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Drying kinetics of pomegranate fruit peel (cv. Wonderful)

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ABSTRACT

Pomegranate juice processing produces large amount of peel as by-product or waste which is a potential source of raw material for food and other bioprocessing industries. Drying the peel offers opportunities for value addition into novel products, thus reducing waste from the fruit processing operations. This study presents the mathematical models of thin layer drying behaviour of pomegranate peels (initial thickness 5.00 ± 0.05 mm and moisture content 70.30% wet basis) using three air temperatures (40 °C, 50 °C and 60 °C) at a constant air velocity of 1.0 m/s. The results obtained showed that drying time decreased as the oven drying temperature increased. The drying process took place mainly in the falling rate period. Ten thin layer drying models were evaluated based on coefficient of determination (r^2) and standard error (e_s). Among the tested drying models, Midilli et al. mathematical model was found to be the best fit for establishing the drying kinetics of pomegranate peel. Furthermore, the effective moisture diffusivity of pomegranate peel ranged from 4.05×10^{-10} to 8.10×10^{-10} m^2/s over the temperature range investigated, with mean activation energy (Ea) of 22.25 kJ/mol.

Introduction

Pomegranate fruit (*Punica granatum* L.) belongs to the Punicaceae family. It is relatively distributed around the world, including Asia, USA, Russia, North Africa, Spain and most recently South Africa [5,15,21]. Pomegranate fruit is popularly consumed as juice and is used in food industry in the manufacture of jellies, concentrates, and flavouring and colouring agent [36]. Pomegranate fruit consumption has continued to gain global interest among consumers due their wealth of nutritional properties and high content of polyphenols [8,17]. The fruit is comprised of peels and arils (which contain juice and seeds/kernels) sacs. During juice processing, the peel is a major by-product and accounts for about 50% of whole fruit mass [5,18,36] The peel is rich in polyphenols including flavonoids, phenolic acids and tannins [16,18,36]. These bioactive compounds possess different biological activities such as scavenging reactive oxygen species (ROS), inhibiting oxidation and microbial growth and reducing the risk of chronic disease such as cancers and cardiovascular disorders [16,36,47].

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Nomenclature

a	positive integer
a_0, a,	coefficient of drying models
D_0	pre-exponential factor of Arrhenuis Eq.
D_{eff}	effective moisture diffusivity, $m^2\,s^{-1}$
DR	drying rate, kg (water) kg^{-1} (dry matter) h^{-1}
Ea	activation energy
e_s	standard error
k	drying coefficient
L	half thickness
M_o	initial moisture content, kg (water) kg^{-1} (dry matter)
M	moisture content, kg (water) kg^{-1} (dry matter)
M_e	equilibrium moisture content, kg (water) kg^{-1} (dry matter)
MR	moisture ratio
Mt	moisture content at any time
N	number of observations
n	exponential coefficient of Page's Eq.
n	positive interger
r^2	coefficient of determination
t	time, s

Since the pomegranate fruit peel is highly susceptible to microbial contamination and rapid spoilage in its wet state, drying could serve as an alternative method of preservation. Drying is an ancient process used to preserve and prolong shelf life of various food products [24,38,43]. The main aim in drying food products is the removal of water in the solid to a level at which microbial spoilage and deterioration resulting from chemical reactions is significantly reduced [9,26,40,43]. This enables the product to be stored for longer periods since the activity of microorganisms and enzymes is inhibited through drying [3]. One of the mostly widely used drying techniques in the agriculture and food industries involves the application of thermal energy [25,33,44].

Studies on drying characteristics and kinetics of by-products of a wide range of agricultural commodities have been reported such as carrot pomace [27], olive pomace [20,29,45], grape marc and pulp [11], apple pomace [42], grape seeds [39], vegetable baggase [46] and waste [28]. Studies on the drying characteristics and kinetics pomegranate peels are limited. Only recently, several papers have been published on the drying kinetics of pomegranate by-products (from juice processing) using cabinet dryer [23], pomegranate peels (cv. Hicaznar) using cabinet dryer [12] and pomegranate seed (cv. Hicaznar) using infrared radiation [13].

