of the average moisture content (on wet basis) values obtained from the experiment and the numerical analysis (with shrinkage) for different drying air temperatures. A difference of approximately 2.2% (40 °C), 2.9% (50 °C) and 6.8% (60 °C) was observed during drying period. Simultaneously, numerical analysis was performed for without shrinkage case. The results of the numerical model with-shrinkage and without-shrinkage cases are also presented in Figure 3(b). For example, approximately 2% difference was obtained for the numerical results of with-shrinkage and without-shrinkage cases for the moisture content of the food.

Food temperature for different air temperatures during drying interval is presented in Figure 4. The average difference between the center temperature values of the product obtained from the experiments and numerical simulation was found to be 7, 8 and 5% for air temperatures of 40 °C, 50 °C and 60 °C, separately. Using the Comsol Multiphysics™ 5.3, the temperatures were obtained at different location of food.

Figure 4(b) indicates the predicted food temperatures at surface (x/b=1), central (x/b=0) and midpoint (x/b=0.5). Center temperature measured experimentally was also plotted in Figure 4(b).

Numerical results (center, surface and midpoint temperatures) show close agreement with each other. As a result, it can be said that there is a suitable coherency between numerical and experimental solutions. Since the moisture distribution inside food is variable, it is difficult to calculate moisture content experimentally, the center. If the dry state cannot be provided, liquid remaining inside food causes to form microorganisms in

the food [20]. However, the moisture distribution in the food can be estimated by using simulation. The amount of evaporation from the food surface is higher when compared to the center.

3.2 Colour measurement results

Figure 5 represents variation with moisture content of the measured colour parameter values L, a, and b for 3 diversified air temperatures (40, 50 and 60 °C). According to these results, it can be said that as the air temperature raises and moisture content decreases, the brightness (L) value of the food decreases remarkably. It was observed that for each air temperature, the value a of the food increased and the value b decreased from Figure 5 and Table 4.

It can also be mentioned that the redness (a) of the food increased while the yellowness (b) decreased during drying period. Equivalent results were obtained in the literature for increase of air temperature in banana drying [13].

When a (red colour) parameter exceeds the value of +3, the food begins to lose yellowness and greenness. If drying is continued, an increase is seen in the redness of the food. This phenomenon is caused by the separation between chlorophyll and carotenoid pigments [22]. Some results obtained in the drying of different foods in the literature are as follows; it was viewed that the L value decreased and a and b increased with the temperature in bean drying [40]. Also, it was discovered that L, a, and b values decreased in date palm and tomato drying [37].

The total colour changes for the food at 40, 50 and 60 °C were calculated to be 24.9±(1.56), 29.1±(2.42) and 31.27±(2.58), respectively.

According to these results, it is seen that the colour change value increases as the drying air temperature rises. Because of browning effect, L parameter increases with temperature. It can be said that total colour changes increase is mainly caused by the change in the parameters of brightness and redness [41]. As a result, it can be considered that the air temperature is especially effective on the L, a, and b colour parameters in the tunnel-type convective dryer.

