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Mathematical Modeling of Thin Layer Drying of Pomegranate (*Punica granatum* L.) Arils: Various Drying Methods

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ABSTRACT

For years, sun and hot air drying have been considered as traditional drying methods. Today, using microwave is one the newest methods of drying. Iran is one of the main producers of pomegranate fruit in the world. To manufacture better product, drying needs to be handled in controlled and optimized process, therefore investigation of process condition kinetic is an obligation. In this study, thin layer drying behavior of pomegranate arils using microwave drier at 4 power levels (180, 360, 540 and 720W), oven drier at 4 temperature levels (45, 55, 65 and 75°C) and sun drying was studied. Page, Henderson and Pabis, Midilli *et al*., Newton, Logarithmic and Two-Term models were compared according to their Root Mean Square error (RMSE), Chi-square (χ^2), Mean Bias Error (MBE) and correlation coefficient (R^2). The results of the studied models indicated that Midilli *et al*., model exhibited the best fit to the data obtained for oven, microwave and sun drying. Increasing the oven drier temperature and the microwave drier power lead to an increase in the drying rate. Dried samples at 75°C exhibited the highest R^2= 0.9998, and the least *RMSE* and χ^2, 0.2059 and 0.5576 respectively in comparison with other samples. While dried samples by microwave, 720W, showed the highest R^2= 0.9998 and the least *RMSE* and χ^2 were 0.1894 and 0.4203, respectively in comparison with other samples. Sun dried samples had the highest R^2 in Midilli Model, the least *RMSE* and X^2 were 0.0338 and 0.7059 respectively.

Keywords: Drying modeling, Microwave drier, Oven drier, Pomegranate arils, Sun drying.

INTRODUCTION

Pomegranate (*Punica Granatum*) is one of the most popular native fruits of Iran. It is extensively cultivated in Iran, Spain, Egypt, Russia, France, China, Japan, USA and in India (Riyahi *et al*., 2011; Daraei Garmakhany *et al*., 2013). There are about 70,000 hectares of pomegranate orchards in Iran, with about 700,000 tons annual production and more than 150,000 tons is exported to other countries (Riyahi *et al*., 2011). The versatile adaptability, table and therapeutic values and better keeping quality are the features responsible for its cultivation on a wide scale (Dhandar and Singh, 2002). They are also used in the preparation of fresh juice, canned beverages, jelly, jam and paste and for flavoring and coloring drinks, etc (Hodgson, 1971; Nagy *et al.*, 1990). Pomegranate is commercially grown for its sweet-acidic taste of the arils (Saxena *et al.*, 1987) which are ranging between 40 and 100 g kg^{-1} of fruit weight depending on cultivar. The seeds of diverse varieties of pomegranate are rich sources of essential oils (essentials fatty acids). Data on fatty acid composition in the seed oil of pomegranate also help to establish the

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chemotaxonomic relationships among the studied varieties.

In addition to being rich in vitamin C, potassium, Calcium, Sodium, Polysaccharides, acids and sugars, pomegranate arils find wide application in traditional Asian medicine for stomachache, diarrhea, bronchitis, etc (Anonymous, 1969). Therefore, due to the benefits of this product, selection of appropriate methods for maintaining and reducing post-harvest losses of it, is necessary. One of these methods is drying. The main objective of drying pomegranate seeds is to use them in domestic foods as a condiment. Dehydrated seeds have acidic property which improves mouth feel and food digestion (Parashar *et al*., 2009; Daraei Garmakhany *et al*., 2013).

Drying process is one of the oldest preservation methods for post- harvest preservation of crops and foods. Natural sun drying is practiced widely in the world and also Iran, but has some problems related to the contamination by dirt and dust and infestation by insects, rodents and other animals (Ertekin and Yaldiz, 2004). Hot-air drying is the most common method to preserve foods. This process leads to the serious damage in product flavor and nutrients, due to the long drying times and high temperatures employed in process (Martin-Esparza *et al*., 2008). In order to reduce the time of drying and obtain better quality in the final product, microwave drying has been used as a modern method for drying agricultural products. Microwaves are electromagnetic waves within the range of long wavelength and frequency of 2,450 MH. When these waves pass through a food product, polar molecules such as water and salts are vibrated thus transforming microwave energy to heat (Zhang *et al*., 2006). Mathematical models have proven to be very useful designs for describing the drying of a product.