'Wonderful' is the most widely grown and consumed pomegranate cultivar globally [21] and accounts for over 64% of pomegranate exports from South Africa. During the past ten years, pomegranate production in South Africa has increased tremendously and currently estimated at over 1000 ha of total planted area, with exports increasing by 193.8% from 2012 to 2017 [34]. The high level of bioactive compounds in the peel as well as the reported health benefits to date make these desirable by-products as functional ingredients in food, nutraceuticals and pharmaceutics [14,16,18]. The aim of the study was to determine the drying characteristics and establish suitable thin-layer drying model for pomegranate peel (cv. Wonderful) over a wide temperature range. Additionally, important drying process parameters (effective moisture diffusivity and activation energy) were determined.

Materials and methods

Fruit material

Pomegranate fruit (cv. Wonderful) were sourced during commercial harvest from Sonlia packhouse in Western Cape (33°34′851″S, 19°00′360″E), South Africa. Fruit were then transported to the Postharvest Technology Laboratory at Stellenbosch University and immediately, healthy fruit were sorted for uniformity in size, shape and color. Fresh pomegranate peel was cut in the dimension of 20 ± 0.5 mm (length), 20 ± 0.5 mm (width) and 5 mm ± 0.5 thicknesses were used. Moisture content was measured using a modified AOAC method 925.45 [6] with slight modifications by drying the peel using the oven at 105 ± 0.5 °C for 24 h. The oven was kept functional for an hour to equilibrate the inner temperature before drying. The accuracy of the inner temperature was monitored using thermometer (Thermco®, Germany).

Oven drying procedure

Three different temperature levels (40, 50 and 60 °C) were used and the oven dryer was operated at an air velocity of 1.0 m/s, parallel to the drying surface of the sample. Moisture loss was recorded by a digital balance (ML3002.E, Mettler

Table 1
Mathematical models applied to the oven drying curves of pomegranate peels.

Model	Mathematical	References
Lewis	$MR = exp(-kt)$	[39]
Henderson and Pabis	$MR = aexp(-kt)$	Ghodake et al., 2006
Logarithmic	$MR = aexp(-kt) + c$	[48]
Two term	$MR = aexp(-k_0 t) + b\,exp(-k_1 t)$	Zielinska and Markowski, 2010
Two-term exponential	$MR = aexp(-kt) + (1-a)exp(-kat)$	Sharaf-Eldeen et al., 1980
Approximation of diffusion	$MR = aexp(-kt) + (1-a)exp(-kbt)$	Dissa et al., 2011
Verma et al.	$MR = aexp(-kt) + (1-a)exp(-gt)$	[31]
Page	$MR = exp(-kt^n)$	Sobukola et al., 2008
Midilli et al.	$MR = aexp(-ktn) + bt$	Mundada et al., 2010
Wang and Singh	$MR = 1 + at + bt^2$	Corzo et al., 2008

Toledo, Switzerland) at an hourly interval during drying for determination of drying curves. Peels were dried until equilibrium (no weight change) was reached. Drying tests were run four times at each temperature.

Modelling of the drying characteristics

Moisture ratio (MR) of pomegranate peels during drying was calculated using Eq. (1) [22,35].

$$MR = (M_t - M_e)/(M_0 - M_e) \tag{1}$$

where M_t represents moisture content at time t (kg water/kg dry matter), M_0 initial moisture content of the sample (kg water/kg dry matter), and M_e equilibrium moisture content (kg water/kg dry matter). The equilibrium moisture content (M_e) was obtained by extending the drying time until no measurable weight loss was observed [41]. In this study, peels were dried until equilibrium (no weight change) was reached. Thus, the value of equilibrium moisture content (M_e) is negligible compared to (M_t) and (M_0). Therefore, MR was simplified to M_t/M_0 instead of $(M_t - M_e)/(M_0 - M_e)$.

The drying rate of pomegranate peel was calculated using Eq. (2):

$$DR = (M_{t1} - M_{t2})/(t_2 - t_1) \tag{2}$$

where t_1 t_1 and t_2 are drying times (h); M_{t1} and M_{t2} are moisture content of the samples at (g water/g dry matter) at time 1 and time 2, respectively [12].

