https://doi.org/10.3311/PPch.38339

Periodica Polytechnica Chemical Engineering, 69(1), pp. 113–122, 2025

Influence of Infrared Radiation of Drying Characteristics, Total Phenolic Content, Antioxidant Capacity and Color Properties of Pomegranate Seeds

İbrahim Doymaz[1*], Elena Borucu[1], Selma Kayacan-Çakmakoglu[2], Osman Sagdic[2]

[1] Department of Chemical Engineering, Yildiz Technical University, Davutpasa Campus, 34220 Istanbul, Türkiye
[2] Department of Food Engineering, Yildiz Technical University, Davutpasa Campus, 34220 Istanbul, Türkiye
[*] Corresponding author, e-mail: doymaz@yildiz.edu.tr

Received: 17 September 2024, Accepted: 22 November 2024, Published online: 08 January 2025

Abstract

The aim of this research is to analyze the drying behavior, antioxidant properties, total phenolic content (TPC), and color alterations of pomegranate seeds subjected to infrared drying at temperatures ranging from 55 °C to 75 °C. Analysis of the data revealed a declining-rate drying phase without evidence of a constant-rate phase. The drying rate and duration were found to be directly proportional to the infrared temperature applied; higher temperatures led to faster drying and reduced drying times. The drying process of pomegranate seeds in thin layers was investigated using twelve mathematical models. Among these models, the one presented by Aghbashlo et al. was determined to provide the most precise representation of the drying kinetics. The effective moisture diffusivity values varied between 8.76×10^{-10} and 1.96×10^{-9} m^2/s, depending on the temperature range under consideration. Additionally, the activation energy was computed to be 59.37 kJ/mol. The range of TPC values in dry samples fluctuated from 6.19 to 8.20 mg gallic acid equivalent (GAE)/g of dry matter. The 1,1-diphenyl-2-picrylhydrazyl (DPPH), 2,2′-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) and copper-reducing antioxidant capacity (CUPRAC) values varied between 5.57–6.13, 24.18–28.18, 10.33–17.59 TE/g dry matter, respectively. The range of ΔE values for the total color change fell between 3.96 and 9.19. Bioactive compound degradation in samples dried at high drying temperature (75 °C) is higher than in samples dried at 55 and 65 °C. When all the results were evaluated, it was determined that 55 °C was suitable for infrared drying of pomegranate seeds.

Keywords

activation energy, bioactive compounds, effective moisture diffusivity, mathematical modeling, pomegranate seeds

1 Introduction

Pomegranate, scientifically known as *Punica granatum* L., is a poly-seeded fruit classified within the Punicaceae family, as noted by Süfer and Palazoğlu [1]. The cultivation of pomegranate fruit is mostly done in Asia, the Mediterranean, the Middle East and North Africa [2]. China, Iran and India are the countries with the highest pomegranate production capacity in the world. It is estimated that the annual total production capacity of these countries is 3 million tons. In addition, according to the data, the annual pomegranate production capacity of the world is 3.8 million tons [3, 4]. Although the pomegranate fruit consists of different parts, the edible part is the grain part. The granular part is rich in vitamins, minerals, organic acids, antioxidants and phenolic compounds [5]. In today's world, the importance of healthy nutrition for human health is understood more and more every day. Pomegranate fruit attracts great attention among consumers due to its high polyphenol content. Due to its high nutrient content, it is recommended to be used in human diets [6]. For this reason, the quality of the pomegranate fruit should be kept at the highest level until it reaches the consumers. However, even if the pomegranate is stored in the best possible conditions, its shelf life is at most 2 weeks. The high water content of the pomegranate causes some spoilage reactions and the fruit to become unusable [7]. With the drying process, the amount of water in the product is reduced and thus the rate of enzymatic and biochemical reactions that can take place is reduced [8].

The drying process has been a method used for preserving foods since ancient times. Today, it is still a widely

Cite this article as: Doymaz, İ., Borucu, E., Kayacan-Çakmakoglu, S., Sagdic, O. "Influence of Infrared Radiation of Drying Characteristics, Total Phenolic Content, Antioxidant Capacity and Color Properties of Pomegranate Seeds", Periodica Polytechnica Chemical Engineering, 69(1), pp. 113–122, 2025. https://doi.org/10.3311/PPch.38339

used industrial preservation method due to its easy application and it is relatively cheaper method compared to other methods [9, 10]. With removal of water from environment, rate of microbiological and enzymatic reactions that deteriorate the quality of food is reduced. In this way, the shelf life of foods is also extended [11, 12]. In addition, the volume of the product is also reduced with drying process. As a result of these, transportation and storage costs are also reduced [13]. There are many different drying methods used industrially [14]. The most commonly used method in the industry for drying foods is the hot air drying method. However, due to the long drying times in this method, energy costs are also quite high [15]. This situation leads to the search for innovative methods that allow higher quality product production [16].

Infrared method is an innovative technique that increases its use today because it has many advantages. Some of these advantages can be summarized as shorter drying time [17], less energy consumption and higher quality final product compared to other methods [18, 19]. In the infrared drying method, infrared energy is absorbed by the surface of the product. The absorbed energy causes the water molecules in the food to vibrate and thus heat up. The drying process is completed with the removal of the heated water molecules from the food [20]. In addition, it is known that infrared drying method has many advantages such as easier equipment installation and use, easier adaptation, uniform heat distribution compared to microwave and vacuum drying methods [21].

There are some studies on the drying of pomegranate seeds. Süfer and Palazoğlu [1], used hot air drying method, Briki et al. [7] used hot air and infrared drying methods, Kaveh et al. [13] dried pomegranate arils with convective and microwave drying, Allahdad et al. [2] used the osmotic drying method by applying ultrasound pre-treatment, Adetoro et al. [22] used hot air drying method by immersion pomegranate arils in hot water and El Broudi et al. [23] used hot air drying method and investigated the biochemical structure of pomegranate arils.

However, studies on infrared drying of pomegranate seeds are extremely scarce in the literature. The main objectives of the study were to investigate the influence of drying temperature on pomegranate seeds in an infrared dryer, to determine drying characteristics, to calculate effective diffusion coefficients (D_{eff}), activation energy (E_a), total phenolic content (TPC), antioxidant activity (AA) and color properties of dried pomegranate seeds.

2 Materials and methods

2.1 Materials

Pomegranates purchased from a supermarket in Maltepe, Istanbul, were kept refrigerated at 4 °C until the start of the experiments. The initial moisture content (*MC*) of the pomegranate seeds was determined using the AOAC method [24], which showed a *MC* of 78.74% on a wet basis.