There are several studies describing the drying behavior of various fruits and vegetables. For examples, onions (Arslan and Ozcan, 2010), mushrooms (Prasad and Giri, 2007), Golden apples (Menges and Ertekin, 2006), apple and strawberry (Martin-Esparza *et al*., 2008), eggplant (Ertekin and Yaldis, 2004), potatoes (Singh and Pandey, 2012; Akpinar *et al*., 2006), carrots (Doymaz, 2004), mint leaves (Ozbek and Dadali, 2007), barley seeds (Aghajani *et al*., 2012) and pumpkin (Mokhtarian *et al*., 2014a and 2014b).

Mathematical modeling and simulation of drying curves under various conditions is imperative to achieve a better control of this unit operation and an overall improvement of the final product quality. These models are often used in order to study the variables involved in the process, optimizing operating parameters and conditions and predict the product drying kinetics (Garau *et al*., 2007). Mathematical models are also the most common methods for the estimation of Moisture Ratio (MR). These models, which are fitted to experimental data, have many problems, such as reduction of computation velocity and accuracy of processing control systems as well as production of numerous equations. The development of a deep-bed drying simulation model is a valuable tool for optimizing design and predicting performance of the drying system for pomegranate arils. Thin-layer drying models are required for stimulating deep-bed drying of pomegranate arils, hereafter referred to as ‘Anardana’. Simulation models provide an opportunity for the assessment of the energy conservation and saving alternative without full scale experiment (Bala and Woods, 1992).

Over time, the models developed have been used in calculations involving the design and construction of new drying systems, optimization of the drying process, and the description of the entire drying behavior including the combined macroscopic and microscopic medium of heat and mass transfer. Thus, it is important to understand the basic idea of modeling the drying kinetics of fruits and vegetables. The drying conditions, type of dryer, and the characteristics of the material to be dried all have an influence on drying kinetics. The drying kinetics models are therefore significant in deciding the ideal drying conditions, which are important parameters in terms of equipment design, optimization, and product quality improvement (Giri and Prasad, 2007). Therefore, to analyze the drying behavior of fruits and vegetables it is important to study the kinetics model of each particular product.

Thin-layer drying is a widely used method for determining the drying kinetics of fruits and vegetables (Kadam *et al.,* 2011). It involves simultaneous heat and mass transfer operations. During these operations, the material is fully exposed to drying conditions of temperature and hot air, thus improving the drying process. The most important aspects of thin-layer drying technology are the mathematical modeling of the drying process and the equipment design which can enable the selection of the most suitable operating conditions. Therefore, there is a need to explore the thin-layer modeling approach as an essential tool in estimating the drying kinetics from the experimental data, describing the drying behavior, improving the drying process and eventually minimizing the total energy requirement (Mokhtarian and Daraei Garmakhany, 2017).

Many studies have been published in the field of drying kinetic modeling in case of various products. For example, Tavakolipour and Mokhtarian (2012) investigated drying kinetic of pistachio nut. The results showed that among all studied models, the Modified Page model had the best result to predict the Moisture Ratio (MR). Taheri-Garavand *et al*. (2011) studied thin layer drying kinetics of tomato undergoing air drying condition. The result indicated that, Midilli model showed satisfactory results for predicting drying curve of tomato. Guiné *et al*. (2010) worked on pumpkin behavior during drying. The results illustrated that the increase of temperature could robustly accelerate the drying process, so that the process was taken at 30℃ for eight hours while the drying was finished at 70℃ just after two hours. The experimental data was fitted to different models for moisture ratio prediction and it was concluded that the best models were Page and modified Page. Diamante *et al*. (2010) developed the new mathematical model for thin layer drying of fruits. They mentioned that the proposed equation gave the highest coefficient of determination for both varieties of kiwifruit and apricot and was closely followed by Page equation. Also, their results indicated that the proposed equation has the best curve fitting ability for both fruits.

