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Kızılötesi kurutmada hurma (*Phoenix dactylifera* L.) pestilinin efektif difüzyon katsayısının belirlenmesi: Pişme süresinin etkisi

Effective diffusivity determination of date (*Phoenix dactylifera* L.) leather in infrared drying: Effect of cooking time

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Öz

Geleneksel kurutma yöntemlerinde gerçekleşen uzun işlem süreleri hızlı teknolojiler kullanılarak iyileştirilebilmektedir. Kızılötesi kurutma bu hızlı yöntemlerden biridir. Sağlık ve zindelik ürünlerine ilişkin tüketici bilinci yükselmiş ve Covid-19 pandemisi ile de güçlenmiştir. Bu nedenle, doğal içeriklerle formüle edilmiş atıştırmalık ürünlerin tüketim eğilimi artmıştır. Bu eğilimin artarak devam edeceği öngörülmektedir. Bu konudan hareketle; bu çalışmada hurma ile pestil üretimi kızılötesi kurutma ile yapılmış ve pişirme süresinin kuruma davranışına etkisi incelenmiştir. Öncelikle hurmalar yıkanıp, çekirdekleri çıkarıldıktan sonra 1:2,5 (hurma:su) oranında su ilave edilerek 30, 45 ve 60 dakika pişirilmiştir. Daha sonra, numuneler preslenmiş ve 10 mm kalınlığında kurutulmuştur. Kuruma eğrileri birinci dereceden kuruma kinetiği göstermiş ve meyve pestillerinin efektif difüzyon katsayıları (D_{eff}) 30, 45 ve 60 dakikalık pişirme süreleri için sırasıyla $1{,}53\times10^{-9}$, $1{,}70\times10^{-9}$ ve $1{,}74\times10^{-9}$ m²/s olarak bulunmuştur.

Anahtar kelimeler: Pişme süresi, Hurma, Efektif nem difüzyon katsayısı, Pestil, Kızılötesi kurutma

Abstract

Longer process times in conventional drying methods can be improved by using rapid technologies. Infrared drying is one of these faster methods. Consumer awareness on health and wellness products has increased and boosted with Covid-19 pandemic. Therefore, the consumption trend of snack products formulated with natural ingredients has increased. It is estimated that this trend will continue to rise. In accordance with this, fruit leather production from dates was done by infrared drying and the effect of cooking time on drying behavior was investigated. Firstly, dates were washed and seeds were removed, then water was added at a ratio of 1:2.5 (dates:water), and cooked for 30, 45 and 60 min. Samples were pressed and dried at 10 mm thickness. Drying curves showed first-order drying kinetics and effective moisture diffusivity (D_{eff}) of fruit leathers were found as 1.53×10^{-9}, 1.70×10^{-9} and 1.74×10^{-9} m²/s for 30, 45 and 60 min of cooking time, respectively.

Keywords: Cooking time, Dates, Effective moisture diffusivity, Fruit leather, Infrared drying

1 Introduction

One of the earliest trees that humans have cultivated is the date palm [1]. Dates are marketed as high-value fruit crops and are mostly grown in the desert areas of Southwest Asia and North Africa [2]. The fruit represents a food security crop in these regions providing value for nutrition for the last 5000 years [3]. Date is a very popular fruit for its tasty sweetness, nutritional, and medicinal properties [4] and can be consumed in fresh or dried form. Dates production volume increased from 8.40 million metric tons in 2017 to 9.66 million metric tons in 2021, it is ranked as second after dried grapes in the global dried fruit production, and the global market value of the date palm industry is expected to be 16.11, 17.07, and 19.76 million U.S. dollars for 2024, 2025, and 2026 [5]. Date has a vital role in economic production not only with the fruit but also with the by-products such as pasta, flour, syrup, vinegar, yeast, and confectionery [6].