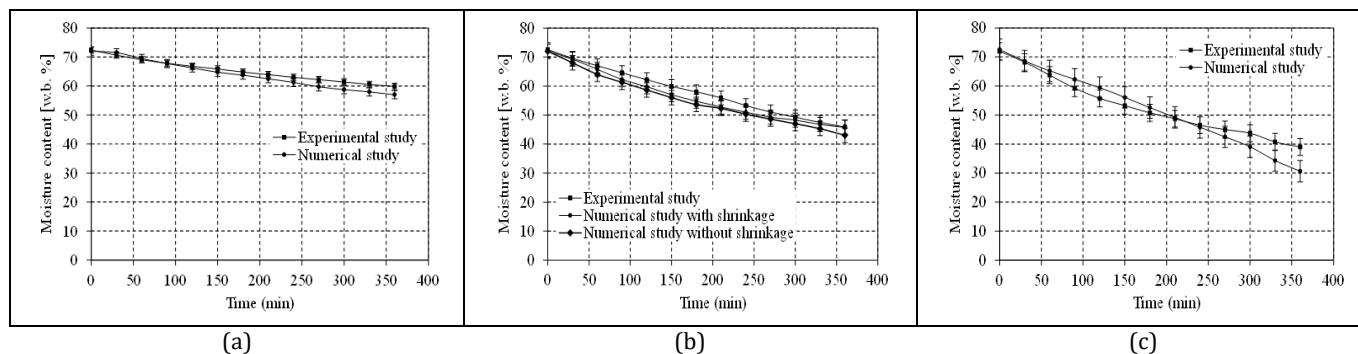


Figure 3. Moisture content (on wet basis)- time relationship of banana at different air temperatures (a- 40 °C, b-50 °C, c-60 °C) and air velocity of 0.5 m s⁻¹.

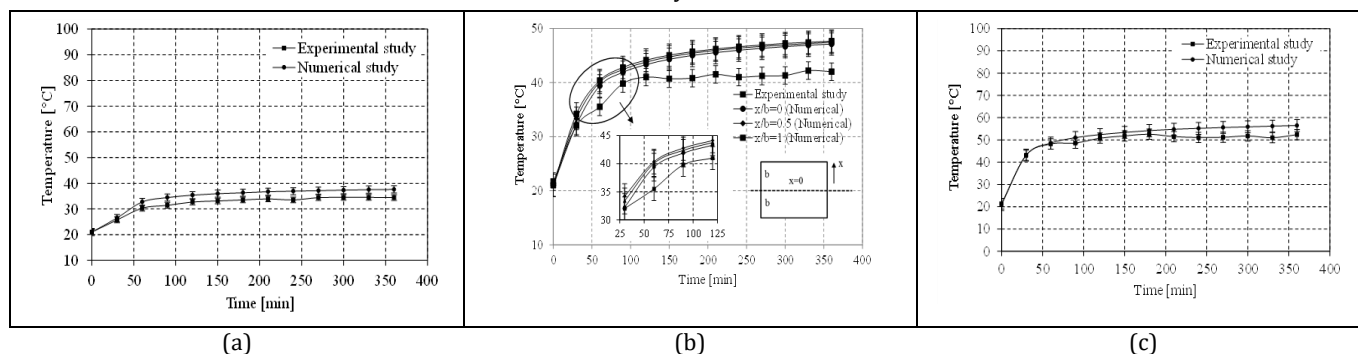


Figure 4. Temperature-time relationship of banana slice for air temperatures (a- 40 °C, b-50 °C, c-60 °C) and air velocity of 0.5 m s⁻¹.

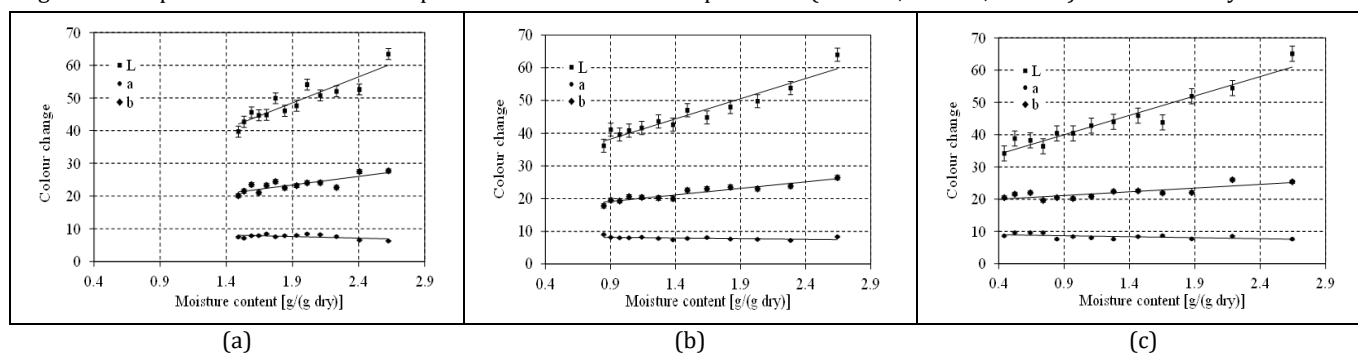


Figure 5. Colour change-moisture content (dry basis) relationship for different air temperatures (a- 40 °C, b-50 °C, c-60 °C) and air velocity of 0.5 m s⁻¹

Table 4. Colour parameter (*L*, *a*, *b*) and colour deviation values of fresh and dry banana slices.