Golpour *et al.* (2015) studied paddy moisture content during thin layer drying and showed that the air temperature had significant effect on the L^*, a^* and b^* values at a probability of 0.01 ($P< 0.01$). The L^* values decreased in the drying process and the b^* (yellowness) and a^* (redness) values increased with increase in the drying time. Changing of color values at 80°C was more than the other temperatures. Artificial Neural Networks (ANNs) was a proper method for predicting moisture content of paddy using extracted color features with image analysis. The best training performance to model moisture content was obtained with topology of 5-7-1 and transfer functions of Logsig and Tansig in hidden layers and output layers. The objectives of this study are: an investigation of the drying behavior of pomegranate arils (*Malas Kashmar*) and determining the best mathematical model that can describe the kinetics of the drying process.

MATERIALS AND METHODS

In this research pomegranate fruits (*Malas Kashmar*) were purchased from Gorgan local market, Gorgan province of Iran and kept in cold storage at 5-6°C. The arils were manually separated from the fruits. Twenty grams of samples was placed in hot oven at 105±1°C for five hours until significant difference was observed between two successive weightings. The initial moisture content of arils was 307.166% dry basis (db).

Drying of Pomegranate Arils

Oven Drying: Hot air drying of pomegranate arils was carried out in the oven dryer (Raymand U30, Iran). Drying experiment was performed at temperatures 45, 55, 65 and 75°C.

Microwave Oven Drying: In the microwave drying (LGMG- 3015 W model, Korea) method, four power levels of 180, 360, 540 and 720W were employed for drying the samples. One dish containing 20 g of sample was placed on the center of a turntable fitted inside the microwave cavity and processed until the pomegranate arils were completely dried. The mass of the sample was measured in 30 minutes during oven and 5 hours during sun drying and every 10 seconds during microwave oven drying using a digital balance, measuring to an accuracy of 0.0001 g (Soysal *et al*., 2006). During sun drying experiment, ambient temperature was 20- 24°C and relative humidity was 45-48%. The experiments were repeated in triplicate.

Mathematical Modeling of Drying Curves

After obtaining the moisture ratio by using statistical nonlinear regression, results were fitted with 6 different moisture ratio models (Table 1) by use of Solver software of Excel (2003). The moisture ratio of dried samples was calculated using Equation (1) (Doymaz, 2004):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

Where, MR is the Moisture Ratio, M_t is Moisture content at a specific time (g water per g dry solids) t, M_0 is initial Moisture content (g water per g dry solids) and M_e is equilibrium Moisture content (g water per g dry solids). Correlation coefficient (R^2) was one of the primary criteria to select the best model. Other statistical parameters such as Chi-square (χ^2), Root Mean Square Error (RMSE) and Mean Bias Error (MBE) were used to determine the quality of the fitted model. The lower the values of the Chi-square, the higher the values of R^2 values which indicate the high fit of the model (Akpinar *et al*., 2006). These parameters can be calculated as follows:

$$R^2 = \frac{\sum_{i-1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2}{\sum_{i-1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2} \quad (2)$$

$$X^2 = \frac{\sum_{i-1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2}{N-m} \quad (3)$$

$$RMSE = \left(\frac{1}{N}\sum_{i-1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2\right)^{\frac{1}{2}} \quad (4)$$

$$MBE = \frac{1}{N}\left(MR_{pre,i} - MR_{\exp,i}\right) \quad (5)$$

Where, $MR_{pre,i}$ is the i^{th} predicted Moisture Ratio value, $MR_{exp,i}$ is the i^{th} Moisture Ratio value determined experimentally, N is the Number of observation and m is the number of drying constants (Akpinar *et al*., 2006; Ertekin and Yaldiz, 2004; Abbasi *et al*., 2010).

RESULTS AND DISCUSSION

Drying Behavior of Pomegranate Arils

The time required for drying pomegranate

Table 1. Mathematical models applied to the moisture ratio values.