Data analysis

Ten thin-layer drying models were selected for fitting the data as detailed in Tables 1 and 2. The r^2 (coefficient of determination) is one of main criteria for selecting the best model to describe drying curves [7]. The best fit model describing the drying characteristics was chosen based on the highest r^2 value and the lowest standard error.

Effective moisture diffusivity determination

According to Pathare and Sharma [37], moisture diffusivity is used to indicate the flow of moisture within a material and is primarily influenced by moisture content and temperature of the material. The moisture diffusivity of infinite slab is described by Eq. (3) [10]. By assessing that there is uniform moisture distribution, the surface is at equilibrium with the drying air, constant diffusivity and shrinkage is negligible [19], we obtain Eq. (4).

$$\frac{\partial M}{\partial t} = \nabla\left[D_{eff}(\nabla M)\right] \tag{3}$$

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

D_{eff} is the effective moisture diffusivity (m^2/s), t is the time (min), L denotes half-thickness of samples (m), and n is a positive integer. In the case of longer drying periods, the above equation can be simplified to the only first term of series, without much affecting the accuracy of the prediction [28,32]:

$$ln\,MR = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}t}{4L^2}\right) \tag{5}$$

From Eq. (5), a plot of ln MR versus drying time give a straight line with a slope (K) of

$$K = \frac{\pi^2 D_{eff}}{4L^2} \tag{6}$$

Table 2
Statistical output of the thin layer drying models for the drying of the pomegranate peels cv. Wonderful at 40 °C.

Model	Parameter	Value	Coefficient of determination (r^2)	Standard error (e_s)
Newton ($M_R = \exp(-kt)$)	$k(\text{h}^{-1})$	0.2223	0.9862	0.0183
Page ($M_R = exp - kt^n$))	$k(\text{h}^{-1})$	0.3041	0.9979	0.0112
	n	0.8178		
Henderson and Pabis ($M_R = aexp(-kt)$)	$k(\text{h}^{-1})$	0.2098	0.9892	0.0228
	a	0.9485		
Asymptotic (logarithmic) ($MR = a_{0+}aexp(-kt)$)	$k(\text{h}^{-1})$	0.2519	0.9986	0.0098
	a	0.9343		
	$a1$	0.0460		
Two term ($MR = (aexp(-k0t) + bexp(-k_1 t)$)	$k0$	0.3217	0.9995	0.0059
	a	0.7448		
	$k1$	0.2491		
	b	0.0898		
Two-term exponential ($MR = aexp(-kt) + (1-a)exp(-kat)$)	k	0.5447	0.9975	0.0102
	n	0.3068		
Midilli et al. ($MR = aexp(-kt^n) + bt$)	$k(\text{h}^{-1})$	0.2868	0.9997	0.0046
	n	0.8789		
	a	1.0021		
	b	0.0014		
Modified page ($MR = exp(-(kt)^n$)	k	0.2969	0.9862	0.0168
	n	0.7486		
Approximation of diffusion ($MR = aexp(-kt) + (1-a)exp(-kbt)$)	k	0.0943	0.9994	0.0060
	a	0.2708		
	b	3.5250		
Verma et al. ($MR = aexp(-kt) + (1-a)exp(-gt)$)	k	0.3323	0.9994	0.0060
	a	0.7291		
	g	0.0943		

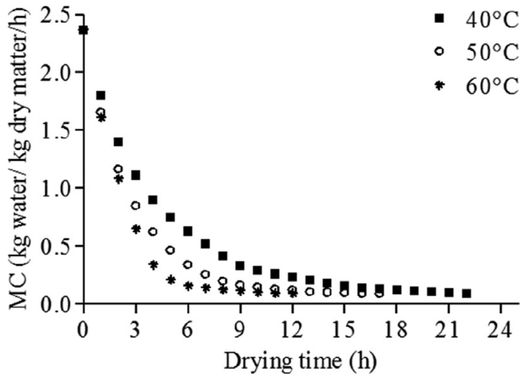

Fig. 1. Drying curves of pomegranate peel at different temperatures.

