Hindawi
Journal of Food Quality
Volume 2023, Article ID 7426793, 12 pages
https://doi.org/10.1155/2023/7426793

Research Article

The Effect of Drying Temperature and Thickness on the Drying Kinetic, Antioxidant Activity, Phenolic Compounds, and Color Values of Apple Slices

Engin Demiray,[1] **Julide Gamze Yazar**,[1] **Özgür Aktok**,[1] **Burçin Çulluk**,[1] **Gülşah Çalışkan Koç**,[2] **and Ravi Pandiselvam**[3]

[1]*Department of Food Engineering, Faculty of Engineering, Pamukkale University, Kinikli, Denizli 20160, Turkey*
[2]*Uşak University, Eşme Vocational High School, Food Processing Department, Food Technology Program, Eşme, Uşak, 64600, Turkey*
[3]*Physiology, Biochemistry and Post-Harvest Technology Division, ICAR-Central Plantation Crops Research Institute, Kasaragod 671124, Kerala, India*

Correspondence should be addressed to Ravi Pandiselvam; r.pandiselvam@icar.gov.in

Received 18 July 2022; Revised 14 February 2023; Accepted 5 April 2023; Published 26 April 2023

Academic Editor: Ayon Tarafdar

Dried fruit slices are important, healthy, and popular snacks and gain importance day by day due to their high nutritional content. In this context, this study mainly focused on the production of healthy apple chips snacks and the determination of degradation kinetics of antioxidant activity, total phenolic compounds, and color values of apple chip snacks during convective hot air drying at three different temperatures (45, 55, and 65°C) and sample thicknesses (1.5 and 5 ± 0.5 mm). The drying kinetics, desorption isotherms, activation energy, and half-life of the apple chip snack were also calculated. The Page and GAB models are the best models for the determination of the drying (>0.992) and desorption (>0.9979) behavior of apple snacks with the highest R^2 values. The drying of all samples took place in the falling rate period. The D_{eff} values increased depending on the increasing air temperature and slice thickness. The antioxidant activity, total phenolic compounds, and total color change of the 5 mm thick samples were degraded following the first-order reaction kinetics. The higher antioxidant activity, phenolic compounds, L^* values, and lower half-life values were observed in conditions where the thickness (1.5 mm) and temperature (45°C) are low. The activation energy values calculated for the total phenolic compounds are higher than those calculated for the antioxidant activity. As a result, it can be concluded that apple chip snacks with high nutritional value can be produced by choosing low temperatures and slice thickness.

1. Introduction

Apple is a very popular fruit consumed both in season and out of season. The high nutritional value (ascorbic acid and polyphenol contents, and antioxidant activity), health-promoting effects (cardioprotective effects, and so on), and the desired taste are among the reasons for the preference for this fruit [1–3]. Apple chip snack, as a novel food product, has desired crispy taste and high nutritional value, and flavor. Apple chip snacks can be obtained by hot air drying, freeze-drying, puffing drying, or combined drying techniques such as hot air drying + puffing drying [4]. Zhu et al. [4] reported that the hot air + CO_2 puffing dried apple chip snacks have a higher rehydration rate, and sensorial and textural properties compared to other drying techniques. In addition, several studies related to the development of functional apple snacks using emerging technologies such as vacuum impregnation [5–7], ohmic heating [7], and novel integrated freeze-drying process [8], are in the literature.

Hot air drying is a suitable technique for the production of apple chip snacks because of providing uniform hot air and temperature distribution over the product, the simplicity of the process, ease of the production, low energy consumption and drying time, and is cheap [9]. The air

temperature, airflow rate, relative humidity, and product thickness are important factors in terms of both determinations of drying behavior and the quality (color, total phenolic content, and antioxidant activity) of the product [9–11]. For this reason, the effect of process parameters has to be investigated and optimum conditions have to be determined. When the studies were examined, although there were studies in which different methods were used to obtain apple chips, there was no study examining the change in the phenolic content and antioxidant activity of apples during the drying process. The aim of this study is to determine the effect of different drying temperatures (45, 55, and 65°C) and thicknesses (1.5 and 5 ± 0.5 mm) on the drying kinetics, drying rate, effective moisture diffusivity, color, antioxidant activity, and total phenolic compounds of apple chip snacks. In addition, desorption isotherms and color, antioxidant activity, and total phenolic degradations during drying were also investigated. The activation energy and half-life of the apple slices were also calculated.

2. Material and Methods

2.1. Material. Granny Smith variety of apples (12 ± 1 cm) that were at the same maturity level were supplied from Pamukkale/Denizli. The apples were taken from equal sizes as much as possible and stored in the refrigerator (4°C) until drying. The apples were washed, dried, peeled, and inedible parts were removed. The thickness of the apple slices was determined using a caliper, and the apples were sliced with a knife (1.5 and 5 ± 0.5 mm).

2.2. Methods

2.2.1. Drying Apple Slices with Hot Air. The apple slices were dried at three different drying temperatures (45, 55, and 65°C) and constant air velocity (0.2 m/s) in a drying cabinet (Yücebaş Makine Tic. Ltd. Şti., İzmir, Turkey). From the beginning, the tray used for weighing was removed from the dryer every 30 min and weighed, and the data were recorded. After drying, the product was first kept at room temperature for 30 minutes in the desiccator, then at 4°C for 1 hour, and then cooled and frozen at −20°C. During the drying process (every 30 min), the total antioxidant and total phenolic compounds, and color values were determined.

Drying kinetics were determined and effective moisture diffusivity (D_{eff}) and activation energy (E_a) values were calculated.

Moisture content (equation (1)) and drying rate (equation (2)) were calculated according to the given equations:

$$M_t = \frac{m - \text{DM}}{\text{DM}}, \tag{1}$$

$$\text{Drying Rate (DR)} = \frac{M_{t+\text{d}t} - M_t}{\text{d}t}, \tag{2}$$

where M_t is the moisture content at any time t (kg water/kg dry matter (DM)), m is the weight of the sample (g), DM is the amount of DM contained in the sample (g), $M_{t+\text{d}t}$ is the moisture content at time $t + \text{d}t$ (kg water/kg DM), and dt is the drying time (min).

D_{eff} was calculated according to Fick's second law (equation (3)); the series was simplified and the first term was used [12].

$$\begin{aligned}\text{MR} &= \frac{M - M_e}{M_0 - M_e} \\ &= \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-(2n+1)^2 \frac{\pi^2}{4} \frac{D_{\text{eff}} t}{L^2}\right],\end{aligned} \tag{3}$$

where t is the time (s), D_{eff} is the effective moisture diffusivity (m^2/s), L is the thickness (m). For long drying times (MR < 0.6), a limiting case of equation (3) was assumed and expressed in the logarithmic form as in the following equation:

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

where D_{eff} is typically calculated by plotting the experimental moisture ratio in the logarithmic form versus drying time. From equation (4), a plot of lnMR versus drying time gives a straight line with a slope of the following equation:

$$\text{Slope} = \frac{\pi^2 D_{\text{eff}}}{4\text{L}^2}. \tag{5}$$

The relationship between the D_{eff} and the air temperature was assumed to be the Arrhenius function and E_a was calculated using the following equation:

$$D_{\text{eff}} = D_0 \exp\left(-\frac{E_a}{\text{RT}}\right), \tag{6}$$

where D_0 is the preexponential factor (m^2/s), E_a is the activation energy (kJ/mol), T is the absolute temperature (K), and R is the gas constant ($R = 8.31451$ J/molK).