Number	Name of model	Equation	Reference
1	Page	$MR = \exp(-kt^n)$	Page (1949)
2	Newton	$MR = \exp(-kt)$	Westerman *et al.* (1973)
3	Henderson and Pabis	$MR = a\exp(-kt)$	Henderson and Pabis (1961)
4	Logarithmic	$MR = a\exp(-kt)+c$	Togrul and Pehlivan (2004)
5	Midilli *et al.*	$MR = a\exp(-kt^n)+bt$	Akpinar *et al.* (2006)

arils from initial moisture content of 307.166% (db) to the final moisture content of 12.24%±1 (db) for the oven drying at 45, 55, 65 and 75˚C were 25, 15, 11 and 8 hours, respectively, for the sun drying it was 8 days and for the microwave drying at 180, 360, 540 and 720W power was, 150, 120, 110 and 110 seconds, respectively according to Figure 1. Application of microwave power higher than 200W was not suggested due to burning of pomegranate arils at these powers. The time was longer for sun drying due to the fluctuating temperature during the drying period. The drying curves of pomegranate arils under microwave drying, sun drying and oven drying conditions are shown in Figure 1. Drying air temperature and microwave power level had an important effect on drying time. This kind of behavior has been reported for fruits and vegetables as well (Ozbek and Dadali, 2007; Akpinar *et al*., 2006; Prasad and Giri, 2007; Aghajani *et al*., 2012a and 2012b; Aghajani *et al*., 2010).

The drying curves were prepared based on the variation of the product water content as a function of time. Plots of the moisture ratio versus time curves are shown in Figure 1. The moisture ratio of pomegranate arils reduced exponentially as the drying time. This is due to the fact that drying at higher temperatures and higher energy power lead to higher temperatures, implying a larger driving force for heat transfer and the acceleration of moisture migration. The entire drying process for the samples occurred in the range of falling rate period. This is in agreement with the result reported for carrot (Doymaz, 2004), apple (Menges and Ertekin, 2006), barley seeds (Aghajani *et al.,* 2012), pumpkin fruits (Mokhtarian *et al.*, 2014a, b) and mushroom (Prasad and Giri, 2007; Arslan and Ozcan, 2010).

The drying rate of pomegranate arils as a function of moisture content is reported in Figure 2. At the initial stage of drying process, the changes of drying rate are dependent to the temperature. As can be seen from Figure 2 drying rate increased with the increase of drying air temperature, and the highest values of drying rate were obtained during the experiments at 75˚C of the drying air.

There is no difference in the drying rates among different power levels, considering the significance of internal resistance to mass transfer at low water content in the samples. The amount of microwave energy absorbed by the material depends upon its dielectric properties and electric field strength. As the values of dielectric constant and loss factors are higher for the material containing higher moisture content, obviously the material absorbs more microwave power and heating is faster at high moisture content. As drying progressed, the loss of moisture content in the product decreases the absorption of microwave power and results in a fall in the drying rate during the later part of drying (Soysal *et al*., 2006; Prasad and Giri, 2007; Ozbek and Dadali, 2007).

Mathematical Modeling of Drying Curves

For modeling, 6 different models were used to predict the moisture content as a function of drying time (Table 1). The most suitable model for describing the drying kinetics of pomegranate arils was selected based on the highest R^2 and the lowest χ^2, *RMSE* and *MBE* values (Tables 2-4). The results indicated that, the lowest values of *RMSE* and χ^2 and highest values of R^2 were observed from the Midilli *et al*. model. It was observed that R^2 values ranged from 0.9709 to 0.9998 for the different models. Doymaz (2012), Kingsly and Singh (2007), Motevali *et al*. (2012), Akpinar *et al*. (2006), Menges and Ertekin (2006), Soysal *et al*. (2006), have reported similar results for drying of Pomegranate arils and other products.