Date (palm *Phoenix dactylifera* L.) fruit is in the family of *Arecaceae* (or *palmae*) [3]. Although commercial cultivars are few, there are more than 5000 date palm cultivars globally that vary in terms of their genetic, morphological, and nutritional characteristics [7]. The fruit is made up of a seed and fleshy pericarp which constitutes 85-90% of the weight of a date fruit [8]. Typical weight per fruit ranges between 2 and 60 g, and length and width can vary from 18 to 110 and 8 to 32 mm, respectively [2]. Sugars including sucrose, fructose, and glucose, which make up two-thirds of date flesh, are found naturally in dates [9]. Fresh dates contain about 4.03 g sucrose, 19.4 g fructose, and 22.8 g glucose in 100 g; whereas average sucrose, fructose, and glucose quantities in dried dates are 11.6 g, 29.4 g, and 30.4 g per 100 g, respectively [2]. Besides its carbohydrates (80-90%), date fruit is also an excellent source of dietary fiber (6.4-11.5%), protein (2.3-5.6%), minerals (0.10-916 mg/ 100 g dry weight), and vitamins (3900 µg Vitamin C, 78.67 µg Vitamin B_1, 116.5 µg Vitamin B_2, 1442 µg of Vitamin B_3, and 28.85 µg Vitamin A per 100 g) [2, 4]. The amount of quantities of these macro- and micro-nutrients depend on the cultivar type and maturity stage [7]. There are 23 different amino acid types in date proteins, and glutamic acid, aspartic acid, histidine, proline, cystine, lysine,

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tyrosine, phenylalanine, arginine, valine, leucine, isoleucine, glycine, threonine, methionine, alanine, and serine are among the amino acids found in the majority of date cultivars, some of these amino acids are not present in popular fruits like bananas, apples, and oranges [9]. Magnesium, copper, selenium, and potassium are among the top ten reported minerals for dates and fruit is a good source of antioxidants, especially phenolics and carotenoids [2]. Varying degrees of antioxidant and antimutagenic activity can be attributed to phenolics and carotenoids (anthocyanins and flavonoids) [9] and total phenolics found in dates have more antioxidant activity with respect to ascorbic acid [10]. Moreover, the date palm has other beneficial properties like antifungal, antiviral, neuroprotective, and hepatoprotective and antihyperlipidemic activity [11]. Due to these mentioned nutritional components and benefits, dates can be regarded as a good example of functional food [2] and can play an important role in nutrition and health. Therefore, the development of food products formulated with dates is essential.

Dates should be dried for safe storage since they are prone to microbial deterioration due to their high moisture content at the time of harvest and drying is one of the earliest methods for food preservation to increase the shelf life [4]. Fruit leather (also known as fruit bar, or fruit slab) is a dried fruit-based confectionery dietary product that is frequently consumed as a snack or dessert [12]. The name for “fruit leather” comes from its chewy and soft texture and the product is a historic method to preserve fruits [13]. Drying has been reported as a fruit preservation technique as early as 1700 BCE and at that time whole and macerated fruits like figs, dates, and apricots were sun-dried till a chewy and leather-like texture was attained [14]. The benefits of fruit leathers include highly dense nutritional value, ease of storage, and potential for value addition, which make them healthy substitutes for snack products [15]. Any type of fruit can be used for fruit leather, the product is made by pureeing the fruits (with or without the addition of other ingredients) and then allowing them to dry sufficiently and then fruit leather is cut into strips, rolled up, and stored for future use [12, 13]. The production process of fruit leather may change due to the fruit type, the nature of other recipe ingredients, and the drying method [12]. Commercial fruit leather production has taken many forms over the years from rolled-up leathers from small vendors to formed fruit snacks, chips, and chews from large-scale producers [13].

Open sun drying is the most simple and traditional method since it is cheap and convenient, however, it leads to low-quality products due to the risk of insect infestation and foreign material contamination [4]. In addition, it depends on weather conditions and requires manual operations [12]. The drying time of fruit leathers has been reported to be 1-2 days when conventional open sun drying is conducted [16]. Hence, alternative drying techniques were developed to overcome these advantages of hygiene and time and they provide safe, fast, and controllable processes [17]. Besides traditional sun drying, tunnel and forced air circulation dryers have been used in the production of fruit leathers and convective dryer with hot air/direct combustion gases constitutes more than 85% of the industrial dryers [12]. Using the wrong drying method causes irreversible damage to the final product’s quality in many processes [18]. Fruit leather can be produced at a high quality with modern drying systems including direct, indirect, infrared, and microwave dryers.