2.2.2. Modeling Studies of the Drying Kinetics. The selected thin-layer drying models are shown in Table 1. The fit of the models was determined by the regression coefficient (R^2), the error of the root mean square (RMSE), and the chi-square (χ^2) values [12].

2.2.3. Modeling of the Desorption Isotherms. The models used to determine the moisture sorption isotherms of foods are given in Table 1. The parameters (k, C, and M_0) of the sorption models were determined from the experimental data by nonlinear regression analysis using the Microsoft Excel program (MS Office Excel 2016). The fit of the models was determined by the regression coefficient (R^2), the error of the root mean square (RMSE), and the chi-square (χ^2) values.

Table 1: Thin layer drying and desorption models.

Models		Equation	Reference
Thin layer drying models	Page	$MR = \exp(-kt^n)$	[13]
	Henderson and Pabis	$MR = a \exp(-kt)$	[14]
	Lewis	$MR = \exp(-kt)$	[15]
	Logarithmic	$MR = a \exp(-kt) + b$	[16]
Desorption models	Guggenheim, Anderson and de Boer (GAB)	$M = (M_0 Cka_w/[(1-ka_w)(1-ka_w+Cka_w)])$	[17]
	Braunauer, Emmett and Teller (BET)	$M = (M_0 Cka_w/[(1-a_w)(1+(C-1)a_w)])$	[18]
	Oswin	$M = k(a_w/1-a_w)^n$	[19]
	Henderson	$M = k(-\ln(1-a_w)/C)^{(1/n)}$	[20]
	Halsey	$M = (-C/\ln a_w)^{(1/n)}$	[21]

2.2.4. Analysis

(1) Water Activity Measurement. The water activity values of fresh and dried apple slices were determined using a water activity measuring device (GBX, Fast-Lab, France) with an accuracy of ±0.001.

(2) Preparation of Extracts. In order to obtain the extract, approximately 2 g of apples were taken during the drying process and crushed with a mortar. The crushed samples were taken into flasks and 10 mL of 70% ethanol was added. It was exposed to ultrasonication in an ultrasonic water bath (Wise Clean Wisd WUC-D06H, Daihan, South Korea) for 10 min, then agitated for 15 min in an orbital shaker (SHO-1D, Daihan, South Korea) at 200 rpm and centrifuged for 10 minutes at 10°C at 7450 rpm (NF 800R, Nüve, Turkey). The upper phase was taken into a 25 mL flask, the remaining residue was passed through the same processes again and the obtained upper combined with the previous one, and the extract was completed with 70% ethanol to 25 mL volume. The prepared extracts were stored at −20°C.

(3) Determination of Antioxidant Activity by DPPH Method. DPPH stock solution was prepared in methanol with a final concentration of 24 mg/100 mL. The solution was diluted with methanol by diluting the stock solution so that the final absorbance was 1.20 ± 0.02. The calibration curve was obtained with Trolox®. Trolox® solution was prepared with a concentration of 12.5 mg/25 mL and a final concentration of less than 50 μM in the spectrophotometer cuvette for the Trolox® calibration curve. In the experiments, 150 μL of the sample or standard 2850 μL of DPPH working solution was mixed in test tube and the reaction was continued for 60 minutes in a dark environment. At the end of the time, the absorbance was read in a spectrophotometer (EMC-11, Duisburg, Germany) at a wavelength of 515 nm. Samples that did not fall within the calibration curve range at the end of the reading were diluted until they entered this range [22].

(4) Determination of Total Phenolic Compounds. The Folin–Ciocalteu (FC) method has used the determination of the total phenolic compounds of samples. The Folin–Ciocalteu agent was diluted 1 : 10 by volume using distilled water. To prepare the sodium carbonate solution (20%), sodium carbonate was weighed to 75 g/L and the measuring flask was filled to the volume line with distilled water. In order to prepare the gallic acid calibration curve, 500 mg/L stock solution was prepared and dilution was made so that the final concentration was 5–100 mg/L in the linear region. 2 mL of sample or standard was taken and 10 mL of diluted FC agent was added. 8 mL of 20% sodium carbonate was added between 1–8 minutes after the reaction started and the mixture was left in a dark environment for 2 hours. At the end of the period, absorbances were read at 760 nm wavelength. If the results read did not fall within the calibration curve, necessary dilutions were made [23].

(5) Color Measurement. The color values of the samples were measured with a colorimeter (Hunter Associates Laboratory, Model: MiniScan XE, USA). In addition, Hue Angle, Chroma, and total color change (ΔE) values were calculated [24].

2.2.5. Modeling Studies for Investigation of Bioactive Components and Color Changes

(1) Kinetic Models. The zero-order, first-order, and second-order kinetic models were presented in equations (7–9), respectively.

$$C = C_0 \pm k_0 * t, \tag{7}$$

$$C = C_0 * \exp(\pm k_1 * t), \tag{8}$$

$$\frac{1}{C} = \frac{1}{C_0} \pm k_2 * t. \tag{9}$$

where C is the value of bioactive component or color parameter at any time t, C_0 is the bioactive component or color parameter value at time $t = 0$, k_0, k_1, and k_2 are the kinetic constants (1/min), and t is the drying time (min).

The degree of dependence of the reaction on temperature was determined by calculating both Q_{10} and activation energy values. The relationship between reaction rate and temperature was defined by Arrhenius in 1889, and this expression, which is still valid today, is given in equation (10). The activation energy was calculated using this equation. E_a was calculated by using the slope of the line obtained by drawing the $1/T$-ln$k$ graph:

$$k = k_0 * \exp\left(\frac{-E_a}{\mathrm{RT}}\right), \quad (10)$$

where k is the kinetic constant (min^{-1}), k_o is the Arrhenius constant or frequency factor, R is the gas constant (8.314 J/mol·K), and T is the temperature (K).

2.2.6. Calculation of the Q_{10} Value and Half-Life Time. Q_{10} value, which is another kinetic coefficient showing the dependence of the reaction on temperature, is a criterion that shows the effect of increasing the temperature by 10°C on the reaction rate [23] and was calculated using the following equation:

$$Q_{10} = \left(\frac{k_2}{k_1}\right)^{\left(10/T_2 - T_1\right)}, \quad (11)$$

where k_1 is the kinetic constant at temperature T_1 (1/min), k_2 is the kinetic constant at temperature T_2 (1/min), T_1 and T_2 are the temperatures (K).

Half-life time is the time required for the loss of 50% of the bioactive components [23]; for the first-order reactions, it is presented in the following equation:

$$t_{(1/2)} = -\ln(0.5) * k^{-1}. \quad (12)$$

2.2.7. Statistical Analysis. The data obtained as a result of the experiments carried out in two parallels and three replications were analyzed by using the SPSS statistical package program 20.0 (SPSS Inc., USA). The level of difference between the means was determined using the Duncan multiple comparison test ($p \leq 0.05$).