The IR desiccator (IR 35 DENVER INSTRUMENTS, Denver, Colorado, USA) used in this study. It contains a moisture analyzer consisting of a heating unit, weighing system and control unit. The device was warmed up for about 10 min in order to maximize treatment consistency. Samples were then dried at 50, 60 and 70 °C. Weight loss was measured at 10 min intervals. Drying was stopped when the *MC* became stable (at 9 ± 0.2%). The dried pomegranate arils were cooled inside the desiccator then packed in polyethylene bags.

2.1.1 Drying process

Pomegranate seeds were dried by infrared drying method by utilizing a MA 50.R model infrared moisture analyzer (Radwag Balances and Scales, Radom, Poland). The moisture analyzer comprises a moisture analyzer consisting of a control panel, a heating unit including a 250 W infrared lamp, a weighing system and pot, and a control unit. The unit was heated for approximately 15 min to maximise process consistency. Pomegranate seeds were weighed approximately 50 g and placed in the pot and then dried 55, 65 and 75 °C. The drying process persisted until the moisture level of the pomegranate seeds diminished to 15% (on a wet basis). The samples were recorded by weighing them at 10-min intervals with a control panel. For each temperature, the experiments were carried out in three replicates ($p < 0.05$).

2.2 Mathematical modelling

Using the experimental data, mathematical modeling of the drying process was made. For this, twelve well-known drying models in Table 1 [25–36] were used. *MC* and moisture ratio (*MR*) of pomegranate seeds were calculated by the Eqs. (1) and (2) [37].

$$MC = \frac{W_i - W_d}{W_d} \tag{1}$$

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{2}$$

W_i represents the mass of the sample in kg, while W_d denotes the dry matter content of the sample, also measured in kg. M_0, M_e, and M_t stand for the initial, equilibrium, and *MC*s at time *t*, respectively, with *MC* expressed as kg water/kg dry matter. The variable *t* signifies the drying time, measured in min. Equation (2) is usually simplified and used as [38]:

$$MR = \frac{M_t}{M_0}. \tag{3}$$

The values of drying rate (*DR*) were computed by using Eq. (4):

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t}. \tag{4}$$

2.3 Data analysis

The suitability of the experimental data to the models was investigated by statistical analysis. The R^2 values were determined with the Statistica (StatSoft, Inc., Tulsa, OK) computer program. The relative percent error (*P*), reduced chi-square (χ^2), and root mean square error (*RMSE*) were determined by using Eqs. (5), (6), and (7), respectively. To identify the optimal drying model, the one exhibiting the lowest *P*, χ^2, and *RMSE* along with the highest R^2 values, was chosen:

$$P = \frac{100}{N}\sum_{i=1}^{N}\frac{\left|MR_{\exp,i} - MR_{\mathrm{pre},i}\right|}{MR_{\exp,i}}, \tag{5}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{\mathrm{pre},i}\right)^2}{N - z}, \tag{6}$$

Table 1 Mathematical models applied to the drying curves

Model number and name	Model[1]	References
Lewis	$MR = \exp(-kt)$	[25]
Henderson and Pabis	$MR = a\exp(-kt)$	[26]
Logarithmic	$MR = a\exp(-kt) + c$	[27]
Page	$MR = \exp(-kt^N)$	[28]
Midilli and Kucuk	$MR = a\exp(-kt^N) + bt$	[29]
Wang and Singh	$MR = 1 + at + bt^2$	[30]
Alibaş	$MR = a\exp[(-kt^N) + bt] + c$	[31]
Aghbashlo et al.	$MR = \exp\left(-\frac{k_1 t}{1 + k_2 t}\right)$	[32]
Logistic	$MR = \frac{a}{\left[1 + b\exp(kt)\right]}$	[33]
Jena and Das	$MR = a\exp(-kt + bt^{0.5}) + c$	[34]
Vega-Gálvez et al.	$MR = (a + kt)^2$	[35]
Vega-Gálvez et al.	$MR = \exp(n + kt)$	[36]

[1] Drying constants and coefficients, denoted as *a*, *b*, *c*, *k*, k_1, k_2, and *N*, represent essential parameters in the process of drying.

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{\mathrm{pre},i} - MR_{\exp,i}\right)^2\right]^{1/2}, \tag{7}$$

where *N* is number of trials and *z* is number of constants. MR_{pre} and $MR_{\exp}$ are predicted and experimental moisture ratio values, respectively.

2.4 Determining the effective moisture diffusivity and E_a through computation

Frequently employed for determining the D_{eff} of agricultural items, the diffusion equation stemming from Fick's second law finds widespread application.

The diffusion equation of Fick's second law is utilized to calculate the D_{eff} of agricultural products.

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

D_{eff} represents the effective diffusion coefficient in square meters per sec, where *n* denotes positive integers, *t* signifies time in sec, and *L* stands for half the thickness of the slab in meters. Since drying is a long-continued process, the other terms of the series can be neglected and only the first term is used in the calculations. Eq. (9) is obtained by substituting the first term ($n = 0$) in Eq. (8).

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}t}{4L^2}\right) \tag{9}$$

The D_{eff} is calculated by using the slope of line of the $\ln(MR)$ versus time (t) graph.

$$\mathrm{Slope} = \frac{\pi^2 D_{eff}}{4L^2} \tag{10}$$

The Arrhenius-type equation is frequently used to explain how changes in temperature affect the behavior of D_{eff}.

$$D_{eff} = D_0\exp\left(-\frac{E_a}{\mathrm{R}(T + 273.15)}\right) \tag{11}$$

In Eq. (11), D_0 stands for the pre-exponential factor measured in m^2/s, E_a represents the activation energy in kJ/mol, R denotes the gas constant in kJ/(mol × K), and *T* signifies the temperature measured in °C.

2.5 Extraction procedure

For the extraction of fresh and dried pomegranate seeds, methanol-water mixture (50:50, v/v) were used in a 1:10 (solid:liquid) ratio. Using an ultraturrax, the mixture of the samples, methanol and water was homogenized

(Daihan, HG-15D). Homogenization was done at 10000 rpm. The mixtures were shaken for 2 h. Following a 10-min centrifugation at 6000 rpm, the samples were filtered using a 0.45 µm syringe filter [39].

2.6 Total phenolic content

The modified method by Singleton and Rossi [40] was employed to define the TPC. In a tube, the following ingredients were mixed: 0.5 mL of diluted pomegranate seed extracts in methanol, 7.5 g/100 g Na_2CO_3, and 2.5 mL of the tenfold diluted Folin Ciocalteu's phenol reagent. The combination was then left in a dark area for 30 min. Absorbance at 760 nm was measured using a UV-Vis spectrophotometer (UV-1800, Shimadzu, Japan). The TPC was quantified and presented as mg of gallic acid equivalent/g dry matter (mg GAE/g dry matter).