Infrared radiation is the part of the sun’s electromagnetic spectrum, which is predominantly responsible for the heating effect of the sun. Infrared radiation can be divided into near-infrared radiation, mid-infrared radiation and far-infrared radiation and lies in the wavelength range between 0.78 and 1000 µm [19]. Radiation impinges the material, penetrates it and the radiation energy is converted into heat when radiation is selected as the heating method for moist materials [20]. As a material is heated intensely, the temperature difference in the material reduces in a short time. Hence, the consumption of energy in infrared heating is lesser. Without heating the surrounding air, infrared energy is transferred from the heating element to the surface of the material [21]. Short heating times, rapid processing, reduced chance of flavor loss, preservation of vitamins in food products, equipment compactness and solute migration absence from inner to outer regions are some of the benefits of infrared radiation with respect to conventional heating methods [22]. Infrared heating is particularly very suitable for the drying of thin layer materials with large surfaces exposed to radiation [23], therefore it is very appropriate to dry fruit leather products. Application of infrared drying methods to dry fruits and vegetables such as apple, quince, grapefruit, lemon, persimmon, banana, peach, mushroom, carrot, pumpkin, garlic, and onion are rather common [23], but studies regarding infrared drying of nutritive and functional dates and fruit leather made from dates is very limited. In a study, heat and mass transfer were investigated for the combined convective and far-infrared drying of longan leather [24]. Shorter drying times of 520, 440, and 400 min were seen for combined convective and far infrared drying at 1.90, 3.03, and 4.20 kW/m^2 heat flux, respectively, whereas it took 750 min in hot air drying at 70°C [24]. Peach leather was produced with different drying methods including infrared drying and it was seen that 210 min of infrared drying resulted in the best color, flavor, and appearance when compared to 300 min of hot air, 210 min of hot air-assisted radio frequency and 180 min of microwave-assisted hot air drying [25]. In another study, rosehip leather was prepared with hot air and infrared drying, and it was observed that infrared drying had 25% shorter drying times with respect to hot air drying at 60°C [26]. Banana leather was also investigated with far infrared assisted refractance window drying and it was seen that 46 min of hot air drying time was reduced by far infrared assisted refractance window to 14 and 12 min at infrared parameters of 50°C and 60°C, respectively [27].

Consumer awareness on health and wellness food products has been increased and boosted with Covid-19 pandemic. Hence, the consumption trend of sweet snack products formulated with natural ingredients such as fruits and vegetables, with no/reduced added sugar and flour and that are convenient to prepare has increased considerably. It is estimated that this trend will continue to rise. Fruit leathers provide important macro- and micro-nutrients, and they are affordable and practical alternatives for eating fruit that does not need to be refrigerated while being transported and stored [28]. Dates leather can be a healthy and convenient option for consumers with key nutritional components like dietary fibers, minerals, vitamins, and antioxidants as mentioned previously. The drying process is one of the most important factors affecting the quality of the final product [29]. The cooking stage is one of the important steps in manufacturing affecting both quality and energy consumption (hence cost) of the final product. Therefore, in this study, it was aimed to produce dates leather with no added sugar and/or flour by infrared drying and to investigate the effect of cooking time on drying behavior. Scarcity of the studies regarding infrared dried fruit leathers might be due to the high cost of infrared dryers. In this study, a moisture analyzer with an infrared drying mechanism was employed for infrared drying. Hence, another aim of the study was to determine the suitability of the instrument for small-batch fruit leather drying trials in an economical, sustainable, and modern way.

2 Material and methods

2.1 Materials

Dried dates with 75 g carbohydrates, 1.8 g proteins, 6.7 g dietary fiber, 0.2 g fat, and 22.98% moisture content were supplied from a local market in İstanbul, Türkiye. Bottled water with 7.34 pH, 32.2 mg/L calcium, 4.2 mg/L magnesium, 0.2 mg/L potassium, and 5.4 mg/L sodium was obtained from a local market in İstanbul, Türkiye and used in the experiments.