3. Results and Discussion

3.1. Drying Kinetics of Apple Slices. The initial moisture content and water activity of the apple slices were found as 6.74 kg water/kg DM and 0.962, respectively. The water activity values of apple chip snacks were measured as 0.348 (45°C), 0.278 (55°C), and 0.299 (65°C) for 1.5 mm thick samples and 0.425 (45°C), 0.396 (55°C), and 0.353 (65°C) for 5 mm thick samples, respectively. The changes in the moisture content of samples versus drying time are given in Figure 1. As can be seen in Figure 1, the drying times decreased with the increase in the drying temperature and the decrease in the slice thickness. The drying time of 1.5 mm and 5 mm thick samples ranged between 120–180 min and 180–330 min, respectively. As a matter of fact, it took 120 min for the moisture content of 1.5 mm thick apple slices to decrease from 6.74 to 0.27 kg water/kg DM at a temperature of 65°C. During the process, the process was completed in 180 minutes for apple slices with a thickness of 5 mm at the same temperature. In this context, it can be said that both drying temperature and slice thickness have a significant effect on the drying time ($p < 0.05$). Similarly, Jeevarathinam et al. [25] reported that temperature has a significant effect on drying time, moisture removal, and drying rates. It is expected that the drying time will decrease as the product thickness decreases and the temperature rises. As the thickness decreases, the amount of water that will evaporate from the product will decrease as well as the distance related to the water reaching the surface will decrease, thus reducing the drying time [26, 27]. With the increase in temperature, the evaporation rate of water increases, which shortens the drying time. It is also known that the temperature gradient is inversely proportional to the drying time. As the temperature increases, the gradient increases, and the drying time becomes shorter. Similar findings were also obtained by several researchers [25, 27–30]. The hot air drying times of apple slices (4 mm thickness × 20 mm radius) were found as 195, 170, and 140 min for 50, 60, and 70°C temperatures and 1.5 m/s air velocity [28]. Hot air (60–65°C, 0.5 m/s), microwave-vacuum (2 W/g), freeze (plate temperature of 30°C at 0.2 kPa), microwave-vacuum (2 W/g) + freeze-drying time (plate temperature of 30°C at 0.2 kPa) of apple slices (20 × 20 × 8 mm) were found as 5.5 h, 0.6 h, 24 h, and 12.5, respectively [29]. The hot air drying times of organic apple slices were found as 400, 300, and 240 min (5 mm thick slices) and 640, 560, and 460 min (9 mm thick slices) for 40, 50, and 60°C drying temperatures, respectively [27]. Different drying techniques, product thicknesses, and drying conditions affect the drying time. A study has investigated the effect of drying temperature (40–50°C), airflow rate (0.6–1.1 m/s), apple slice thickness (4–12 mm), and relative humidity (25–28–40–45%); it was stated that the most important factor was found as slice thickness. The 3-fold increase in apple slice thickness increased the drying time by more than 500 min. In addition, researchers reported that, although the thickness is not important in the presence of free water to be removed at the beginning of drying, the importance of the thickness increases as the amount of water that will evaporate decreases [31].

Table 2 shows the model parameters of selected thin-layer drying models for the determination of the drying behavior of apple snacks. When Table 2 is examined, it is seen that all selected thin-layer models explain the drying behavior of apple chips with a high R^2 value (>0.972). The highest R^2 and lowest X^2 and RMSE values were generally obtained from the Page model. In addition, mathematical models that are simple and contain fewer terms are generally preferred to describe the drying behaviors of food materials. In this context, it is appropriate to choose the Page model. Similarly, in the literature, it is reported that the Page model could adequately describe the drying behavior of fluidized bed drying of apple cubes [32], and the hot air drying behavior of cylindrical apple slices at different temperatures, slice thicknesses, air velocities, and relative air humidities [31]. The drying (k, h^{-1}) and model (n, dimensionless) constants of the Page model generally increased with increasing temperature. Vega-Gálvez et al. [33] reported that the drying constant increased whereas the model constant of the Page model decreased depending on the increasing temperature. In addition, the drying constants of the Page model obtained for 1.5 mm thick samples are higher than that obtained for 5 mm. It is thought that the reason for this situation is that the apple slices dried faster at high

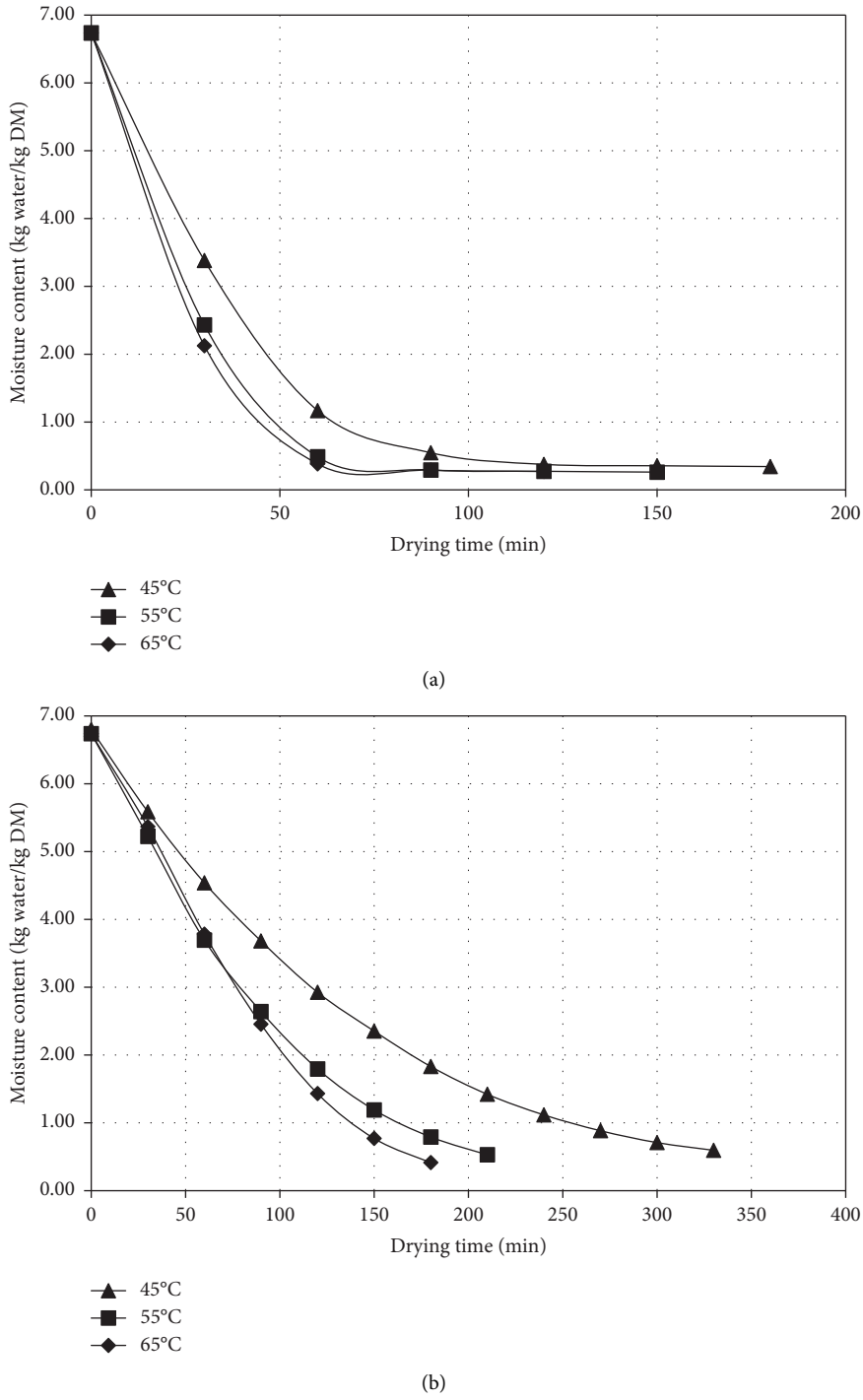


Figure 1: Changes in the moisture content values of apple slices during drying ((a) = 1.5 ± 0.5 mm thickness, (b) = 5 ± 0.5 mm thickness).

temperatures and low thickness due to the high evaporation rate. MR values that are calculated with the Page model versus experimental MR values are shown in Figure 2. MR values were generally gathered around a straight line. This shows that the Page model explains the hot air drying behavior of apple slices to a high extent.