Determination of activation energy

According to Aghbashlo et al. [2] the dependence of effective moisture diffusivity on temperature is described by Arrhenius equation.

$$D_{eff} = D_0 exp\left(-\frac{E_a}{R(T + 273.15)}\right) \tag{7}$$

where D_0 is the pre-exponential factor of Arrhenuis equation (m^2/s), Ea is activation energy (kJ/mol), R is the universal gas constant (kJ/mol.K), and T is temperature (°C).

Results and discussion

The changes in pomegranate peel moisture content versus drying time for different drying temperatures are presented in Fig. 1. The result showed that the moisture content of pomegranate peel decreased exponentially as the drying time increased resulting in 0.093, 0.094, 0.096 kg water/ kg DM for 40 °C, 50 °C and 60 °C drying temperature, respectively. The drying time required to achieve a final moisture content of the peel were, 22, 17 and 12 h at the oven temperature of 40 °C, 50 °C and 60 °C, respectively. It can be observed that increment in air temperature substantially decreased drying time. Rapid moisture ratio decrease is due to increased air heat supply rate to the peels which results in accelerated moisture migration

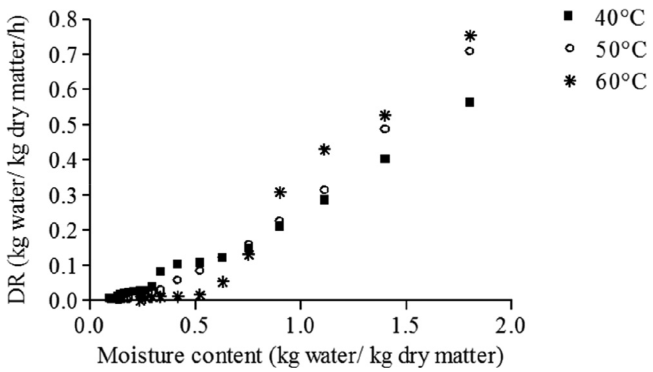

Fig. 2. Variation of drying rate as a function of moisture content of pomegranate peel.

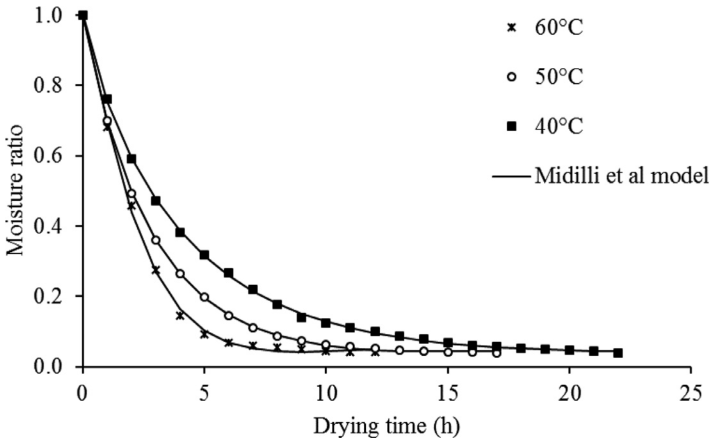

Fig. 3. Comparison between the experimental moisture ratios of pomegranate peels and those predicted by Midilli et al. [30] model.

out of the peel. Similar results were also obtained by several researchers on drying various agricultural by-products such as olive cake [45]; pomegranate by-product after juice processing [23] and prickly pear seed [31].

The drying rate (kg water/kg dry matter/h) versus moisture content is presented in Fig. 2. The average drying rate of the pomegranate peel at the oven temperature of 40 °C, 50 °C and 60 °C were 0.0010, 0.0031 and 0.0085 kg water/kg dry matter/h, respectively. As can be observed, higher temperature resulted in higher drying rate. Average drying rate was greater at the beginning of the drying process possibly due to evaporation and moisture from peel surface which later declined with decreasing moisture content for all the drying temperature range. In addition, constant rate drying was not well noticeable as the drying took place at the normal falling rate for all the temperature range indicating that internal mass transfer has occurred by diffusion. According to Pathare and Sharma [37] the accelerated drying rate was presumed to be attributed to internal heat generation. The results are in agreement with those findings reported by Doymaz [12] using pomegranate peel and Kara and Doymaz [23] using pomegranate by-product (after juice processing) and vegetable such as carrot [27].