2.2 Preparation of fruit leather

Figure 1 demonstrates the preparation steps of fruit leather from dates. First of all, the seeds of the dried dates were removed with the use of knife and bottled water was added to the dates at 1:2.5 (dates:water) ratio. The sample was cooked in a pot for 30 min or 45 min or 60 min with electric heating (Kumtel KH/LX 7010, Kayseri, Türkiye). Then, the sample was pressed with a blender (Moulinex, DDF4 Optipro, Cedex, France) to obtain a homogeneous marmalade. Marmalade was transferred into a weighted petri dish, kept in 100°C oven and the sample stayed in the oven until steady state mass was reached for the determination of initial moisture content. Infrared drying experiments were conducted with a moisture analyzer instrument (Mettler Toledo, HG 53, Greisensee, Switzerland) operating with infrared heating at 3 W power and 160°C drying temperature. Moisture analyzer utilizes thermogravimetric principle, in which the fruit leather sample is weighted initially by the instrument before being immediately heated by the infrared dryer unit causing the moisture to evaporate. It continually measures the fruit leather's weight during the drying process and shows the moisture loss on the screen. Fruit leathers of 10 mm thickness were dried for 155 minutes, and drying data from the screen of the instrument were recorded.

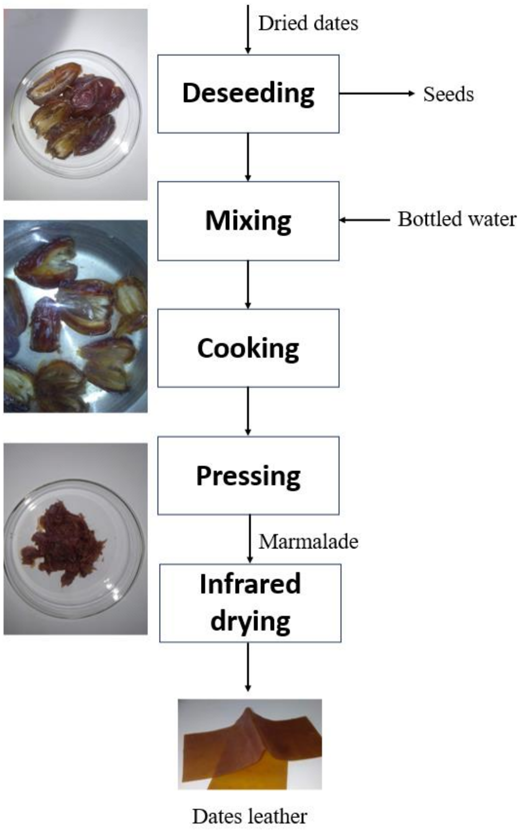

Figure 1. Preparation of fruit leather from dates

2.3 Effective moisture diffusivity

Diffusion is the main mechanism for moisture transport to the surface for evaporation, and effective moisture diffusion coefficient (D_{eff}) can be used to describe inherent moisture content of biological materials [30]. D_{eff} determines the diffusion characteristics of moisture [31]. Fick's Second Law of Diffusion is used to interpret experimental drying data for describing drying behavior and for determination of moisture diffusivity [32, 33]. With the assumptions of uniform initial moisture distribution, constant diffusivity, uni-dimensional moisture movement without volume change, negligible resistance, and long drying time (system reached equilibrium at the end of the drying); solution for Fick's diffusion equation can be written in the form of Equation (1) for slab [31, 32, 33, 17] as:

$$M_R = \frac{M - M_e}{M_i - M_e} = \frac{8}{\pi^2} \exp(-\frac{\pi^2 D_{eff} t}{L^2}) \quad (1)$$

where M_R shows moisture ratio (dimensionless), M is moisture content at any time (kg water/kg dry solids), M_e is equilibrium moisture content (kg water/kg dry solids), M_i is initial moisture content (kg water/kg dry solids), D_{eff} is effective moisture diffusion coefficient (m^2/s), t is drying time (s), and L is half of the leather thickness (m). The thickness of the fruit leather samples was 10 mm.

Equation (1) can be written in a linear form by taking the natural logarithm of both sides as Equation (2) and effective moisture diffusivity was calculated from the slope of Equation (2) [31, 32].

$$\ln M_R = -\frac{\pi^2 D_{eff} t}{L^2} + \ln \frac{8}{\pi^2} \qquad (2)$$

2.4 Statistical analysis

CurveExpert Professional 2.7.3 with 95% level of confidence was used to find the slope of the linear Equation (2). Fitted and experimental data were analyzed with coefficient of determination (R^2). Experiments were carried out in three replications.