2.7 Antioxidant activity

Three different methods were utilized to measure the AA of pomegranate seeds extracts. For the 1,1-diphenyl-2-picrylhydrazyl (DPPH) method, 4.9 mL of 0.1 mmol/L DPPH that had been dissolved in methanol were added to 0.1 mL of extract. After incubating in the dark for 30 min, the absorbance at 517 nm was measured [41]. For the 2,2′-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) method, 100 µL sample was added to the tube containing 2 mL of ABTS working standard solution. To prepare this solution, 7 mM ABTS and 2.45 mM potassium persulfate were mixed and kept in the dark at room temperature for 12–16 h to allow the ABTS + radicals to form. After 10 min of incubation at 30 °C, spectrophotometry was used to measure the absorbance at 734 nm [42]. For copper-reducing antioxidant capacity (CUPRAC) method, 1 mL of distilled water, 1 mL of neocuproine (7.5 mmol/L), 1 mL of $CuCl_2$ (10 mmol/L), and 1 mL of ammonium acetate (1 mol/L) were added to the reaction mixture to complete up to 4.1 mL. After 60 min in dark incubation, spectrophotometry was used to measure the absorbance at 450 nm [43]. AA was expressed in terms of Trolox equivalents (TE)/g dry matter, denoted as mg GAE/g dry matter).

2.8 Color parameters

To ascertain color characteristics of both fresh and dried fruits, a colorimeter (CR-400 Konica, Minolta, Tokyo, Japan) was utilized. The colorimeter was calibrated using a standard illuminant D65, representing daylight conditions. Each color parameter was measured thrice and expressed as L^*, a^*, and b^*. L^* denotes the degree of blackness to whiteness, with values ranging from 0 (black) to 100 (white). Similarly, a^* represents the spectrum from green to red, with values spanning from −60 (green) to +60 (red). Lastly, b^* signifies the range from blue to yellow, with values varying from −60 (blue) to +60 (yellow). Total color change (ΔE) was computed by using L^*, a^*, and b^* using the Eq. (12):

$$\Delta E = \sqrt{\left(\Delta L^*\right)^2 + \left(a^*\right)^2 + \left(\Delta b^*\right)^2}. \tag{12}$$

Chroma (C^*), which is compared to grey color with the same luminance to assess the degree of change in hue, is a quantitative indicator of colorfulness. The formula for calculating C^* is as follows:

$$C^* = \sqrt{a^{*2} + b^{*2}}. \tag{13}$$

2.9 Statistical analysis

The analysis was performed utilizing JMP 9 software [44]. Employing a significance level of $p < 0.05$, the arithmetic means and standard deviations for each variable were calculated employing both the independent Tukey test and one-way analysis of variance. Each measurement underwent three repetitions.

3 Results and discussion

3.1 Drying curves

The *MC* data for pomegranate seeds were graphed against drying time (Fig. 1). Notably, elevating the air temperature led to a reduction in drying duration. For instance, reaching the final *MC* required approximately 540, 240, and 165 min between 55–75 °C, respectively. This indicates

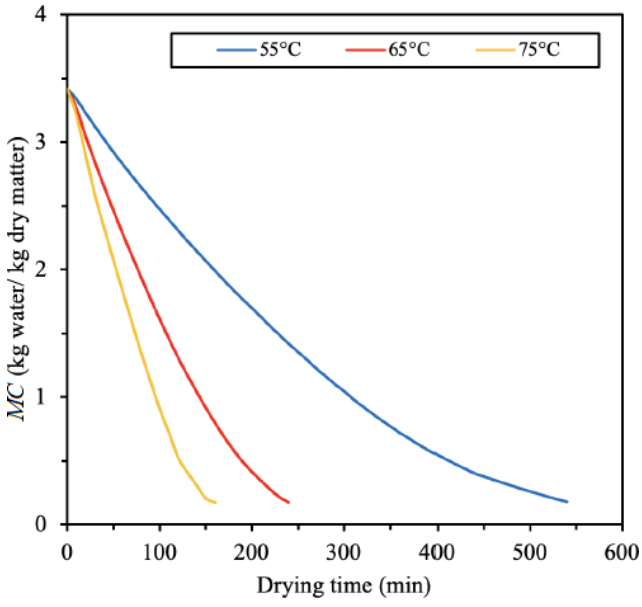

Fig. 1 The fluctuations in *MC* over time

a notable 3.3-fold increase in the average drying rate when the temperature rose from 55 to 75 °C. The heightened temperature prompts more significant heat generation within the material, thereby intensifying the vapor pressure gradient between its core and surface, consequently accelerating the drying process. Consistent with prior research, similar trends have been documented in pomegranate drying studies, underscoring the inverse relationship between drying time and temperature elevation [1, 45, 46].

3.2 Drying rate

Fig. 2 illustrates the variations in drying rate over time, revealing distinct distribution curves at different air temperatures. Notably, as the drying temperature increased, so did the drying rate, peaking at 75 °C. Analysis of the curves showed that drying predominantly occurred during the falling-rate period, without a discernible constant-rate phase. These findings align with previous research, including studies on pomegranate seeds by Adetoro et al. [22], Horuz and Maskan [46], and Alaei and Chayjan [47], which also observed a correlation between higher temperatures and accelerated drying rates, leading to reduced drying times.

3.3 Evaluation of drying models

MC values of pomegranate seeds were converted into *MR* values using Eq. (3) for mathematical modelling. The moisture ratios obtained in the experimental study were compared for compatibility with the drying models outlined through non-linear regression analysis (Table 1). Table 2 presents the R^2, P, χ^2, and *RMSE* values resulting from this statistical analysis. It is evident from Table 2 that the Aghbashlo et al. [32] model exhibited the best fit for the drying processes at various air temperatures. The R^2, P, χ^2, and *RMSE* values obtained from non-linear regression analysis for drying processes at different air temperatures ranged between 0.9994–0.9999, 0.006614–3.4038, 0.000008–0.000060, and 0.006614–0.020502, respectively. In addition, Fig. 3 holds a candle to the empirical data with data estimated using the Aghbashlo et al. [32] model for different air temperatures. As can be seen in Fig. 3, the estimated data fall on the y = x line take part