Since the moisture *vs.* time curves showed a decent flow, hence by increasing time case hardening effects and moisture content decreased. Increasing temperature from 45 to 75˚C and microwave power from 180 to 720 reduced the time of drying and increased drying rate. By increasing microwave power inner temperature, the entered beams increase, thus more heat and

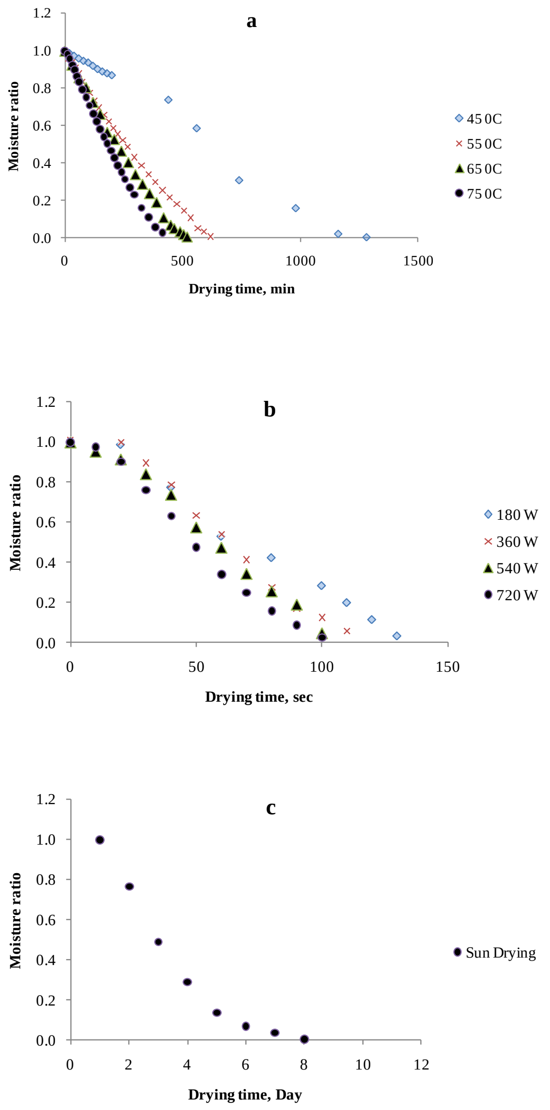

Figure 1. Changing moisture ratio with drying time at oven (a), microwave (b) and sun drying (c).

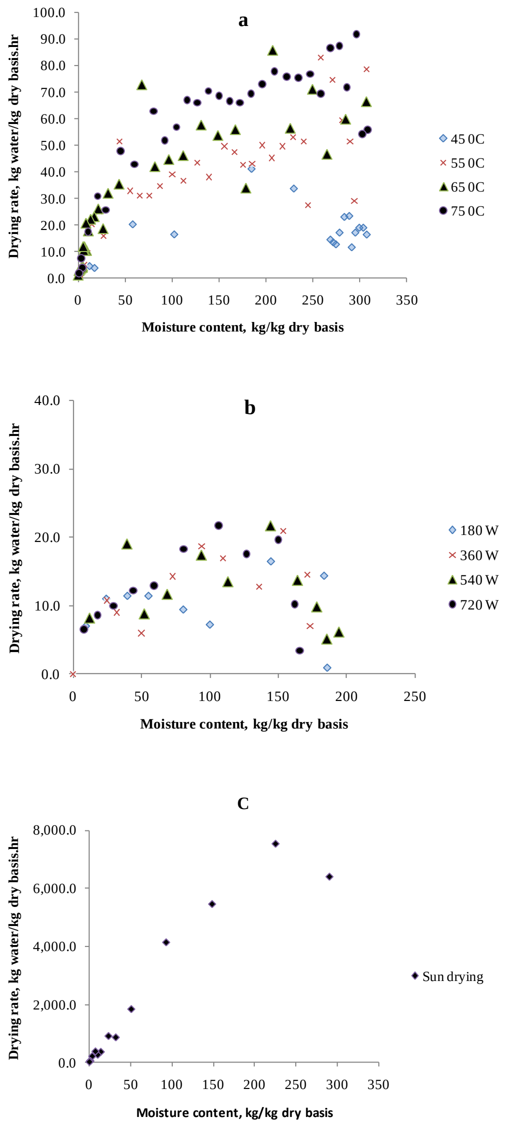

Figure 2. Drying rate curves with moisture content (d.b.) Oven (a), microwave (b) and sun drying (c)

mass transfer lead to more moisture reduction. All these results were in agreement with Prasad and Giri (2007).

In sun drying methods longer time is required to reach final moisture content due to temperature variations and no control on atmospheric conditions which is in agreement with Arslan and Ozcan (2010) report.