3 Results and discussion

Initial moisture content of fruit leathers was found as 2.08, 1.86, and 1.39 g water/g dry solids for 30, 45, and 60 min of cooking, respectively. The effect of cooking time on drying curves for dates leather is shown in Figure 2. The moisture content of all samples decreased with the increase in drying time. Curves showed a clear effect of cooking time in the preparation stage of fruit leathers on the overall drying behavior of the samples. The impact was seen especially for the first 60 min of drying, where the moisture decrease was more rapid. This was expected since maximum amount of water in the fruit leathers was available at the initial periods of drying, thin layers of samples absorbed more heat and higher amount of moisture evaporated from the leathers was higher [25].

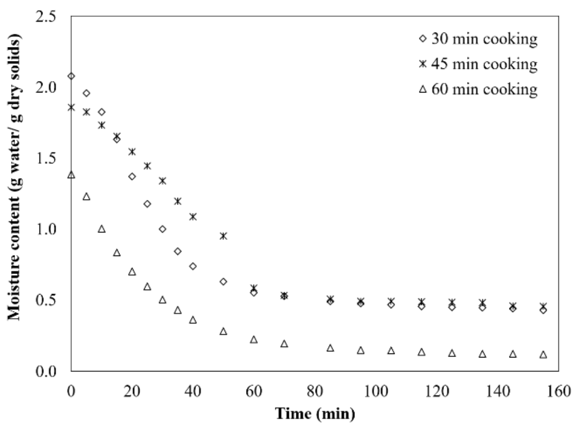

Figure 2. Effect of cooking time on moisture content during infrared drying of dates leather

It was also observed that 1.65, 1.40, and 1.27 g moisture/g dry solids were removed during 155 min of infrared drying for the fruit leathers cooked for 30, 45, and 60 min of cooking, respectively. It was seen that the highest amount of moisture was removed for the dates leather which had the shortest cooking time of 30 min. This was an anticipated result with the sample having the highest initial moisture content. There is a direct penetration to the product in infrared dryers [34]. Water possesses very strong infrared radiation absorption and the O-H bonds in water absorb infrared energy [35]. Therefore, when there is more moisture in the product there are more O-H bonds absorbing the infrared energy and leading to more evaporation of moisture.

The effective moisture diffusion coefficient (D_{eff}) values were found using the experimental data and Equation (2) derived from Fick's second law of diffusion, where there is a linear relationship between ln M_R and drying time t and shown in Figure 3. R^2 values showing the agreement between the fitted and experimental values were found to be good as they were in the range of 0.9332-0.9918. After processing the data, D_{eff} of dates leather samples were calculated from the slopes of the curves given in Figure 3 as 1.53×10^{-9}, 1.70×10^{-9} and 1.74×10^{-9} m^2/s for 30, 45 and 60 min of cooking time, respectively. These values were found acceptable. Because D_{eff} of food materials is reported as in the range between 10^{-10} and 10^{-8} m^2/s in infrared drying [31, 36]. Moreover, the standard ranges for D_{eff} of agricultural products were mentioned as 10^{-11}-10^{-9} m^2/s [27]. Although D_{eff} values for several fruit leathers are available in the literature for other drying techniques, it is difficult to find the values for the leathers produced with infrared drying. Rajoriya et al. [27] found D_{eff} of banana leathers as 9.36×10^{-11} and 1.04×10^{-10} m^2/s prepared with refractive window combined with 50 and 60°C infrared drying, respectively. Du et al. [31] obtained D_{eff} of paddy grain samples as 4.83-16.37×10^{-9} m^2/s with infrared drying at temperatures between 35 and 60°C.

It was also observed that as the cooking time in the preparation of leathers increased, the slope of the plots in Figure 3 and hence D_{eff} was also increased. D_{eff} shows the characteristics of the moisture mass transfer through the food, and it depends on temperature, moisture content [37], composition and porosity [38]. Since drying temperature of the equipment used in the experiments and the formulation of samples was constant, moisture content of the leathers affected the D_{eff}. The cooking time of the leathers might have also influenced the porosity of the leathers and hence might have an impact on D_{eff}. This might be due to the fact that as the cooking time increased moisture content decreased, and water vapor permeability increased since it gave more open pore structure [38]. The highest initial moisture content of 2.08 g water/g dry solids was seen for the sample cooked for the shortest time (30 min) and the lowest moisture content of 1.39 g water/g dry solids was observed for the one cooked for the longest time (60 min). Similarly, Younis et al. [39] reported an increase in D_{eff} with the decrease in moisture content of 2.5 mm thick infrared dried garlic slices and found D_{eff} values of 5.83×10^{-11}- 7.66×10^{-10} m^2/s at 0.075-0.3 W/cm^2. Likewise, Sharma et al. [38] mentioned the increase of D_{eff} with the decrease in water content of infrared dried thin layer onion slices and Celma et al. [40] reported similar dependence of D_{eff} on the moisture content of thin layer infrared dried industrial tomato by-products. Another point that can be concluded from the experiments was that the hygroscopic material might approach a non-hygroscopic behavior since it lost more moisture due to evaporation during cooking which lowered the material's water-binding property.