Parameter		<i>L</i> **	<i>a</i> **	<i>b</i> **	ΔE **
40 °C	Fresh	63.4±(0.97) ^a	6.24±(0.31) ^a	27.7±(0.6) ^a	24.9±(1.56) ^a
	Dried	39.7±(1.98) ^b	7.44±(0.37) ^a	20.1±(0.5) ^a	
50 °C	Fresh	64±(2.12) ^a	8.34±(0.31) ^a	26.42±(0.19) ^a	29.1±(2.42) ^a
	Dried	36.1±(2.32) ^b	9±(0.96) ^a	17.8±(0.94) ^a	
60 °C	Fresh	65.07±(1.83) ^a	7.6±(0.51) ^a	25.4±(0.4) ^a	31.27±(2.58) ^a
	Dried	34.2±(1.93) ^b	8.6±(0.74) ^a	20.5±(0.5) ^a	

L, brightness; *a*, red colour value; *b*, yellow colour value; ΔE , colour deviation.

***P*<0.01; Column mean values with different superscripts are significantly different.

3.3 Drying characteristic of banana

Moisture contents were fitted to the five drying models. The statistical results obtained from these models for $P < 0.001$ were presented collectively in Table 5.

For the air temperature of 40 °C, R^2 , SEE, and χ^2 values in the Two Term and Midilli model were calculated to be 0.99, 0.0021, and 4.5×10^{-6} and 0.99, 0.0029 and 8.4×10^{-6} , respectively. For the air temperature of 50 °C, the R^2 , SEE, and χ^2 values in the Midilli model were calculated to be 0.99, 0.0041 and 1.6×10^{-5} , respectively. For 60 °C, the R^2 , SEE, and χ^2 values in the Midilli model were calculated to be 0.99, 0.0038 and 1.4×10^{-5} , respectively. The thin layer model where R^2 value is the closest to 1 and SEE, χ^2 values is the smallest is the Midilli model. According to these results, it can be said that the Midilli model gives better predictions among the other models and is the most appropriate model.

3.4 Calculation of the effective diffusion coefficient activation energy and shrinkage coefficient

From Eq. 6, the effective diffusion coefficient for the air temperatures of 40, 50 and 60 °C was obtained to be 2.02×10^{-10} , 5.05×10^{-10} and $8.08 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$, respectively. In most of the banana drying studies notified in the literature, it was shown that the effective diffusion coefficients varied between 10^{-9} and $10^{-11} \text{ m}^2 \text{ s}^{-1}$ [11],[13]. The relationship between the effective diffusion coefficient and the air temperature was found to be $\text{Deff} = 0.303T - 10.1$ and $R^2 = 1$ (Figure 6(b)). It can be seen that increasing the air temperature causes an increase in the effective diffusion coefficient [11]. The activation energy was computed using the slope of the $\ln(\text{Deff}) - 1/T$ graph shown in Figure 6(a) and was found to be $61.1 \text{ kJ} (\text{mol})^{-1}$. The activation energies of most foods vary from $12.7 \text{ kJ} (\text{mol})^{-1}$ to $110 \text{ kJ} (\text{mol})^{-1}$ [42].

The shrinkage effect should be considered to understand the drying kinetics of the food. Samples dried at each temperature value (40, 50 and 60 °C) were used for the examination of the shrinkage effect occurring in the food. The shrinkage coefficients in the food for the drying air temperatures of 40, 50 and 60 °C were found to be approximately 23%, 32%, and 40% respectively. The volumetric change of approximately 8.5% occurred in the food at every 10 °C temperature increase. Figure 7 illustrates the relationship between the moisture

content and the shrinkage coefficient. According to these results, it can be said that the drying air temperature is an effective argument on the food shrinkage [43].