The drying rates of apple slices were calculated and graphs were drawn of the drying rate versus moisture content (Figure 3). Although a temperature rise period was observed for the 5 mm thick apple slices that were drying at 55 and 65°C temperatures, the drying of all samples took place in the falling rate period. This is expected for biological materials. It shows that the moisture movement in the apple slices is mainly controlled by molecular diffusion [28]. In addition, with the increase in temperature, the evaporation rate of water increased and the drying rate increased. This is

Table 2: Thin layer mathematical models.

Models	Thickness (mm)	Drying air temperature (°C)	Model parameters			χ^2	RMSE	R^2
Page	1.5	45	$k = 1.566$	$n = 1.103$		0.0012	0.0287	0.992
		55	$k = 2.342$	$n = 1.175$		0.0009	0.0249	0.995
		65	$k = 2.533$	$n = 1.112$		0.0008	0.0220	0.996
Henderson and Pabis		45	$k = 1.540$	$a = 1.007$		0.0013	0.0299	0.992
		55	$k = 2.163$	$a = 1.003$		0.0011	0.0266	0.994
		65	$k = 2.397$	$a = 1.001$		0.0009	0.0229	0.996
Lewis		45	$k = 1.531$			0.0011	0.0300	0.992
		55	$k = 2.159$			0.0009	0.0266	0.994
		65	$k = 2.394$			0.0007	0.0229	0.996
Logarithmic		45	$k = 1.653$	$a = 0.987$	$b = 0.024$	0.0013	0.0270	0.993
		55	$k = 2.295$	$a = 0.985$	$b = 0.019$	0.0011	0.0240	0.995
		65	$k = 2.521$	$a = 0.986$	$b = 0.016$	0.0011	0.0210	0.997
Page	5	45	$k = 0.403$	$n = 1.072$		$1.48E-05$	0.0035	0.999
		55	$k = 0.588$	$n = 1.173$		$1.55E-05$	0.0034	0.999
		65	$k = 0.581$	$n = 1.413$		$3.11E-05$	0.0047	0.999
Henderson and Pabis		45	$k = 0.439$	$a = 1.016$		0.0001	0.0101	0.999
		55	$k = 0.664$	$a = 1.029$		0.0007	0.0226	0.995
		65	$k = 0.732$	$a = 1.054$		0.0035	0.0500	0.977
Lewis		45	$k = 0.431$			0.0002	0.0118	0.998
		55	$k = 0.645$			0.0008	0.0257	0.993
		65	$k = 0.695$			0.0035	0.0550	0.972
Logarithmic		45	$k = 0.400$	$a = 1.047$	$b = -0.040$	$5.18E-05$	0.0062	0.999
		55	$k = 0.538$	$a = 1.117$	$b = -0.104$	0.0002	0.0123	0.998
		65	$k = 0.423$	$a = 1.372$	$b = -0.350$	0.0009	0.0228	0.995

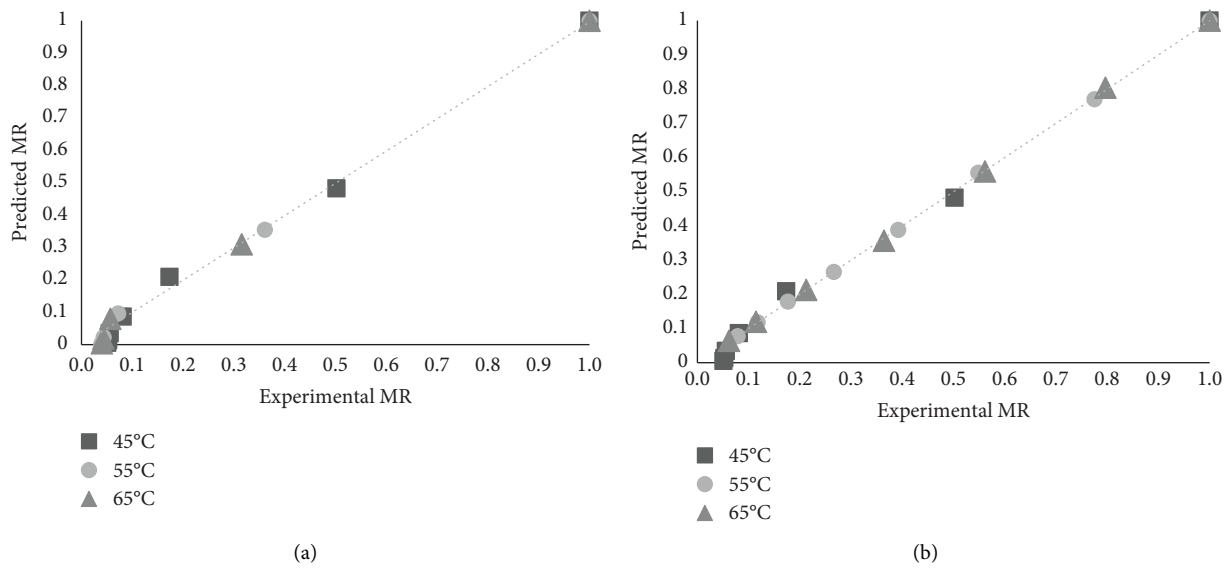
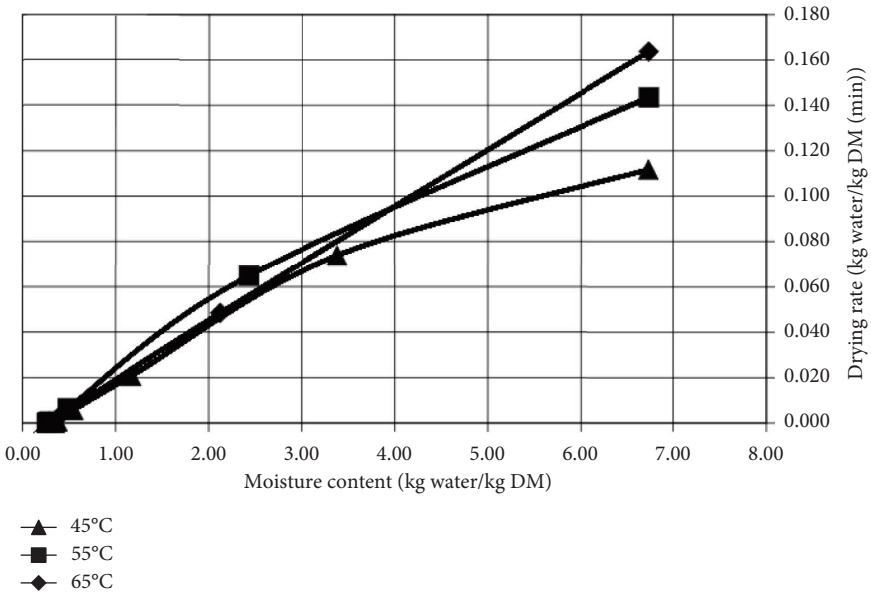
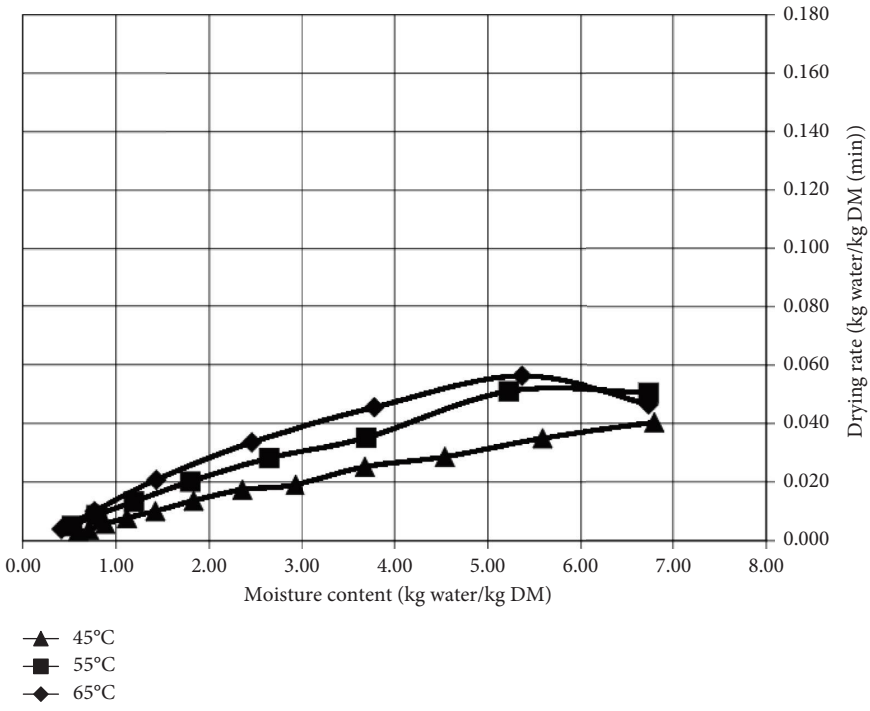