Even though R^2 of all plots given in Figure 3 were good for the total drying time, closer examination of the data points revealed that each plot contained three separate drying zones. Therefore, D_{eff} values were also calculated separately for these zones and shown in Figures 4, 5, and 6. For the drying curve of the dates leather sample cooked for 30 min, drying zones 1, 2, and 3 were seen in the periods of 5-35, 40-70, and 85-145 min, respectively. D_{eff} values were found as 1.87×10^{-9}, 1.65×10^{-9}, and 1.23×10^{-9} m^2/s by using the slopes of the plots given in Figure 4 for zones 1, 2, and 3, respectively, with higher R^2 values ranging between 0.9740 and 0.9878. Separate drying zones of 45 min cooked sample were seen in 5-50, 60-85, and 95-135 min (Figure 5) and D_{eff} were determined as 9.75×10^{-10} m^2/s for zone 1, 1.53×10^{-9} m^2/s for zone 2, and 3.38×10^{-10} m^2/s for zone 3 with R^2 of 0.9488-0.9796. A similar behavior was also observed for the leather sample with a cooking time of 60 min. For this sample, D_{eff} was found as 1.80×10^{-9} m^2/s at 5-40 min, 1.43×10^{-9} m^2/s at 50-105 min, and 2.74×10^{-9} m^2/s at 115-145 min by using the slopes given in Figure 6, and R^2 were found between 0.9839 and 0.9993. The change in the value of slopes through different drying zones is a sign of non-uniform drying showing initial, constant-rate and falling-rate periods. This behavior might also be attributed to the material being dried or case hardening occurred during drying. In addition, slope trends were different for each of the samples. The slope decreased for 30 min cooked leather (Figure 4), and it increased for 60 min cooked one (Figure 5) through all drying zones. On the other hand, the slope first increased from zone 1 to zone 2 and then decreased from zone 2 to zone 3 (Figure 6). These differences, which also affected the changes in D_{eff}, might be due to the increases in the deformation in the internal structures during infrared drying.

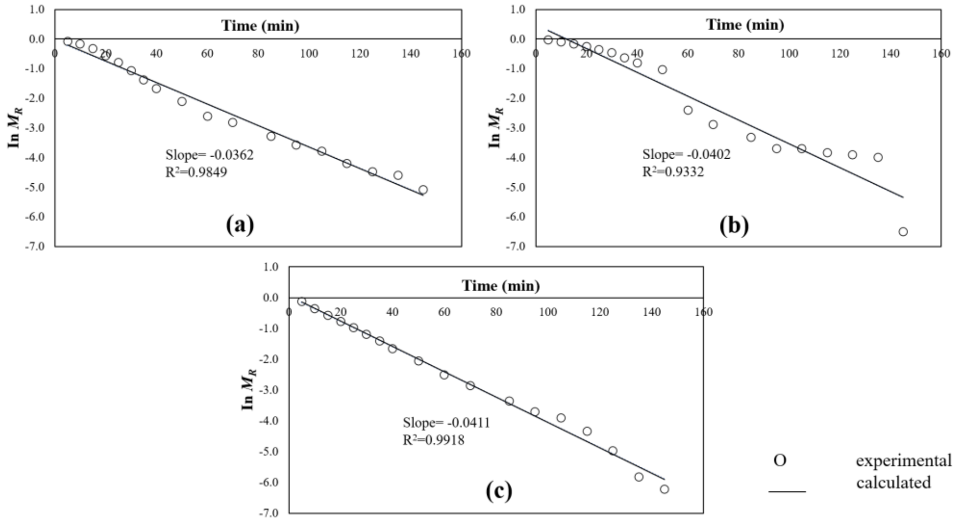

Figure 3. Values of ln M_R versus drying time t of dates leather cooked for (a) 30 min, (b) 45 min, and (c) 60 min