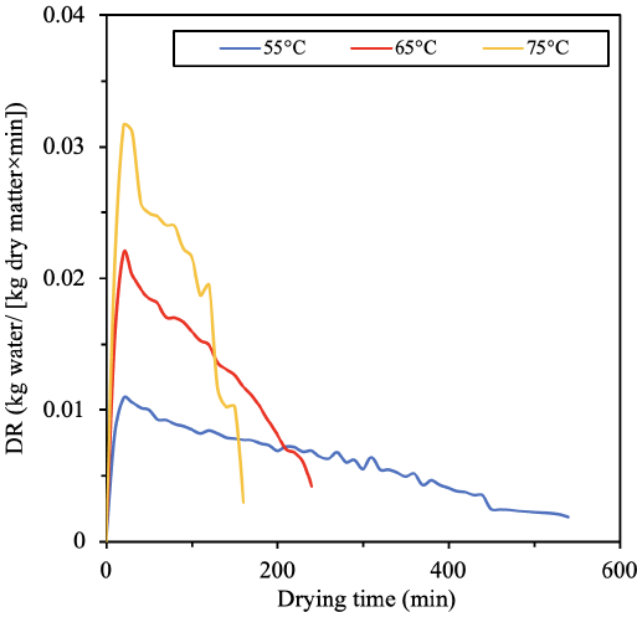

Fig. 2 Changes in the drying rate (DR) over time

Table 2 Results of the statistical analysis

T (°C)	Model number	R^2	P	χ^2	RMSE
55	1	0.9768	23.6415	0.001926	0.292710
	2	0.9842	19.1416	0.001336	0.237968
	3	0.9990	4.9030	0.000086	0.057626
	4	0.9969	7.2729	0.000255	0.103174
	5	0.9994	3.0682	0.000044	0.042318
	6	0.9998	1.9244	0.000014	0.023953
	7	0.9996	2.1872	0.000027	0.032887
	8	**0.9998**	**1.4351**	**0.000009**	**0.020157**
	9	0.9989	4.4071	0.000094	0.062386
	10	0.9928	12.1872	0.000619	0.156920
	11	0.9997	2.8790	0.000022	0.025505
	12	0.9842	19.1412	0.001336	0.237968
65	1	0.9694	27.9294	0.002786	0.230676
	2	0.9792	22.8802	0.001970	0.186579
	3	0.9990	4.4465	0.000095	0.037561
	4	0.9971	8.1214	0.000274	0.069409
	5	0.9997	2.1493	0.000025	0.020089
	6	0.9994	2.9672	0.000055	0.030366
	7	0.9751	23.5119	0.002721	0.201094
	8	**0.9999**	**0.5407**	**0.000008**	**0.006614**
	9	0.9986	5.7685	0.000131	0.047105
	10	0.9909	15.0668	0.000895	0.124823
	11	0.9996	1.7029	0.000036	0.021712
	12	0.9792	22.8800	0.001970	0.186579
75	1	0.9600	36.0175	0.004046	0.229372
	2	0.9717	30.0595	0.003051	0.190267
	3	0.9974	8.3684	0.000300	0.052992
	4	0.9965	9.3052	0.000377	0.066830
	5	0.9990	4.8130	0.000119	0.033297
	6	0.9976	7.2960	0.000254	0.050677
	7	09766	27.3933	0.003151	0.166414
	8	**0.9994**	**3.4038**	**0.000060**	**0.020502**
	9	0.9981	6.8938	0.000214	0.050979
	10	0.9882	19.4105	0.001355	0.126572
	11	0.9978	5.5661	0.000235	0.048677
	12	0.9717	30.0601	0.003051	0.190267

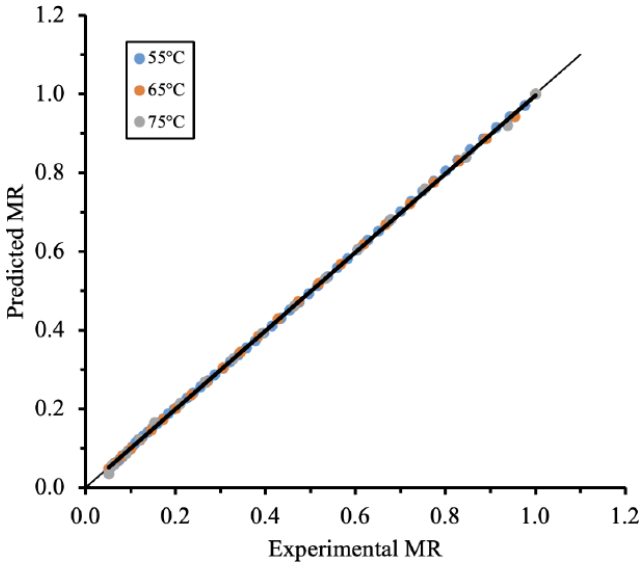

Fig. 3 Actual moisture ratios versus predicted values using the Aghbashlo et al. [32] model

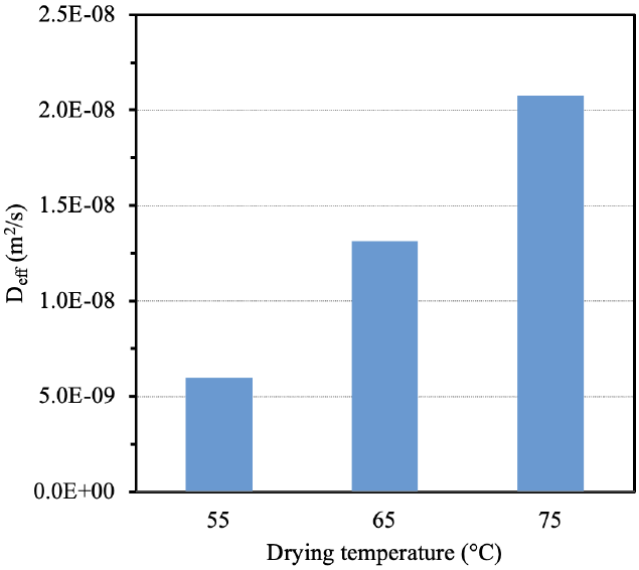

Fig. 4 The D_{eff} values at varied temperatures

on the beeline. This proves that the Aghbashlo et al. [32] model is compatible with the experimental data. Similarly, Alaei and Chayjan [47] reported that the most compatible model with the drying kinetics of pomegranate arils was the Aghbashlo et al. [32] thin-layer drying model.

3.4 The D_{eff} values

The values for D_{eff} were determined using Eq. (10) for different temperatures. The D_{eff} values for drying experiments performed at different temperatures varied between 8.76×10^{-10} and 1.96×10^{-9} m²/s, which is a typical range for drying of biological samples [48]. Increasing temperature was the main factor increasing the D_{eff} values. The calculated D_{eff} values are shown in Fig. 4 for each temperature. Similar D_{eff} values have been calculated by some authors as a result of drying pomegranate seeds with different drying methods. For example, in a study conducted by Doymaz [45], it was declared that D_{eff} values vary between $0.93–3.42 \times 10^{-10}$ m²/s. In another study, Briki et al. [7] found that D_{eff} values were between $0.87–2.64 \times 10^{-9}$ m²/s. Karaaslan et al. [49] reported in their study that D_{eff} values varied between $1.43–6.03 \times 10^{-9}$ m²/s.