Figure 2: Predicted MR versus experimental MR ((a) = 1.5 ± 0.5 mm thickness, (b) = 5 ± 0.5 mm thickness).

an expected situation. It was also observed that there was an inverse relationship between the thickness and the drying rate. When the drying rates of apple slices were examined depending on the thickness, it can be said that the drying rates of 1.5 mm thick apple slices are approximately 3–4 times higher than those with a thickness of 5 mm. Similar findings were also obtained by Wang and Chao [34] and Sacilik and Elicin [27]. Wang and Chao [34] studied the effect of different thicknesses (3, 5, and 7 mm) and air temperatures (50, 60, and 75°C) on the drying rate of the Fuji apple slices, and the researchers stated that the drying rate increased with increasing drying temperature and decreasing slice thickness. The effective diffusion coefficient was calculated from the slope obtained by plotting the graph of ln MR versus ln t (min). D_{eff} values were calculated as $3.37E-07$ ($R^2 = 0.982$), $3.73E-07$ ($R^2 = 0.9335$), and $4.29E-07$ ($R^2 = 0.9405$) m^2/s for 1.5 mm slice thickness and $3.07E-06$ ($R^2 = 0.9458$), $3.12E-06$ ($R^2 = 0.9062$), and



(a)



(b)

Figure 3: Changes in the drying rate of apple slices versus moisture content ((a) = 1.5 ± 0.5 mm thickness, (b) = 5 ± 0.5 mm thickness).

$4.31E-06$ ($R^2 = 0.9551$) m^2/s for 5 mm slice thickness at 45, 55, and 65°C temperatures. These values were found lower compared to the estimated values for apple slices. The D_{eff} values of hot air-dried apple slices were calculated as $4.85E-9\ m^2/s$ [35], $1.9E-10$ and $7.0E-10\ m^2/s$ [31], $2.27E-10$ and $4.97E-10\ m^2/s$ [27], $0.964E-09$ and $2.28E-09$ [36], $1.70E-09$-$4.45E-09\ m^2/s$ [37], $0.841E-9$-$2.060E-9\ m^2/s$ [38]. Different drying conditions (temperature, air flow rate, and so on) and slice thickness may be the reason for different values. The D_{eff} values increased depending on the increasing air temperature and slice thickness. Similar findings were also obtained by [4, 27, 31]. This is thought to be due to the fact that air temperatures accelerate moisture diffusion. In addition, Zhu et al. [35] reported that the temperature rising intensified the mobility of water molecules. Activation energy values were calculated as 10.56 kJ/mol and 14.70 kJ/mol for 1.5 mm and 5 mm sample thicknesses, respectively. It can be stated that 5 mm thick samples are more susceptible to temperature change compared to 1.5 mm thick samples. Higher E_a values such as

28.37 kJ/mol [39], 19.80 kJ/mol [28], 19.34 kJ/mol [36], and 113.018 kJ/mol [35] were observed for hot air-dried apple slices. It can also be stated that 5 mm thick samples are more susceptible to temperature change compared to 1.5 mm thick samples.

3.2. Desorption Isotherms. In order to determine the desorption isotherms of apple slices, the water activity values of samples were measured at half-hour intervals during drying, and the compatibility of these values with the models was examined and the results were given in Table 3. When Table 3 is examined that although χ^2 and RMSE values for GAB model are higher than BET and OSWIN models for 1.5 mm slice thickness, the highest R^2 values were obtained from the GAB model. The lowest R^2 values were obtained from the BET model. The BET model gives the most suitable results in water activity values between 0.05 and 0.45, however, our water activity values are not in this range. It may be the reason for low R^2 values [40]. For both thicknesses, it can be said that the GAB model is the best model for the determination of the desorption behavior of apple slices with the highest R^2 value. GAB model was also found the best model for representing the desorption isotherm 5 mm thick apple slices at 45°C [33]. According to the monolayer (C) values which ranged between 0 and 2 (except for the BET model for 1.5 mm thickness), it can be stated that all isotherms are J-Type [41]. It can be said that there is an increase in the k value depending on the temperature, but there is no trend for the monolayer (C) and monolayer moisture content (M_0) values. In addition, the k values calculated for 1.5 mm thick samples were higher than that calculated for 5 mm, and the opposite effect was observed for the C value.

3.3. Antioxidant Activity, Total Phenolic Compounds, and Color Values. The antioxidant activity and total phenolic compounds of fresh apple slices were found as 289.24 μmol Trolox equivalence/100 g DM and 957.63 mg Gallic acid equivalence/100 g DM, respectively. During the drying process, quality losses of dried foods occur depending on the drying conditions. For this reason, the changes in antioxidant activity, total phenolic compounds, and color values of apple chips during the drying process were investigated. While 1.5 mm thick samples lost 50% of their antioxidant activity in the first half-hour, 5 mm thick samples were lost in 1 hour. It was also observed that 90% of the antioxidant activity was lost as a result of the drying process for all thicknesses and temperature values. The antioxidant activity values of apple chips were measured as 32.37, 34.44, and 31.60 μmol Trolox equivalence/100 g DM for 1.5 mm thickness and 24.41, 31.45, and 25.79 μmol Trolox equivalence/100 g DM for 5 mm at 45, 55, and 65°C, respectively. According to the antioxidant activity values, it can also be said that the highest values were observed for 55°C temperature and 1.5 mm thickness. The drying times of the 5 mm thick sample were longer than the 1.5 mm thick sample. It may be the reason for lower antioxidant activity. Lower drying times result in higher quality in the dried product by minimizing undesirable changes [42, 43]. It is known that polyphenols and ascorbic acid contribute to the antioxidant activity of apples [2]. As a result of the drying process, approximately 55% decrease occurs in the total phenolic compounds of apples, while the loss of antioxidant activity is around 90%. It is known that ascorbic acid decomposes under the influence of heat, light, and metal. This is thought to be due to the loss of ascorbic acid.