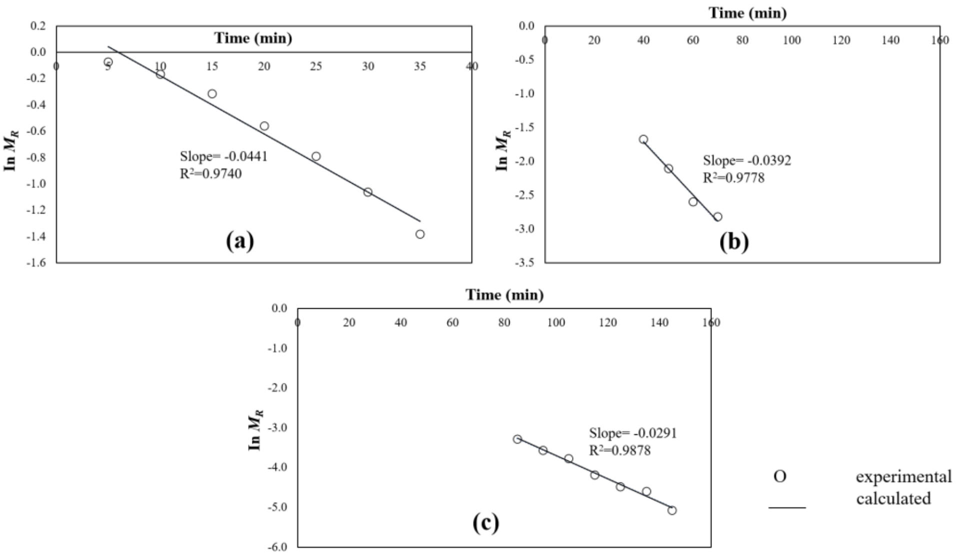

Figure 4. Values of ln M_R versus drying time t of dates leather cooked for 30 min in (a) drying zone 1, (b) drying zone 2, and (c) drying zone 3.

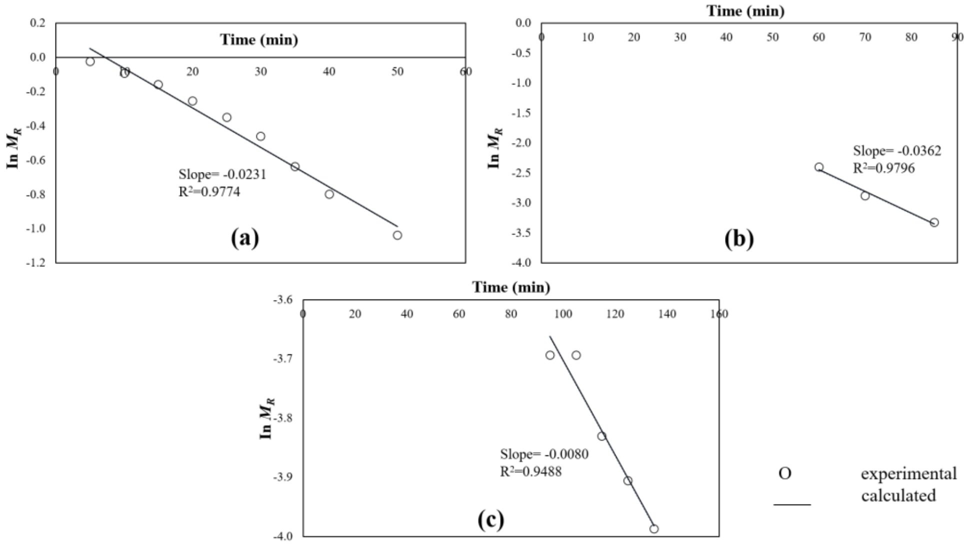

Figure 5. Values of ln M_R versus drying time *t* of dates leather cooked for 45 min in (a) drying zone 1, (b) drying zone 2, and (c) drying zone 3.