Drying curve in sun drying and hot air methods showed an increasing flow as a result of more moisture content in the beginning of the process and more drying from product surface. Both heat and mass transfer occur on the surface, therefore drying rate is determined by outer conditions of food stuff, while in decreasing rate stage, drying rate reduces and mass transfer to the food stuff will determine the process conditions. In microwave drying, there is no constant rate of drying which arises from short drying time in microwave method. Microwave ability in drying process depends on dielectric properties of food. Obviously,

Table 2. Statistical results of mathematical modeling of moisture ratio in hot oven drying process.

Model	Air temperature (˚C)	R^2	X^2	*RMSE*	*MBE*
Page	45	0.9967	2.2298	0.0867	-0.0687
	55	0.9996	1.1843	0.3305	-0.2904
	65	0.9988	1.4894	0.2844	-0.2629
	75	0.9998	0.4932	0.1950	-0.1661
Newton	45	0.9881	4.4803	0.5052	-0.3336
	55	0.9996	1.1331	0.3227	-0.2838
	65	0.9992	1.9400	0.4432	-0.4085
	75	0.9992	0.7576	0.0584	-0.2581
Henderson and Pabis	45	0.9881	4.7524	0.5052	-0.3336
	55	0.9996	2.9904	1.6255	-1.3374
	65	0.9992	1.9401	0.4432	-0.4085
	75	0.9992	0.7838	0.3251	-0.2731
Logarithmic	45	0.9881	5.0798	0.5059	-0.3347
	55	0.9996	1.2010	0.3232	-0.2844
	65	0.9992	-23.9111	0.0761	-0.4091
	75	0.9992	0.9287	0.3829	-0.3483
Midilli *et al*.	45	0.9983	0.7727	0.0247	-0.0134
	55	0.9998	1.2433	0.3196	-0.2771
	65	0.9995	1.0207	0.1473	-0.1360
	75	0.9999	0.5577	0.2059	-0.1753
Two-term	45	0.9940	4.7524	0.5029	-0.3320
	55	0.9998	1.1655	0.3228	-0.2838
	65	0.9992	1.9401	0.4432	-0.4085
	75	0.9996	0.7838	0.3251	-0.2731

Table 3. Statistical results of mathematical modeling of moisture ratio in microwave drying process.

Model	Microwave power (W)	R^2	χ^2	*RMSE*	*MBE*
Page	180	0.9866	2.7323	0.2126	-0.5677
	360	0.9709	1.8709	0.1799	-0.5106
	540	0.9966	0.2895	0.0275	-0.0769
	720	0.9993	0.2187	0.0132	-0.0340
Newton	180	0.9880	2.4288	0.2126	-0.5677
	360	0.9750	1.9352	0.2103	-0.6025
	540	0.9893	1.9328	0.2320	-0.6543
	720	0.9854	1.7813	0.3616	-0.3353
Henderson and Pabis	180	0.9880	2.7321	0.2126	-0.5676
	360	0.9750	2.1287	0.2103	-0.6025
	540	0.9872	1.6621	0.1701	-0.4747
	720	0.9806	2.7130	0.1868	-0.5354
Logaritmic	180	0.9880	3.1285	0.2132	-0.5694
	360	0.9750	2.3677	0.2106	-0.6036
	540	0.9872	1.8505	0.1705	-0.4763
	720	0.9962	3.9373	0.1838	-0.5256
Midilli *et al*.	180	0.9942	3.6075	0.2099	-0.5602
	360	0.9882	2.3170	0.1780	-0.5046
	540	0.9946	2.0605	0.1683	-0.4697
	720	0.9998	0.4203	0.0189	-0.0545
Two-term	180	0.9940	2.7320	0.2126	-0.5676
	360	0.9871	1.8707	0.1799	-0.5105
	540	0.9881	1.7654	0.1832	-0.5134
	720	0.9927	1.9595	0.1203	-0.3353

Table 4. Statistical results of mathematical modeling of moisture ratio in sun drying process.