The total phenolic compounds of the apple chips decreased depending on the increasing drying temperature and increasing thickness (411.90, 398.00, and 361.86 mg Gallic acid equivalence/100 g DM for 1.5 mm thickness and 368.45, 340.94, and 303.99 mg Gallic acid equivalence/100 g DM for 5 mm thickness at 45, 55, and 65°C, respectively). The phenolic compound loss is around 55%. Kidoń and Grabowska [42] reported that the initial total phenolic content of red flesh apple is 421 mg GAE/100 g DM and convective drying (60°C) and convective (60°C) + microwave vacuum (60 s at 1.0 kW, 60 s at 0.2 kW, 20 s without microwave radiation at 28 kPa) drying processes caused 20% reduction in the total phenolic content.

The color values of fresh apple slices were measured as $L = 72.41$, $a = 0.41$, and $b = 19.63$, respectively. The color values of 1.5 mm thick samples were $L = 70.49$, $a = 8.37$, and $b = 34.50$; $L = 65.35$, $a = 15.05$, and $b = 36.26$; $L = 73.52$, $a = 9.54$, and $b = 35.32$ for 45, 55, and 65°C, respectively. The color values of 5 mm thick samples were $L = 62.06$, $a = 13.65$, and $b = 38.68$; $L = 62.81$, $a = 10.28$, and $b = 34.42$; $L = 68.72$, $a = 10.21$, and $b = 39.99$ for 45, 55, and 65°C, respectively. According to the color values of the final product, it can also be said that the L value was generally found to be lower than the initial value (fresh apple), and the a and b values were found to be higher. Similar findings were also obtained for hot air-dried, freeze-dried, hot air + puffing dried, and hot air + CO_2 puffing dried apple slices [4], microwave + freeze-dried, microwave-vacuum + freeze-dried, freeze-dried, and hot air-dried apple slices [29]. Sacilik and Elicin [27] also reported that higher temperatures resulted in darker apple slices. Although the L value of the samples with a thickness of 5 mm was found to be lower than those with a thickness of 1.5 mm, generally higher a, and b values were obtained. In addition, a general decrease in color values was observed depending on the temperature. The heat effect and enzymatic and nonenzymatic browning reactions may be the reason for the formation of brown pigments that cause the lower and higher a, b, and ΔE values [42]. The ΔE values of apple slices were calculated as 16.97, 23.25, and 18.19 for 1.5 mm thickness and 25.40, 20.20, and 22.90 for 5 mm thickness at 45, 55, and 65°C, respectively. In light of these findings, it can be said that the total color change increases significantly as the thickness increases ($p < 0.05$). In addition, although the effect of temperature change in 1.5 mm thick samples was found to be statistically significant

Table 3: Desorption model parameters and statistical results.

Models	Thickness (mm)	Drying air temperature (°C)	Model parameters			χ^2	RMSE	R^2
		45	$k = 0.983$	$C = 4.885$	$M_0 = 0.316$	0.250	0.378	0.9992
GAB		55	$k = 1.162$	$C = 0.321$	$M_0 = 1.097$	1.871	3.270	0.9979
		65	$k = 2.001$	$C = 0.463$	$M_0 = 0.239$	0.641	0.506	0.9999
		45		$C = 13.587$	$M_0 = 0.258$	0.005	0.058	0.5706
BET		55		$C = 3.917$	$M_0 = 0.334$	1.164	0.881	0.5051
		65		$C = 81.090$	$M_0 = 0.272$	0.968	0.762	0.3014
		45	$k = 0.531$		$n = 0.754$	0.122	0.295	0.9112
Oswin	1.5	55	$k = 0.582$		$n = 0.829$	0.858	0.756	0.7934
		65	$k = 0.760$		$n = 0.715$	1.040	0.790	0.8920
		45		$C = 0.708$	$n = 0.020$	11.710	2.892	0.9662
Henderson		55		$C = 0.647$	$n = -0.168$	26.981	3.902	0.8536
		65		$C = 0.566$	$n = 0.607$	41.995	5.020	0.9128
		45		$C = 1.127$	$n = 1.012$	17.612	9.011	0.8940
Halsey		55		$C = 0.974$	$n = 1.022$	13.367	10.554	0.7582
		65		$C = 0.872$	$n = 0.870$	14.254	12.771	0.8757
		45	$k = 0.941$	$C = 1.209$	$M_0 = 0.665$	0.138	0.326	0.9992
GAB		55	$k = 0.979$	$C = 1.036$	$M_0 = 0.459$	0.643	0.671	0.9979
		65	$k = 0.991$	$C = 1.742$	$M_0 = 0.348$	0.324	0.450	0.9999
		45		$C = 4.238$	$M_0 = 0.331$	0.400	0.582	0.5706
BET		55		$C = 1.098$	$M_0 = 0.293$	0.849	0.824	0.5051
		65		$C = 1.335$	$M_0 = 0.271$	0.416	0.558	0.3014
		45	$k = 0.520$		$n = 0.839$	0.171	0.380	0.9112
Oswin	5	55	$k = 0.420$		$n = 0.906$	0.699	0.748	0.7934
		65	$k = 0.324$		$n = 0.964$	0.314	0.485	0.8920
		45		$C = 1.131$	$n = 0.562$	0.057	0.220	0.9662
Henderson		55		$C = 1.361$	$n = 0.426$	0.585	0.684	0.8536
		65		$C = 1.334$	$n = 0.491$	0.343	0.507	0.9128
		45		$C = 0.359$	$n = 1.020$	0.481	0.638	0.8940
Halsey		55		$C = 0.256$	$n = 0.756$	4.039	1.798	0.7582
		65		$C = 0.243$	$n = 0.850$	0.739	0.744	0.8757

Table 4: 0, 1st and 2nd order reaction kinetic constants.

Temperature (°C)		Thickness (mm)	0 order reaction kinetic constant (k_0)	R^2	1st order reaction kinetic constant (k_1)	R^2	2nd order reaction kinetic constant (k_2)	R^2
	45		74.25	0.7338	0.7182	0.9220	0.0097	0.9914
	55	1.5	85.60	0.6890	0.7863	0.8991	0.0100	0.9956
Antioxidant activity	65		117.81	0.7980	1.1067	0.9480	0.0149	0.9865
	45		44.98	0.8620	0.4792	0.9848	0.0074	0.9524
	55	5	70.88	0.9492	0.6101	0.9892	0.0080	0.8246
	65		82.68	0.8319	0.8090	0.9853	0.0120	0.9623
	45		191.03	0.9918	0.2941	0.9940	0.0005	0.9724
	55	1.5	222.42	0.9981	0.3432	0.9774	0.0006	0.9235
Total phenolic compounds	65		303.65	0.9958	0.4933	0.9807	0.0009	0.9357
	45		107.42	0.9794	0.1728	0.9966	0.0003	0.9957
	55	5	181.53	0.9682	0.3118	0.9905	0.0006	0.9848
	65		214.65	0.9721	0.3897	0.9931	0.0008	0.9699
	45		8.7268	0.9749	0.5902	0.9208	0.0426	0.8496
	55	1.5	8.1814	0.6736	0.1855	0.7320	0.0077	0.7603
Total color change (ΔE)	65		3.6072	0.8530	0.1625	0.8697	0.0100	0.8561
	45		0.7939	0.9976	0.0334	0.9969	0.0014	0.9959
	55	5	9.0028	0.9675	0.6317	0.9881	0.0520	0.9540
	65		11.309	0.7587	0.7099	0.8240	0.0542	0.8978

Table 5: Kinetic parameters of antioxidant activity and total phenolic compounds degradation of apple slices.