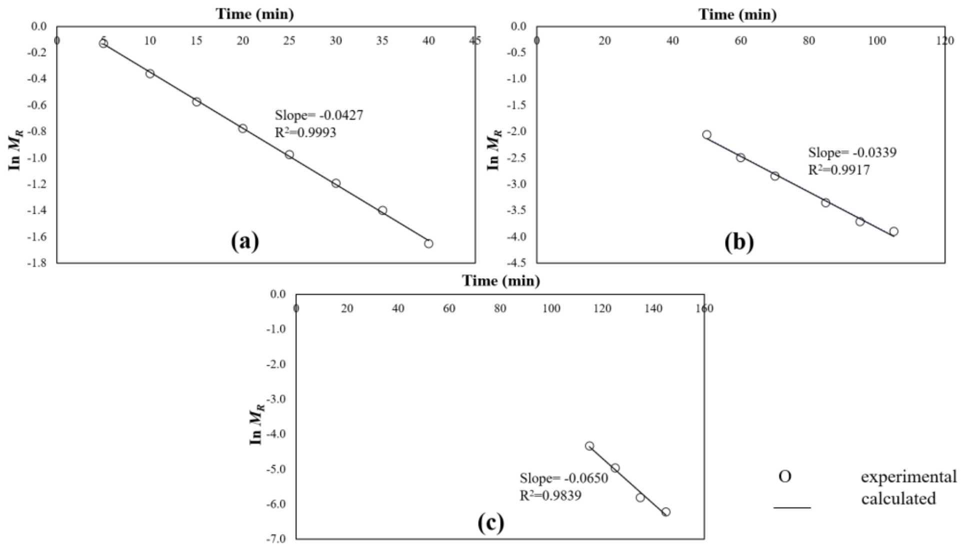

Figure 6. Values of ln M_R versus drying time *t* of dates leather cooked for 60 min in (a) drying zone 1, (b) drying zone 2, and (c) drying zone 3.

Table 1. Effective moisture diffusivities of dates leather with different cooking time at separate drying zones

Cooking time (min)	D_{eff} (m²/s)			
	Zone 1	Zone 2	Zone 3	Average
30	1.86×10^{-9}	1.65×10^{-9}	1.23×10^{-9}	1.58×10^{-9}
45	0.98×10^{-9}	1.53×10^{-9}	0.34×10^{-9}	0.95×10^{-9}
60	1.80×10^{-9}	1.43×10^{-9}	2.74×10^{-9}	1.99×10^{-9}

Averages of the diffusivities for different drying zones were calculated and tabulated in Table 1. It was realized that the average value of D_{eff} was closer to the value fitted from Figure 3.(a) for the total drying time of 155 min for the sample cooked for 30 min, and it was in the same order of magnitude for the one cooked for 60 min when D_{eff} found from Figure 3.(b) and average value (Table 1) were compared. However, the average of D_{eff} for the three of the drying zones was 0.95×10^{-9} m²/s and it was smaller than the D_{eff} obtained from Figure 3.(c). Besides the mentioned increase of deformations in the leather samples during drying, the change in D_{eff} during drying is a complicated process [39] since this intrinsic mass transport property of moisture includes molecular, liquid, and vapor diffusion besides hydrodynamic flow and other mechanisms [40].

4 Conclusion

Infrared drying has many advantages mainly shorter drying times and higher product quality with respect to the conventional techniques in thin-layer drying. Therefore, thin-layer fruit leathers are very suitable healthy snack products to involve infrared dryers in the manufacturing process. In this study, date leathers with different cooking times were produced by infrared drying. Effective moisture diffusivity was affected by cooking time and found as 1.53×10^{-9}, 1.70×10^{-9} and 1.74×10^{-9} m^2/s for 30, 45 and 60 min of cooking, respectively when the first order drying curves were investigated through total drying time. The cooking time of fruit leather was an important parameter to investigate since hygroscopic material might approach a non-hygroscopic behavior because it lost more water due to evaporation and lowered water binding property. The presence of three separate drying zones was realized in each plot at different time intervals when data points were examined closely in spite of the high R^2 for the total drying time. To explain the differences in D_{eff} is complicated as it includes molecular, liquid, and vapor diffusion besides hydrodynamic flow and other mechanisms and it might be due to the increases in the deformation in the internal structures of dates leather during infrared drying.

Another point that can be concluded from the study is that it is practical, convenient, and cost-effective for the food industry to use moisture analyzer instrument with infrared heating mechanism for the initial formulation trials in laboratory scale in small batches prior to the investment of the high-capacity industrial infrared dryers to produce thin layer fruit leather products.

Conflict of interest

The author declares that there is no conflict of interest.

Similarity rate (iThenticate): 15%

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