3.5 The E_a value

E_a represents the energy needed to surpass the barrier for the drying process to initiate [50]. When $\ln(D_{eff})$ is plotted against $1/(T + 273.15)$, it yields a linear relationship with a slope equivalent to $(-E_a/R)$, thus enabling a straightforward estimation of E_a (Fig. 5). Eq. (14) indicates the effect of temperature on D_{eff} of the samples:

$$D_{eff} = 17.691 \exp\left(-\frac{71415}{(T+273.15)}\right) \quad \left(R^2 = 0.9817\right) \qquad (14)$$

The E_a value of samples was 59.37 kJ/mol. E_a values for different food materials generally span from 12.7 to 110 kJ/mol, as indicated by research conducted by Zogzas et al. [48]. The E_a determined in our research closely aligns with the 49.47 kJ/mol reported by Doymaz [45] for pomegranate arils. Briki et al. [7] also found a similar E_a of 45.92 kJ/mol when drying pomegranate arils using a convective dryer.

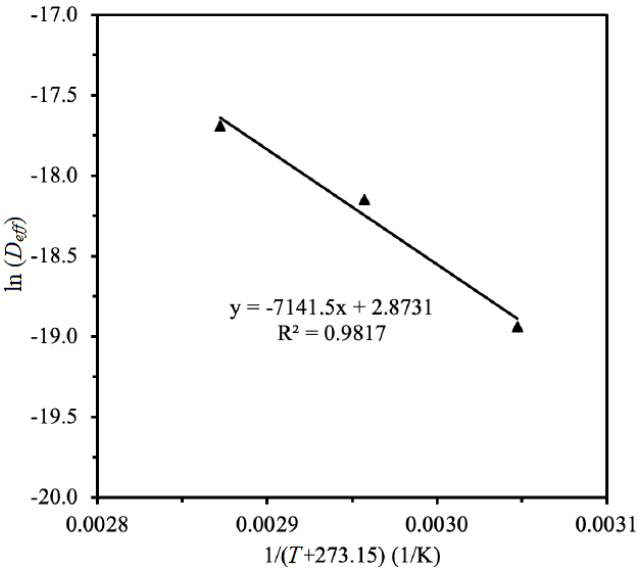

Fig. 5 Arrhenius-type relationship for temperature dependence D_{eff} of pomegranate seeds

3.6 Effects of drying on TPC and AA

Table 3 illustrates the TPC and AA of both fresh and dried pomegranate seeds across varying temperatures. The TPC analysis revealed a value of 8.58 ± 0.19 mg GAE/g dry matter for fresh pomegranate seeds. This finding aligns with previous studies reporting TPC values of 7.57 mg GAE/g dry matter [51] and 9246.81 mg GAE/kg dry matter [49]. Upon drying, a significant decrease in TPC of fresh pomegranate arils was observed ($p < 0.05$), consistent with previous research indicating a decline in TPC with increasing temperatures [7, 52, 53]. It was reported that the breakdown of phenolic compounds was triggered by the comparatively high interior temperature caused by the infrared radiation [15]. TPC value at 65 °C was significantly lower than the TPC value at 75 °C ($p < 0.05$). This may be due to the breakdown of some bioactive components into other phenolics at high temperature [1]. DPPH, ABTS and CUPRAC techniques were utilized to evaluate for AA. The results were 5.57–9.62 mg TE/g dry matter, 24.18–34.28 mg TE/g dry matter and 10.33–20.74 mg TE/g dry matter for DPPH, ABTS and CUPRAC, respectively. AA of the pomegranate resulted from its phenolic, flavonoid and anthocyanin content and their collective free radical scavenging activity [54]. Consistent with the TPC results, AA of fresh samples decreased after drying. DPPH results showed that AA results at 65 °C and 75 °C were not significantly different, but ABTS and CUPRAC results showed that AA result at 75 °C was higher than at 65 °C. This may be due to the Maillard reaction allowing the generation of some antioxidant compounds [52]. These results indicated the necessity of using more than one AA method.

3.7 Color values

Color stands as one of the utmost critical attributes that profoundly impacts the quality of the end product and shapes consumer preferences. Fruits and vegetables will lose market value if their color changes more intensely after drying [53]. The effects of drying methods on color parameters of pomegranate seeds were presented in Table 4. L^*, a^* and b^* values of fresh pomegranate arils were measured as 29.17, 12.24 and −1.83, respectively. L^* value of pomegranate seeds decreases after drying for 65 and 75 °C ($p < 0.05$). As the drying temperature increased, the decrease in L^* value was higher. This indicates that browning increases with increasing drying temperature. Similarly to our experiment, Briki et al. [7] dried pomegranate arils with convective and infrared heating at 50, 60 and 70 °C, they reported that the value of L^* decreased as the temperature increased. a^* values of drying pomegranate seeds were found 15.21, 17.67, 18.65 for 55, 65 and 75, respectively. It is possible that it resulted from the Maillard reaction, which causes red pigments to degrade and/or transform into dark pigments [1]. It was reported that decreasing in L^* value and increasing in a^* value may result from fruit browning [54]. To show the color change of dried samples, ΔE value is a significant factor [55]. ΔE values were found 3.96, 7.43 and 9.19 for 55, 65 and 75 °C, respectively. The increase in temperature resulted an increase in the total color change. It has been determined

Table 3 TPC, DPPH, ABTS and CUPRAC outcomes of both fresh and dried pomegranate seeds

Bioactive properties	Fresh pomegranate seeds	Dried pomegranate seeds		
		55 °C	65 °C	75 °C
TPC[1]	8.58 ± 0.19[a]	8.20 ± 0.12[b]	6.19 ± 0.08[c]	6.56 ± 0.08[d]
DPPH[2]	9.66 ± 0.25[a]	6.13 ± 0.12[b]	5.62 ± 0.18[c]	5.57 ± 0.05[c]
ABTS[3]	34.28 ± 0.00[a]	28.18 ± 0.15[b]	24.18 ± 0.92[d]	26.62 ± 0.34[c]
CUPRAC[4]	20.74 ± 0.58[a]	17.59 ± 0.12[b]	10.33 ± 0.36[d]	11.31 ± 0.41[c]

[a–d] Different lowercase letters on the same line indicate differences among samples subjected to different drying methods ($p < 0.05$).
[1] TPC expressed as mg GAE/g dry matter, [2] DPPH expressed as mg TE/g dry matter, [3] ABTS expressed as mg TE/g dry matter, and [4] CUPRAC expressed as mg TE/g dry matter.