Fitting of the drying curves

Fig. 3 presents the variation of experimental and predicted moisture ratio using the best model with drying time for dried pomegranate peel. The best model selected was based on the highest coefficient of determination (r^2) and the lowest standard error (e_s) values (Tables 1–4). Midilli et al. model was identified as the best descriptive model for all the drying temperatures with the highest r^2 and the lowest e_s value compared to other layer drying models. The values for coefficient of determination and e_s were in the range of 0.9988–0.9999 and 0.0028–0.0112, respectively indicating that the thin layer drying of pomegranate peels occurs in the falling rate period. The results are similar to those found by [12], who dried pomegranate peel cv. Hicaznar in thin layer with drying temperature in the range of 50–70 °C. The author observed that Midilli model obtained the best fit. Likewise, Kara and Doymaz [23] found that Midilli et al. model represented the thin layer drying characteristics of pomegranate by-products (from juice processing) with drying air temperature in the range of 50–80 °C.

Table 3
Statistical output of the thin layer drying models for the drying of the pomegranate peels cv. wonderful at 50 °C.

	Parameter	Value	Coefficient of determination (r^2)	Standard error (e_s)
Verma et al. ($MR = aexp(-kt) + (1-a)exp(-gt)$)	$k(\mathrm{h}^{-1})$	0.3323	0.9994	0.0060
	a	0.7291		
	g	0.0943		
Newton ($M_R = \exp(-kt)$)	$k(\mathrm{h}^{-1})$	0.4196	0.9923	0.0262
Page ($M_R = exp - kt^n)$)	$k(\mathrm{h}^{-1})$	0.3952	0.9928	0.0237
	n	1.0577		
Henderson and Pabis ($M_R = exp - kt^n)$)	$k(\mathrm{h}^{-1})$	0.4245	0.9925	0.0258
	a	1.0123		
Asymptotic (logarithmic) ($MR = a_{0+}aexp(-kt)$)	$k(\mathrm{h}^{-1})$	0.4565	0.9946	0.0232
	a	0.9974		
	$a1$	0.0230		
	n	1.0285		
Two term ($MR = (aexp(-k0t) + bexp(-k_1 t)$)	$k0$	0.4565	0.9946	0.0233
	n	0.9974		
	$k1$	0.0230		
	b	0.0000		
Two-term exponential ($MR = aexp(-kt) + (1-a)exp(-kat)$)	k	0.4630	0.9923	0.0265
	a	0.7165		
Midilli et al. ($MR = aexp(-kt^n) + bt$)	k	0.3657	0.9988	0.0112
	n	1.1939		
	a	0.9970		
	b	0.0040		
Modified page ($MR = exp(-(kt)^n$)	$k(\mathrm{h}^{-1})$	0.4080	0.9923	0.0261
	n	1.0285		
Approximation of diffusion ($MR = aexp(-kt) + (1-a)exp(-kbt)$)	k	0.4529	0.9933	0.0220
	a	1.0875		
	b	5.5494		
Verma et al. ($MR = aexp(-kt) + (1-a)exp(-gt)$)	k	0.4460	0.9941	0.0235
	a	0.9787		
	g	0.0000		

Table 4
Statistical output of the thin layer drying models for the drying of the pomegranate peels cv. Wonderful at 60 °C.