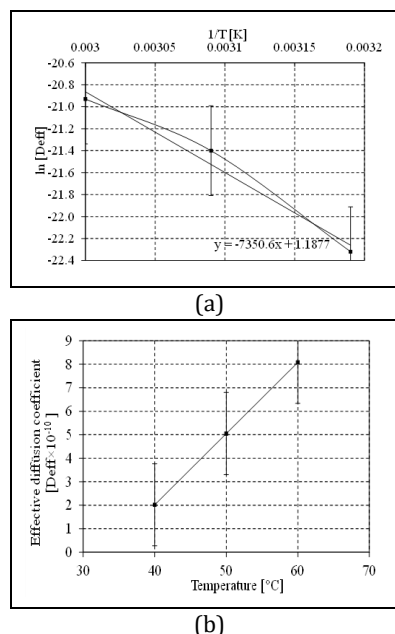


Figure 6. (a): The variation of effective diffusion coefficient with temperature (1/T). (b): Effective diffusion coefficient versus air temperature.

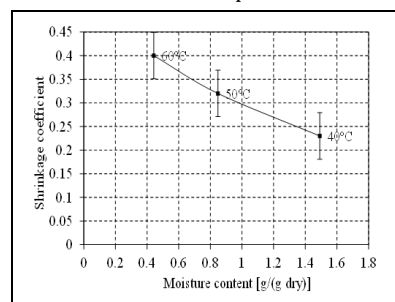


Figure 7. Experimental moisture content-shrinkage coefficient relationship of banana at varied air temperatures and air velocity of 0.5 m s⁻¹.

Table 5. Statistical parameter values and coefficients.

Model	40 °C			50 °C			60 °C		
	R^2	SEE	χ^2	R^2	SEE	χ^2	R^2	SEE	χ^2
1	0.94	0.0315	1.0×10^{-3}	0.98	0.0274	8.0×10^{-4}	0.99	0.0171	3.0×10^{-4}
2	0.97	0.0223	5.0×10^{-3}	0.99	0.0213	5.0×10^{-4}	0.99	0.0137	2.0×10^{-4}
3	0.99	0.0021	4.5×10^{-6}	0.99	0.0047	2.1×10^{-5}	0.99	0.0084	7.0×10^{-5}
4	0.99	0.0119	1.0×10^{-4}	0.99	0.0160	3.0×10^{-4}	0.99	0.0224	5.0×10^{-4}
5	0.99	0.0029	8.4×10^{-6}	0.99	0.0041	1.6×10^{-5}	0.99	0.0038	1.4×10^{-5}
1	$k = 1.8 \times 10^{-3}$			$k = 3.5 \times 10^{-2}$			$k = 4.9 \times 10^{-3}$		
2	$k = 1.6 \times 10^{-3}$			$k = 3.3 \times 10^{-3}$			$k = 4.7 \times 10^{-3}$		
3	$a = 1.4 \times 10^{-2}$			$a = 1.7 \times 10^{-1}$			$a = 9.4 \times 10^{-1}$		
4	$k_0 = 1.5 \times 10^{-2}$			$k_0 = 1.6 \times 10^{-2}$			$k_0 = 4.6 \times 10^{-3}$		
5	$a = -2.0 \times 10^{-3}$			$a = -3.3 \times 10^{-3}$			$a = -3.9 \times 10^{-3}$		
	$b = 2.0 \times 10^{-4}$			$b = 2.0 \times 10^0$			$b = 1.0 \times 10^0$		
	$n = 7.7 \times 10^{-1}$			$n = 8.5 \times 10^{-1}$			$n = 7.8 \times 10^{-1}$		

R^2 , coefficient of determination; SEE, Standard error of estimate; χ^2 , chi-square; k, k_0 , k_1 , drying constant (min^{-1}); a, b, coefficients; n, drying constant.

4 Conclusions

The drying kinetics of banana was looked into in this study. Some remarkable results obtained from the study can be briefly summarized as follows;

It was observed that the air temperature have a great effect on the drying rate. The drying of bananas occurred only in the falling rate period for all temperatures and there is no constant rate period of drying.