Table 4 Color outcomes of both fresh and dried pomegranate seeds

Color parameters	Fresh pomegranate seeds	Dried pomegranate seeds		
		55 °C	65 °C	75 °C
L^*	29.17 ± 0.71[a]	28.56 ± 0.45[a]	26.31 ± 0.96[b]	23.86 ± 0.67[c]
a^*	12.24 ± 0.97[c]	15.21 ± 1.20[b]	17.67 ± 0.36[a]	18.65 ± 1.20[a]
b^*	−1.83 ± 0.21[d]	−1.13 ± 0.23[c]	1.46 ± 0.06[b]	2.06 ± 0.12[a]
ΔE	–	3.96[c]	7.43[b]	9.19[a]
C^*	12.37[d]	15.92[c]	17.73[b]	18.76[a]

[a–d] Different lowercase letters on the same line indicate differences among samples subjected to different drying methods ($p < 0.05$).

in other studies that the ΔE value increases as the temperature increases in infrared drying [53, 56]. The high chroma value of the samples shows how intense the color is as seen by humans [57]. The C^* value of the fresh sample was determined to be significantly lower compared to the dried samples, with a statistical significance level of $p < 0.05$. The cause of this is due to the rising in a^* and b^* values with the increase of pigment degradation due to non-enzymatic browning with increasing temperature. Similar results for the C^* value was detected in another study [1].

4 Conclusions

In this study, pomegranate seeds were dried in an infrared dryer at different air temperatures. It was observed that the temperature value was the main parameter affecting the drying process. It was clearly found that pomegranate seeds dried at higher temperatures dried faster. The drying process was modelled mathematically and the Aghbashlo et al. [32] model was determined as the most appropriate model. The D_{eff} values of pomegranate seeds ranged between 8.76×10^{-10} and 1.96×10^{-9} m^2/s. The E_a was determined as 59.37 kJ/mol using the Arrhenius equation. It was determined that pomegranate seeds dried at 55 °C had higher TPC, AA and lower color change compared to 65 °C and 75 °C. It has been reported that the color values of pomegranate seeds are directly affected by temperature. Therefore, this study recommends drying pomegranate seeds at 55 °C with an infrared dryer.

References

[1] Süfer, Ö., Palazoğlu, T. K. "A study on hot-air drying of pomegranate", Journal of Thermal Analysis and Calorimetry, 137(6), pp. 1981–1990, 2019. https://doi.org/10.1007/s10973-019-08102-1

[2] Allahdad, Z., Nasiri, M., Varidi, M., Varidi, M. J. "Effect of sonication on osmotic dehydration and subsequent air-drying of pomegranate arils", Journal of Food Engineering, 244, pp. 202–211, 2019. https://doi.org/10.1016/j.jfoodeng.2018.09.017

[3] Šavikin, K., Nastić, N., Janković, T., Bigović, D., Miličević, B., Vidović, S., Menković, N., Vladić, J. "Effect of Type and Concentration of Carrier Material on the Encapsulation of Pomegranate Peel Using Spray Drying Method", Foods, 10(9), 1968, 2021. https://doi.org/10.3390/foods10091968

[4] Melgarejo-Sánchez, P., Núñez-Gómez, D., Martínez-Nicolás, J. J., Hernández, F., Legua, P., Melgarejo, P. "Pomegranate variety and pomegranate plant part, relevance from bioactive point of view: a review", Bioresources and Bioprocessing, 8(1), 2, 2021. https://doi.org/10.1186/s40643-020-00351-5

[5] Hamid, Thakur, N. S., Thakur, A., Kumar, P. "Effect of different drying modes on phenolics and antioxidant potential of different parts of wild pomegranate fruits", Scientia Horticulturae, 274, 109656, 2020. https://doi.org/10.1016/j.scienta.2020.109656

[6] Mphahlele, R. R., Pathare, P. B., Opara, U. L. "Drying kinetics of pomegranate fruit peel (cv. Wonderful)", Scientific African, 5, e00145, 2019. https://doi.org/10.1016/j.sciaf.2019.e00145

[7] Briki, S., Zitouni, B., Bechaa, B., Amiali, M. "Comparison of convective and infrared heating as means of drying pomegranate arils (*Punica granatum* L.)", Heat and Mass Transfer, 55(11), pp. 3189–3199, 2019. https://doi.org/10.1007/s00231-019-02644-8

[8] Kumar, N., Pratibha, Neeraj, Sami, R., Khojah, E., Aljahani, A. H., Al-Mushhin, A. A. M. "Effects of drying methods and solvent extraction on quantification of major bioactive compounds in pomegranate peel waste using HPLC", Scientific Reports, 12(1), 8000, 2022. https://doi.org/10.1038/s41598-022-11881-7

[9] Aksoy, A., Karasu, S., Akcicek, A., Kayacan, S. "Effects of Different Drying Methods on Drying Kinetics, Microstructure, Color, and the Rehydration Ratio of Minced Meat", Foods, 8(6), 216, 2019. https://doi.org/10.3390/foods8060216

[10] Kong, D., Wang, Y., Li, M., Liu, X., Huang, M., Li, X. "Analysis of drying kinetics, energy and microstructural properties of turnips using a solar drying system", Solar Energy, 230, pp. 721–731, 2021. https://doi.org/10.1016/j.solener.2021.10.073

[11] Menon, A., Stojceska, V., Tassou, S. A. "A systematic review on the recent advances of the energy efficiency improvements in non-conventional food drying technologies", Trends in Food Science & Technology, 100, pp. 67–76, 2020. https://doi.org/10.1016/j.tifs.2020.03.014

[12] Thamkaew, G., Sjöholm, I., Galindo, F. G. "A review of drying methods for improving the quality of dried herbs", Critical Reviews in Food Science and Nutrition, 61(11), pp. 1763–1786, 2021. https://doi.org/10.1080/10408398.2020.1765309

[13] Kaveh, M., Golpour, I., Gonçalves, J. C., Ghafouri, S., Guiné, R. "Determination of drying kinetics, specific energy consumption, shrinkage, and colour properties of pomegranate arils submitted to microwave and convective drying", Open Agriculture, 6(1), pp. 230–242, 2021. https://doi.org/10.1515/opag-2020-0209

[14] Delfiya, D. S. A., Prashob, K., Murali, S., Alfiya, P. V., Samuel, M. P., Pandiselvam, R. "Drying kinetics of food materials in infrared radiation drying: A review", Journal of Food Process Engineering, 45(6), e13810, 2022. https://doi.org/10.1111/jfpe.13810