	Parameter	Value	Coefficient of determination (r^2)	Standard error (e_s)
Verma et al. ($MR = aexp(-kt) + (1-a)exp(-gt)$)	$k(\mathrm{h}^{-1})$	0.3323	0.9994	0.0060
	a	0.7291		
	g	0.0943		
Newton ($M_R = \exp(-kt)$)	$k(\mathrm{h}^{-1})$	0.4196	0.9923	0.0262
Page ($M_R = exp - kt^n)$)	$k(\mathrm{h}^{-1})$	0.3952	0.9928	0.0237
	n	1.0577		
Henderson and Pabis ($M_R = exp - kt^n)$)	$k(\mathrm{h}^{-1})$	0.4245	0.9925	0.0258
	a	1.0123		
Asymptotic (logarithmic) ($MR = a_{0+}aexp(-kt)$)	$k(\mathrm{h}^{-1})$	0.4565	0.9946	0.0232
	a	0.9974		
	$a1$	0.0230		
	n	1.0285		
Two term ($MR = (aexp(-k0t) + bexp(-k_1 t)$)	$k0$	0.4565	0.9946	0.0233
	n	0.9974		
	$k1$	0.0230		
	b	0.0000		
Two-term exponential ($MR = aexp(-kt) + (1-a)exp(-kat)$)	k	0.4630	0.9923	0.0265
	a	0.7165		
Midilli et al. ($MR = aexp(-kt^n) + bt$)	k	0.3657	0.9988	0.0112
	n	1.1939		
	a	0.9970		
	b	0.0040		
Modified page ($MR = exp(-(kt)^n$)	$k(\mathrm{h}^{-1})$	0.4080	0.9923	0.0261
	n	1.0285		
Approximation of diffusion ($MR = aexp(-kt) + (1-a)exp(-kbt)$)	k	0.4529	0.9933	0.0220
	a	1.0875		
	b	5.5494		
Verma et al. ($MR = aexp(-kt) + (1-a)exp(-gt)$)	k	0.4460	0.9941	0.0235
	a	0.9787		
	g	0.0000		

Table 5
Effective moisture diffusivity at various drying oven temperatures.

Temperature (°C)	D_{eff} (m^2/s)
40	4.05×10^{-10}
50	5.06×10^{-10}
60	8.10×10^{-10}

Effective moisture diffusivity (D_{eff})

The values of D_{eff} were obtained using Eq. (7) and are presented in Table 5. In the present study, the calculated D_{eff} showed an increasing trend with the increasing drying temperature. The effective moisture diffusivity of the pomegranate peels at the drying temperature was 4.05×10^{-10}, 5.06×10^{-10} and 8.10×10^{-10} m^2/s at 40 °C, 50 °C and 60 °C, respectively. The D_{eff} observed in the study was within general range observed by several researchers such as pomegranate by-product from juice processing (1.22 – 4.29×10^{-10} m^2/s), [23], pomegranate peel cv. Hicaznar (4.02 – 5.31×10^{-9} m^2/s) [12], and grape seed (1.57–8.03×10^{-10} m^2/s) [39] using various air temperatures in the range of 40–80 °C.

Activation energy (E_a)

Activation energy is a measure of the temperature sensitivity of D_{eff} and is the energy needed to initiate moisture diffusion within the peels [1]. In the present study, the activation energy of pomegranate peels was found to be 21.98 kJ/ mol. According to Zogzas et al. [49], the value of E_a is within the general range of 12.7–110 kJ/mol for numerous food materials. Our results are in agreement with those reported by several researchers for various agricultural crops and by-products. For instance, the activation energy was found to be 23.05 kJ/mol in carrot [27], 39.66 kJ/mol for pomegranate peel cv. Hicaznar [23], 25.41 kJ/mol for grape marc [11], 13.47 kJ/mol for grape pulp [11] and 52.10 kJ/mol for tomato pomace [4].

Conclusions

This study established that the characteristic drying behaviour of pomegranate peels occurs in the falling rate period. Increasing air drying temperature increased the drying potential and, therefore, decreased drying time. Higher drying rate was observed for higher drying air temperature. Midilli et al. model best explained the drying characteristics of pomegranate peels therefore, represents a good approximation for estimating the drying time of this by-product. The values of effective moisture diffusivity at different air temperatures investigated were in the range of 4.05–8.10×10^{-10} m^2/s, with average action energy of 21.98 kJ/ mol.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

CRediT authorship contribution statement

Rebogile R. Mphahlele: Data curation, Formal analysis, Writing - original draft. **Pankaj B. Pathare:** Formal analysis, Writing - review & editing. **Umezuruike Linus Opara:** Conceptualization, Funding acquisition, Supervision, Writing - review & editing.

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