As a result of the nonlinear regression analysis, it can be said that the best model in describing the drying kinetics of banana is the Midilli model.

It was detected that for drying air temperatures, the L and b value decreased, a value increased. The maximum darkening of the food colour occurred at 60 °C. Furthermore, total colour change of the food were calculated, and the maximum deviation occurred with 31.27 ± 2.58 at 60 °C. The closest conditions to the fresh food were obtained at 60 °C for yellowness and at 50 °C for redness.

The effective diffusion coefficients of 40, 50 and 60 °C air temperatures were found to be 2.02×10^{-10} , 5.05×10^{-10} , and $8.08 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$, respectively. According to this result, it was determined that the drying air temperature was an efficient parameter on the effective diffusion coefficient. Moisture diffusivity in agricultural products is an important feature in areas where mass transfer is effective, such as drying and storage. The activation energy of the banana was computed to be $61.1 \text{ kJ (mol)}^{-1}$.

The shrinkage coefficient was accounted for the change in the food volume, and the maximum volumetric change was indicated with 40% at 60°C air temperature. Shrinkage coefficient was increased by increasing air temperature. It can be said that air temperature is an effective parameter on drying. The reduction in food volume during drying is important in terms of transportation costs.

Experimental and numerical solutions were compared and it is shown that it is a good coherence between experimental and numerical results. The numerical model can be used to determine the moisture and temperature distribution at any location inside food during drying. Therefore, it can become possible to prevent this deterioration by using a numerical solution when the moisture distribution inside the food cannot be determined experimentally.

It is suggested that investigation into drying of food should be carried out with hot air and infrared dryers. The effect of exergy efficiency on drying can be examined. In addition, the numerical method used in this study will provide useful data on food drying for both academic and industrial users.

5 Nomenclature

C	: Colour parameter,
c_p	: Specific heat [kJ (kgK) ⁻¹],
D_{AB}	: Binary diffusion coefficient (water-air) [m ² (s) ⁻¹],
D_{eff}	: effective moisture diffusivity [m ² (s) ⁻¹],
DR	: Drying rate [g water (g dry matter min) ⁻¹],
D_o	: Coefficient,
E_o	: Aktivation energy [kJ (mol) ⁻¹],
h_m	: Mass transfer coefficient [m (s) ⁻¹],
h_t	: Heat transfer coefficient [W (m ² K) ⁻¹],
k	: Thermal conductivity of food [W (mK) ⁻¹],
L	: Lenght (m),

MR	: Moisture ratio,
N	: Number of experimental data points,
Nu	: Nusselt number= $[h_t L (k)^{-1}]$,
Pr	: Prandtl number= $[\gamma (\alpha)^{-1}]$,
R	: Universal gas constant [kJ (mol.K) ⁻¹],
Re	: Reynolds number = $[uL (\gamma)^{-1}]$,
R^2	: Coefficient of determination,
S_b	: Shrinkage coefficient (%),
Sc	: Schmidt number= $[\gamma (D_{AB})^{-1}]$,
Sh	: Sherwood number= $[h_m L (D_{AB})^{-1}]$,
SEE	: Standard error of estimate,
t	: Drying time (min.),
T	: Temperature (K),
u	: Air velocity [m (s) ⁻¹],
V	: Volume (m ³),
χ^2	: Chi-square,
α	: Coefficient of thermal expansion [m ² (s) ⁻²],
Δa	: Red colour deviation,
Δb	: Yellow colour deviation,
ΔE	: Total colour deviation,
λ	: Enthalpy of evaporation [J (kg) ⁻¹],
ρ	: Density [kg (m) ⁻³],
γ	: Viscosity [m ² (s) ⁻¹].

Subscripts

b, o	: Initial, reference,
e	: Equilibrium,
h	: Air,
DB	: Dry basis,
s	: Solid, surface,
t	: Time, moment,
$t+\Delta t$: $t+\Delta t$ moment,
w	: Water,
WB	: Wet basis.

6 References

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