Temperature (°C)		Thickness (mm)	Q_{10} value	k (1/min)	$t_{1/2}$ (h)	E_a (kJ/mol)
Antioxidant activity	45	1.5	1.031	0.0097	0.36	19.02
	55			0.0100	0.35	
	65		1.490	0.0149	0.23	
	45	5	1.273	0.4792	1.45	23.39
	55			0.6101	1.14	
	65		1.326	0.8090	0.86	
Total phenolic compounds	45	1.5	1.164	191.03	2.50	20.65
	55			222.42	2.16	
	65		1.365	303.65	1.58	
	45	5	1.804	0.1728	4.01	36.53
	55			0.3118	2.22	
	65		1.250	0.3897	1.78	

($p < 0.05$), the effect of temperature on the total color values of 5 mm thick samples was found to be insignificant ($p > 0.05$).

3.4. Modeling Studies for Investigation of Bioactive Components and Total Color Changes. Their degradations were investigated using zero, first- and second-order reaction kinetic models, and the results are given in Table 4. The reaction kinetics, in which the highest R^2 values were obtained, was chosen as suitable. The total phenolic compounds of the 1.5 mm thick samples conformed to the 0^{th}-order reaction kinetics. Both the antioxidant activity and total phenolic compounds of the 5 mm thick samples were degraded in accordance with the 1st-order reaction kinetics. However, the antioxidant activities of 1.5 mm thick samples were degraded in accordance with the second-order reaction kinetics. Arora et al. [2] also reported that the degradation kinetic of the antioxidant activity and total phenolic content of apples after cutting followed the first-order reaction kinetics. It was observed that the ΔE values of the apple slices changed in accordance with the first-order reaction kinetics. Palazón et al. [44] reported that a higher correlation coefficient was obtained from the zero-order reaction kinetic model for L^*, a^*, b^*, and ΔE^* values of apple-based beikost samples stored at 37°C, whereas the higher correlation coefficient was obtained from 1^{st}-order reaction kinetic model for vitamin C and HMF. Saavedra et al. [45] reported that the pseudo-zero-order reaction kinetic model satisfactorily described the changes in ΔE^* values of apple cluster snacks stored at 18, 25, and 35°C.

It is important to determine the shelf life, which refers to the nutritional and sensory acceptability of foods [45]. Considering these reaction kinetics, Q_{10} value, half-life, and activation energy values were calculated and the results are given in Table 5. In all three reaction kinetics, the reaction rate constants increased with the increase in temperature and decreased as the thickness increased. For both antioxidant activity and total phenolic compounds, the Q_{10} value calculated for 65–55°C temperatures was found to be greater than that calculated according to 45–55°C temperatures. The half-life decreased with increasing temperature and increased with thickness. Higher activation energy values were calculated for 5 mm thick samples. In addition, it can be said that the activation energy values calculated for the total phenolic compounds are higher than those calculated for the antioxidant activity.

4. Conclusion

Nowadays, as the perception of living a healthy life has grown, there is an increase in the pattern of consumption of healthy snacks. One of the products frequently consumed within the scope of these snacks is apple chips. In this study, the changes in the quality characteristics of apple slices at different air temperatures and slice thicknesses were investigated during the production of apple slices consumed as a healthy snack. According to the findings of this study, it was concluded that during the drying process, approximately 45% of the total phenolic compounds and 10% of the antioxidant activity of apple chips were preserved. It is also concluded that the thinner samples (1.5 mm) were dried faster and the biochemical quality are better preserved than thick samples (5 mm). Although the drying temperature of 65°C is advantageous in terms of drying time and rate, it was observed that the antioxidant activity, phenolic compounds, and color of the samples dried at 45°C were better preserved. In this context, conditions, where the thickness and temperature are low, can be considered advantageous in terms of preserving the quality characteristics of apple chip snacks. It is predicted that the findings obtained from this study will shed light on the selection of drying conditions to preserve the quality properties of apple slices for scientific studies on the drying of apple slices. Furthermore, work will be carried out on the effect of different drying techniques such as freeze and puffing on the antioxidant activity and total phenolic compounds of the apple chip snacks.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] V. Rasooli Sharabiani, M. Kaveh, R. Abdi, M. Szymanek, and W. Tanaś, "Estimation of moisture ratio for apple drying by convective and microwave methods using artificial neural network modeling," *Scientific Reports*, vol. 11, no. 1, p. 9155, 2021.

[2] B. Arora, S. Sethi, A. Joshi, V. R. Sagar, and R. R. Sharma, "Antioxidant degradation kinetics in apples," *Journal of Food Science and Technology*, vol. 55, no. 4, pp. 1306–1313, 2018.

[3] N. P. Bondonno, C. P. Bondonno, N. C. Ward, J. M. Hodgson, and K. D. Croft, "The cardiovascular health benefits of apples: whole fruit vs. isolated compounds," *Trends in Food Science and Technology*, vol. 69, pp. 243–256, 2017.

[4] J. Zhu, Y. Liu, C. Zhu, and M. Wei, "Effects of different drying methods on the physical properties and sensory characteristics of apple chip snacks," *LWT - Food Science and Technology*, vol. 154, Article ID 112829, 2022.

[5] E. Betoret, N. Betoret, A. Arilla et al., "No invasive methodology to produce a probiotic low humid apple snack with potential effect against *Helicobacter pylori*," *Journal of Food Engineering*, vol. 110, no. 2, pp. 289–293, 2012.

[6] E. Betoret, E. Sentandreu, N. Betoret, P. Codoñer-Franch, V. Valls-Bellés, and P. Fito, "Technological development and functional properties of an apple snack rich in flavonoid from Mandarin juice," *Innovative Food Science and Emerging Technologies*, vol. 16, pp. 298–304, 2012.

[7] J. Moreno, J. Echeverria, A. Silva et al., "Apple snack enriched with L-arginine using vacuum impregnation/ohmic heating technology," *Food Science and Technology International*, vol. 23, no. 5, pp. 448–456, 2017.

[8] H. Wang, Q. Fu, S. Chen, Z. Hu, and H. Xie, "Effect of hot-water blanching pretreatment on drying characteristics and product qualities for the novel integrated freeze-drying of apple slices," *Journal of Food Quality*, vol. 2018, Article ID 1347513, 12 pages, 2018.

[9] W. P. da Silva, A. F. Rodrigues, C. M. D. P. S. e Silva, D. S. de Castro, and J. P. Gomes, "Comparison between continuous and intermittent drying of whole bananas using empirical and diffusion models to describe the processes," *Journal of Food Engineering*, vol. 166, pp. 230–236, 2015.

[10] S. V. Jangam, "An overview of recent developments and some R&D challenges related to drying of foods," *Drying Technology*, vol. 29, no. 12, pp. 1343–1357, 2011.

[11] D. I. Onwude, N. Hashim, R. B. Janius, K. Abdan, G. Chen, and A. O. Oladejo, "Non-thermal hybrid drying of fruits and vegetables: a review of current technologies," *Innovative Food Science and Emerging Technologies*, vol. 43, pp. 223–238, 2017.

[12] Z. Erbay and F. Icier, "A review of thin layer drying of foods: theory, modeling, and experimental results," *Critical Reviews in Food Science and Nutrition*, vol. 50, no. 5, pp. 441–464, 2010.

[13] G. E. Page, *Factors Influencing the Maximum Rates of Air Drying Shelled Corn in Thin Layers," ProQuest Dissertations and Theses*, Purdue University, West Lafayette, IN, USA, 1949.