[15] Huang, D., Yang, P., Tang, X., Luo, L., Sunden, B. "Application of infrared radiation in the drying of food products", Trends in Food Science & Technology, 110, pp. 765–777, 2021. https://doi.org/10.1016/j.tifs.2021.02.039

[16] Cheng, S., Su, W., Yuan, L., Tan, M. "Recent developments of drying techniques for aquatic products: With emphasis on drying process monitoring with innovative methods", Drying Technology, 39(11), pp. 1577–1594, 2021. https://doi.org/10.1080/07373937.2021.1895205

[17] Kipcak, A. S., Doymaz, İ. "Microwave and infrared drying kinetics and energy consumption of cherry tomatoes", Chemical Industry & Chemical Engineering Quarterly, 26(2), pp. 203–212, 2020. https://doi.org/10.2298/CICEQ190916039K

[18] Kipcak, A. S., Doymaz, İ., Derun, E. M. "Infrared Drying Kinetics of Blue Mussels and Physical Properties", Chemical Industry & Chemical Engineering Quarterly, 25(1), pp. 1–10, 2019. https://doi.org/10.2298/CICEQ170808014K

[19] Salehi, F. "Recent Applications and Potential of Infrared Dryer Systems for Drying Various Agricultural Products: A Review", International Journal of Fruit Science, 20(3), pp. 586–602, 2020. https://doi.org/10.1080/15538362.2019.1616243

[20] Wang, H., Liu, Z.-L., Vidyarthi, S. K., Wang, Q.-H., Gao, L., Li, B.-R., Wei, Q., Liu, Y.-H., Xiao, H.-W. "Effects of different drying methods on drying kinetics, physicochemical properties, microstructure, and energy consumption of potato (*Solanum tuberosum* L.) cubes", Drying Technology, 39(3), pp. 418–431, 2021. https://doi.org/10.1080/07373937.2020.1818254

[21] Doymaz, İ. "Influence of Infrared Drying on Some Quality Properties of Nashi Pear (*Pyrus pyrifolia*) Slices", Erwerbs-Obstbau, 65(1), pp. 47–54, 2023. https://doi.org/10.1007/s10341-022-00786-4

[22] Adetoro, A. O., Opara, U. L., Fawole, O. A. "Effect of Blanching on Enzyme Inactivation, Physicochemical Attributes and Antioxidant Capacity of Hot-Air Dried Pomegranate (*Punica granatum* L.) arils (cv. Wonderful)", Processes, 9(1), 25, 2021. https://doi.org/10.3390/pr9010025

[23] El Broudi, S., Zehhar, N., Abdenouri, N., Boussaid, A., Hafidi, A., Bouamama, H., Benkhalti, F. "Investigation of drying kinetics and drying conditions on biochemical, sensory, and microstructural parameters of "Sefri" pomegranate arils (*Punica Granatum* L. a Moroccan variety)", Revista Mexicana de Ingeniería Química, 21(3), Alim2813, 2022. https://doi.org/10.24275/rmiq/Alim2813

[24] AOAC "Official Method of Analysis (Volume 1)", Association of Official Analytical Chemists, 1990. ISBN 0-935584-42-0 [online] Available at: https://law.resource.org/pub/us/cfr/ibr/002/aoac.methods.1.1990.pdf [Accessed: 21 November 2024]

[25] Lewis, W. K. "The Rate of Drying of Solid Materials", Journal of Industrial & Engineering Chemistry, 13(5), pp. 427–432, 1921. https://doi.org/10.1021/ie50137a021

[26] Henderson, S. M., Pabis, S. "Grain drying theory: IV. The effect of air flow rate on the drying index", Journal of Agricultural Engineering Research, 7(2), pp. 85–89, 1962.

[27] Kingsly, A. R. P., Balasubramaniam, V. M., Rastogi, N. K. "Effect of high-pressure processing on texture and drying behavior of pineapple", Journal of Food Process Engineering, 32(3), pp. 369–381, 2009. https://doi.org/10.1111/j.1745-4530.2007.00221.x

[28] Page, G. E. "Factors influencing the maximum rates of air drying shelled corn in thin layers", MSc Thesis, Purdue University, 1949.

[29] Midilli, A., Kucuk, H. "Mathematical modeling of thin layer drying of pistachio by using solar energy", Energy Conversion and Management, 44(7), pp. 1111–1122, 2003. https://doi.org/10.1016/S0196-8904(02)00099-7

[30] Wang, C. Y., Singh, R. P. "Use of variable equilibrium moisture content in modeling rice drying", Transactions of American Society of Agricultural Engineers, 11(6), pp. 668–672, 1978.

[31] Alibaş, İ. (2012). "Asma yaprağının (*Vitis vinifera* L.) mikrodalga enerjisiyle kurutulması ve bazı kalite parametrelerinin belirlenmesi" (Microwave Drying of Grapevine (*Vitis vinifera* L.) Leaves and Determination of Some Quality Parameters), Journal of Agricultural Sciences, 18(1), pp. 43–53. (in Turkish) https://doi.org/10.1501/Tarimbil_0000001191

[32] Aghbashlo, M., Kianmehr, M. H., Khani, S., Ghasemi, M. "Mathematical modelling of thin-layer drying of carrot", International Agrophysics, 23(4), pp. 313–317, 2009.

[33] Chandra, P. K., Singh, R. P. "Applications", In: Applied Numerical Methods for Food and Agricultural Engineers, CRC Press, 1994, pp. 290–320. ISBN 9781315137650 https://doi.org/10.1201/9781315137650

[34] Jena, S., Das, H. "Modelling for vacuum drying characteristics of coconut presscake", Journal of Food Engineering, 79(1), pp. 92–99, 2007. https://doi.org/10.1016/j.jfoodeng.2006.01.032

[35] Vega-Gálvez, A., Lemus-Mondaca, R., Bilbao-Sáinz, C., Yagnam, F., Rojas, A. "Mass transfer kinetics during convective drying of red pepper var. Hungarian (*Capsicum annuum* L.): Mathematical modeling and evaluation of kinetic parameters", Journal of Food Process Engineering, 31(1), pp. 120–137, 2008. https://doi.org/10.1111/j.1745-4530.2007.00145.x

[36] Vega-Gálvez, A., Andrés, A., Gonzalez, E., Notte-Cuello, E., Chacana, M., Lemus-Mondaca, R. "Mathematical modelling on the drying process of yellow squat lobster (*Cervimunida jhoni*) fishery waste for animal feed", Animal Feed Science and Technology, 151(3–4), pp. 268–279, 2009. https://doi.org/10.1016/j.anifeedsci.2009.01.003

[37] Kipcak, A. S., İsmail, O. "Comparison of the microwave drying kinetics of culture and natural asparagus", Acta Scientiarum. Technology, 40, e39922, 2018. https://doi.org/10.4025/actascitechnol.v40i1.39922