Model	R^2	X^2	*RMSE*	*MBE*
Page	0.9986	0.2182	0.0143	0.0006
Newton	0.9961	0.5384	0.0325	0.0248
Henderson and Pabis	0.9961	0.5798	0.0249	0.0248
Logarithmic	0.9922	0.6285	0.0325	0.0247
Midilli *et al*.	0.9995	0.7059	0.0338	0.0267
Two-term	0.9961	0.5798	0.0325	0.0248

foodstuffs absorb more microwave power and faster heating occurs in high moisture contents. These results are in agreement with Akpinar *et al*. (2006); Prasad and Giri (2007). Results also showed that the most describing and fitted model was Midilli model (Motevali *et al*., 2012).

CONCLUSIONS

Drying of pomegranate arils in hot oven drying, microwave and sun drying was examined. The drying method and temperatures were found to have a significant effect on the rate of moisture loss of pomegranate arils. The highest drying rate occurred in microwave drying and the lowest rate was obtained in the sun drying. The entire process of pomegranate arils drying occurred in the falling rate period. The drying curves could be well fitted by the Midilli *et al*. 2002, model. Drying in hot oven with 75°C temperature, produced samples with better quality attributes than sun and microwave drying methods. Results revealed that drying of pomegranate seeds by sun drying method is time consuming and there is no possibility of reaching a moisture balance due to temperature and humidity difference of the environment. Drying by oven at 45˚C exhibited more time of drying in comparison with other temperatures (55, 65, 75˚C). Due to the absence of moisture balance during microwave drying process, surface burning occurs especially in microwave powers higher than 200W.

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مدلسازی ریاضی خشک کردن لایه نازک اناردان: روش های مختلف خشک کردن

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چکیده

سالهای متمادی روش خشک کردن با خورشید و هوای داغ از روش های رایج خشک کردن بوده است. امروزه استفاده از مایکروویو یکی از روش‌های جدید در خشک کردن می باشد. ایران از بزرگ ترین تولیدکنندگان انار در جهان یه شمار می رود. به منظور تولید محصولی با کیفیت، لازم است که خشک کردن تحت شرایط کنترل شده و بهینه انجام شود، به این منظور بررسی سینتیک خشک کردن شرایط فرایند ضروری است. در این مطالعه رفتار خشک کردن لایه نازک اناردان با استفاده از خشک کن مایکروویو در ۴سطح توان (۱۸۰، ۳۶۰، ۵۴۰ و ۷۲۰ وات)، خشک کن آون در ۴ سطح دما (۴۵، ۵۵، ۶۵ و ۷۵ ^{o}C) و خشک کردن خورشیدی مورد مطالعه قرار گرفت. مدل های پیج، هندرسون و پابیس، میدیلی و همکاران، نیوتن، لگاریتمی و توترم با توجه به مقادیر مجذور میانگین مربعات خطا (RMSE)، مربع کای (χ^2)، میانگین بایاس خطا (MBE) و ضریب همبستگی (R^2) با هم مقایسه شدند. با توجه به نتایج مدل‌های مورد مطالعه مشخص شد که مدل میدیلی و همکاران بهترین برازش را با داده های حاصل از آون، مایکروویو و خشک کردن خورشیدی داشت. افزایش دما در خشک کن آون و توان در مایکروویو، باعث افزایش شدت خشک کردن شد. نمونه های خشک شده در ۷۵ ^{o}C بیشترین ضریب همبستگی (R^2=۰/۹۹۹۸) و کمترین RMSE و χ^2 (به ترتیب ۰/۲۰۵۹ و ۰/۵۵۷۶) را در مقایسه باسایر نمونه ها نشان دادند. در نمونه های خشک شده با مایکروویو، توان ۷۲۰ وات بیشترین

ضریب همبستگی (R^2=۰/۹۹۹۸) و کمترین RMSE و χ^2 (به ترتیب ۰/۱۸۹۴ و ۰/۴۲۰۶) را در مقایسه باسایر نمونه ها نشان دادند. نمونه های خشک شده خورشیدی بیشترین R^2 و کمترین RMSE و χ^2 (به ترتیب ۰/۰۳۳۸ و ۰/۷۰۵۹) را در مدل میدیلی و همکاران داشتند.