[14] S. M. Henderson and S. Pabis, "Grain drying theory, I. Temperature effect on drying constant," *Journal of Agricultural Engineering Research*, vol. 6, pp. 21–26, 1961.

[15] W. K. Lewis, "The rate of drying of solid materials," *Journal of Industrial and Engineering Chemistry*, vol. 13, no. 5, pp. 427–432, 1921.

[16] A. Yagcioglu, "Drying characteristic of laurel leaves under different conditions," in *Proceedings of the 7th International Congress on Agricultural Mechanization and Energy*, pp. 565–569, Adana, Turkey, May 1999.

[17] C. Van Den Berg and S. Bruin, "Water activity and its estimation in food systems," *Theorical Aspects in Water Activity: Influence on Food Quality*, pp. 12–45, Academic Press, Cambridge, MA, USA, 1981.

[18] S. Brunauer, P. H. Emmett, and E. Teller, "Adsorption of gases in multimolecular layers," *Journal of the American Chemical Society*, vol. 60, no. 2, pp. 309–319, 1938.

[19] C. R. Oswin, "The kinetics of package life. III. The isotherm," *Journal of the Society of Chemical Industry*, vol. 65, no. 12, pp. 419–421, 1946.

[20] T. L. Thompson, R. M. Peart, and G. H. Foster, "Mathematical simulation of corn drying a new model," *Transaction of the ASAE*, vol. 11, no. 4, pp. 582–586, 1968.

[21] G. Halsey, "Physical adsorption on non-uniform surfaces," *The Journal of Chemical Physics*, vol. 16, no. 10, pp. 931–937, 1948.

[22] K. Thaipong, U. Boonprakob, K. Crosby, L. Cisneros-Zevallos, and D. Hawkins Byrne, "Comparison of ABTS, DPPH, FRAP, and ORAC assays for estimating antioxidant activity from guava fruit extracts," *Journal of Food Composition and Analysis*, vol. 19, no. 6-7, pp. 669–675, 2006.

[23] B. Cemeroglu, *Food analysis*, Food Technology Association Publications, Ankara, Turkey, 2 edition, 2010.

[24] P. B. Pathare, U. L. Opara, and F. A. J. Al-said, "Colour measurement and analysis in fresh and processed foods: a review," *Food and Bioprocess Technology*, vol. 6, no. 1, pp. 36–60, 2013.

[25] G. Jeevarathinam, R. Pandiselvam, T. Pandiarajan et al., "Design, development, and drying kinetics of infrared-assisted hot air dryer for turmeric slices," *Journal of Food Process Engineering*, vol. 45, no. 6, Article ID 13876, 2022.

[26] G. N. Roman, E. Rotstein, and M. J. Urbicain, "Kinetics of water desorption from apples," *Journal of Food Science*, vol. 44, no. 1, pp. 193–197, 1979.

[27] K. Sacilik and A. K. Elicin, "The thin layer drying characteristics of organic apple slices," *Journal of Food Engineering*, vol. 73, no. 3, pp. 281–289, 2006.

[28] M. Beigi, "Hot air drying of apple slices: dehydration characteristics and quality assessment," *Heat and Mass Transfer*, vol. 52, no. 8, pp. 1435–1442, 2016.

[29] Z. W. Cui, C. Y. Li, C. F. Song, and Y. Song, "Combined microwave-vacuum and freeze drying of carrot and apple chips," *Drying Technology*, vol. 26, no. 12, pp. 1517–1523, 2008.

[30] P. Jiang, W. Jin, Y. Liu et al., "Hot-Air drying characteristics of sea cucumber (*apostichopus japonicus*) and its rehydration properties," *Journal of Food Quality*, vol. 2022, Article ID 5147373, 9 pages, 2022.

[31] M. J. Royen, A. W. Noori, J. Haydary, and J. Haydary, "Experimental study and mathematical modeling of convective thin-layer drying of apple slices," *Processes*, vol. 8, no. 12, p. 1562, 2020.

[32] A. Kaleta, K. Górnicki, R. Winiczenko, and A. Chojnacka, "A Evaluation of drying models of apple (var. Ligol) dried in a fluidized bed dryer," *Energy Conversion and Management*, vol. 67, pp. 179–185, 2013.

[33] A. Vega-Gálvez, M. Miranda, C. Bilbao-Sáinz, E. Uribe, and R. Lemus-Mondaca, "Empirical modeling of drying process for apple (cv. *Granny smith*) slices at different air temperatures," *Journal of Food Processing and Preservation*, vol. 32, no. 6, pp. 972–986, 2008.

[34] J. Wang and Y. Chao, "Drying characteristics of irradiated apple slices," *Journal of Food Engineering*, vol. 52, no. 1, pp. 83–88, 2002.

[35] R. Zhu, S. Jiang, D. Li et al., "Dehydration of apple slices by sequential drying pretreatments and airborne ultrasound-assisted air drying: study on mass transfer, profiles of phenolics and organic acids and PPO activity," *Innovative Food Science and Emerging Technologies*, vol. 75, Article ID 102871, 2022.

[36] J. Srikiatden and J. S. Roberts, "Moisture loss kinetics of apple during convective hot air and isothermal drying," *International Journal of Food Properties*, vol. 8, no. 3, pp. 493–512, 2005.

[37] D. Velić, M. Planinić, S. Tomas, and M. Bilić, "Influence of airflow velocity on kinetics of convection apple drying," *Journal of Food Engineering*, vol. 64, no. 1, pp. 97–102, 2004.

[38] E. K. Akpınar, Y. Biçer, and A. Midilli, "Modeling and experimental study on drying of apple slices in a convective cyclone dryer," *Journal of Food Process Engineering*, vol. 26, no. 6, pp. 515–541, 2003.

[39] T. K. Tepe and B. Tepe, "The comparison of drying and rehydration characteristics of intermittent-microwave and hot-air dried-apple slices," *Heat and Mass Transfer*, vol. 56, no. 11, pp. 3047–3057, 2020.

[40] R. D. Andrade P, R. Lemus M, and C. E. Pérez C, "Models of sorption isotherms for food: uses and limitations," *Vitae*, vol. 18, no. 3, pp. 325–334, 2011.

[41] J. Blahovec and S. Yanniotis, "GAB generalized equation for sorption phenomena," *Food and Bioprocess Technology*, vol. 1, pp. 82–90, 2008.

[42] M. Kidoń and J. Grabowska, "Bioactive compounds, antioxidant activity, and sensory qualities of red-fleshed apples dried by different methods," *LWT - Food Science and Technology*, vol. 136, Article ID 110302, 2021.

[43] D. Witrowa-Rajchert, A. Bawoł, J. Czapski, and M. Kidoń, "Studies on drying of purple carrot roots," *Drying Technology*, vol. 27, no. 12, pp. 1325–1331, 2009.

[44] M. A. Palazón, D. Pérez-Conesa, P. Abellán, G. Ros, F. Romero, and M. L. Vidal, "Determination of shelf-life of homogenized apple-based beikost storage at different temperatures using Weibull hazard model," *LWT - Food Science and Technology*, vol. 42, no. 1, pp. 319–326, 2009.

[45] J. Saavedra, A. Córdova, L. Gálvez, C. Quezada, and R. Navarro, "Principal Component Analysis as an exploration tool for kinetic modeling of food quality: a case study of a dried apple cluster snack," *Journal of Food Engineering*, vol. 119, no. 2, pp. 229–235, 2013.