[38] Kipcak, A. S., Derun, E. M., Tugrul, N., Doymaz, İ. "Drying characteristics of blue mussels by traditional methods", Chemical Industry & Chemical Engineering Quarterly, 27(3), pp. 279–288, 2021. https://doi.org/10.2298/CICEQ200920046K

[39] Kayacan, S., Karasu, S., Akman, P. K., Goktas, H., Doymaz, I., Sagdic, O. "Effect of different drying methods on total bioactive compounds, phenolic profile, *in vitro* bioaccessibility of phenolic and HMF formation of persimmon", LWT, 118, 108830, 2020. https://doi.org/10.1016/j.lwt.2019.108830

[40] Singleton, V. L., Rossi, J. A. "Colorimetry of Total Phenolics with Phosphomolybdic-Phosphotungstic Acid Reagents", American Journal of Enology and Viticulture, 16(3), pp. 144–158, 1965. https://doi.org/10.5344/ajev.1965.16.3.144

[41] Singh, R. P., Chidambara Murthy, K. N., Jayaprakasha, G. K. "Studies on the Antioxidant Activity of Pomegranate (*Punicagranatum*) Peel and Seed Extracts Using in Vitro Models", Journal of Agricultural and Food Chemistry, 50(1), pp. 81–86, 2002. https://doi.org/10.1021/jf010865b

[42] Re, R., Pellegrini, N., Proteggenete, A., Pannala, A., Yang, M., Rice-Evans, C. "Antioxidant activity applying an improved ABTS radical cation decolorization assay", Free Radical Biology and Medicine, 26(9–10), pp. 1231–1237, 1999. https://doi.org/10.1016/S0891-5849(98)00315-3

[43] Apak, R., Güçlü, K., Özyürek, M., Karademir, S. E. "Novel Total Antioxidant Capacity Index for Dietary Polyphenols and Vitamins C and E, Using Their Cupric Ion Reducing Capability in the Presence of Neocuproine: CUPRAC Method", Journal of Agricultural and Food Chemistry, 52(26), pp. 7970–7981, 2004. https://doi.org/10.1021/jf048741x

[44] JMP "JMP Statistical Discovery softwer, (9.0)", [computer program] Available at: https://www.jmp.com/en_us/software/data-analysis-software.html [Accessed: 03 November 2024]

[45] Doymaz, İ. "Prediction of Drying Characteristics of Pomegranate Arils", Food Analytical Methods, 5(4), pp. 841–848, 2012.

[46] Horuz, E., Maskan, M. "Hot air and microwave drying of pomegranate (*Punica granatum* L.) arils", Journal of Food Science and Technology, 52(1), pp. 285–293, 2015. https://doi.org/10.1007/s13197-013-1032-9

[47] Alaei, B., Chayjan, R. A. "Drying Characteristics of Pomegranate Arils Under Near Infrared-Vacuum Conditions", Journal of Food Processing and Preservation, 39(5), pp. 469–479, 2015. https://doi.org/10.1111/jfpp.12252

[48] Zogzas, N. P., Maroulis, Z. B., Marinos-Kouris, D. "Moisture Diffusivity Data Compilation in Foodstuffs", Drying Technology, 14(10), pp. 2225–2253, 1996. https://doi.org/10.1080/07373939608917205

[49] Karaaslan, M., Yilmaz, F. M., Cesur, Ö., Vardin, H., Ikinci, A., Dalgiç, A. C. "Drying kinetics and thermal degradation of phenolic compounds and anthocyanins in pomegranate arils dried under vacuum conditions", International Journal of Food Science & Technology, 49(2), pp. 595–605, 2014. https://doi.org/10.1111/ijfs.12342

[50] Resende, O., de Oliveira, D. E. C., Chaves, T. H., Ferreira, J., Bessa, V. "Kinetics and thermodynamic properties of the drying process of sorghum (*Sorghum bicolor* [L.] Moench) grains", African Journal of Agricultural Research, 9(32), pp. 2453–2462, 2014. https://doi.org/10.5897/AJAR2014.8808

[51] Calín-Sánchez, Á., Figiel, A., Hernández, F., Melgarejo, P., Lech, K., Carbonell-Barrachina, Á. A. "Chemical Composition, Antioxidant Capacity, and Sensory Quality of Pomegranate (*Punica granatum* L.) Arils and Rind as Affected by Drying Method", Food and Bioprocess Technology, 6(7), pp. 1644–1654, 2013. https://doi.org/10.1007/s11947-012-0790-0

[52] Bchir, B., Besbes, S., Karoui, R., Attia, H., Paquot, M., Blecker, C. "Effect of Air-Drying Conditions on Physico-chemical Properties of Osmotically Pre-treated Pomegranate Seeds", Food and Bioprocess Technology, 5(5), pp. 1840–1852, 2012. https://doi.org/10.1007/s11947-010-0469-3

[53] Doymaz, İ., Karasu, S., Baslar, M. "Effects of infrared heating on drying kinetics, antioxidant activity, phenolic content, and color of jujube fruit", Journal of Food Measurement and Characterization, 10(2), pp. 283–291, 2016. https://doi.org/10.1007/s11694-016-9305-4

[54] Başlar, M., Karasu, S., Kiliçli, M., Us, A. A., Sağdiç, O. "Degradation Kinetics of Bioactive Compounds and Antioxidant Activity of Pomegranate Arils during the Drying Process", International Journal of Food Engineering, 10(4), pp. 839–848, 2014. https://doi.org/10.1515/ijfe-2014-0080

[55] Goztepe, B., Kayacan, S., Bozkurt, F., Tomas, M., Sagdic, O., Karasu, S. "Drying kinetics, total bioactive compounds, antioxidant activity, phenolic profile, lycopene and β-carotene content and color quality of Rosehip dehydrated by different methods", LWT, 153, 112476, 2022. https://doi.org/10.1016/j.lwt.2021.112476

[56] Cao, Z.-Z., Zhou, L.-Y., Bi, J.-F., Yi, J.-Y., Chen, Q.-Q., Wu, X.-Y., Zheng, J.-K., Li, S.-R. "Effect of different drying technologies on drying characteristics and quality of red pepper (*Capsicum frutescens* L.): A comparative study", Journal of the Science of Food and Agriculture, 96(10), pp. 3596–3603, 2016. https://doi.org/10.1002/jsfa.7549

[57] Pathare, P. B., Opara, U. L., Al-Julanda Al-Said, F. "Colour Measurement and Analysis in Fresh and Processed Foods: A Review", Food and Bioprocess Technology, 6(1), pp. 36–60, 2013. https://doi.org/10.1007/s11947-012-0867-9