ORIGINAL ARTICLE

Drying kinetics, moisture diffusivity and lycopene retention of watermelon pomace in different dryers

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Abstract Drying kinetics of watermelon pomace was investigated in fluidized-bed and cabinet dryers using 2–6 kg/m^2 tray loads at 50–70 °C. Drying behavior was described by the Page's model with high coefficient of determination ($\geq$0.96), lower standard error ($\leq$0.03) and scattered residual plot. Effective moisture diffusivity of pomace during drying varied from 0.880×10^{-8} to 3.541×10^{-8} m^2/s for fluidized bed and 0.347×10^{-8} to 0.868×10^{-8} m^2/s for cabinet dryers. Arrhenius's equation adequately explained the relationship between the drying rate constant/effective moisture diffusivity and drying air temperature. Lycopene content of dehydrated watermelon pomace was 11.0–17.3 mg/100 g dry basis in fluidized-bed dryer and 9.3–15.4 mg/100 g dry basis in cabinet dryer.

Keywords Watermelon · Pomace · Lycopene · Drying · Moisture diffusivity

Introduction

Watermelon (*Citrullus lanatus* Thunb) is cultivated throughout the warmer parts of the world. The watermelon production of the world was 105 million tons and leading growers are China, Turkey, Iran, Brazil and United States (FAO 2014). Fruit is consumed in hot and dry season on account of its cool, refreshing and sweet taste. Processing of watermelon yields major solid waste pomace rich in pigments. Fresh pomace contains 20 mg/100 g lycopene content which is about 4.5 times higher than the flesh (Arocho et al. 2012). Watermelon pomace has moisture content of about 95 % making it susceptible to microbial deterioration leading to environement problems (Kerje and Grum 2003). However, it can be preserved by reducing the moisture to a safe level where microorganisms cannot grow and cause spoilage (Falade et al. 2007).

Lycopene is the main carotenoid in watermelon, accounting for 84–97 % of total carotenoids (Perkins-Veazie and Collins 2006; Kang et al. 2010) with higher relative antioxidant potential (Perkins-Veazie et al. 2006; Pinto et al. 2011). Lycopene quenches free radicals formed during normal metabolism and deactivate DNA chain breaking agents that are implicated in some cancers (Sies and Stahl 1998). Lycopene undergoes degradation via isomerization and oxidation which has direct impact on the sensory quality and health benefits of finished products (Shi et al. 2002). Watermelon pomace is an excellent source of lycopene having potential application in food products to increase their aesthetic and therapeutic value. It can also be used in animal feed like poultry, cattle, swine, aquaculture etc. or as a fuel in boilers or extraction of pectin and fibers. This investigation has been carried out to study drying behavior of watermelon pomace.

Materials and methods

Materials

Mature ripe fruits of watermelons cultivar "*Namdhari*" were procured from the farm located in Kapurthala (India). Fruits

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Highlights • Watermelon pomace is generated during processing of watermelon.
• It is generally discarded as waste leading to environment problems.
• Watermelon pomace contains more lycopene as compared to its flesh.
• Dehydration can increase the shelf life of pomace.
• Pigment extracted can be used in different food products.

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were thoroughly washed, cut into quarters and rind was removed by stainless steel knife manually. Flesh was cut into small pieces and passed through the screw juice extractor (Kalsi Industries Ltd., Ludhiana, India). The pomace was collected and used for study.

Drying of watermelon pomace

Pomace was dried in a fluidized bed dryer (Endecotts Ltd., London, U.K.) and cabinet dryer (La Parmigiana, Fidenza, Italy) at different temperatures (50, 60 and 70 °C) and feed rates (2, 4 and 6 kg/m^2). The initial weight was considered as the mass at zero time. The change in weight was observed at 10 min interval in fluidized bed dryer and at hourly interval in cabinet dryer. The drying was carried out till three constant readings were obtained. The initial moisture content of watermelon pomace was determined by keeping in a vacuum oven (Narang Scientific Pvt Ltd., New Delhi, India) at 60±2 °C and 100 mm Hg pressure for 24 h.

Drying model

The Page's model was used to describe drying behavior of watermelon pomace:

$$MR = (m_t - m_e) / (m_o - m_e) = \exp(-k\, t^n) \quad (1)$$

where MR- moisture ratio; m_t –moisture content dry basis (% db) at any given instant time t; m_e - equilibrium moisture content (% db); m_o - initial moisture content (% db); t - time (h); k – drying rate constant (l/h); n - dimensionless coefficient.

Effective moisture diffusivity

Fick's second law of diffusion assuming uni-dimensional moisture movement without volume change, constant diffusivity, uniform initial moisture distribution and negligible resistance was used to compute moisture diffusivity from experimental drying data (Crank 1975; Sinija and Mishra 2009). The second law of diffusion can be transformed in the form of following equation (Doymaz et al. 2004; Akpinar and Toraman 2013; Koua et al. 2013).

$$MR = \frac{8}{\pi^2} \times \exp\left((-\pi^2 D.t) / 4l^2\right) \quad (2)$$

where D: effective moisture diffusivity (m^2/s); l: average sample thickness (2 kg/m^2 is 0.007 m, 4 kg/m^2 is 0.009 m, 6 kg/m^2 is 0.011 m).

The correlation between drying rate constant and effective moisture diffusivity was also found using linear, exponential and power models. The adequacy of the model was evaluated on the basis of coefficient of determination (R^2).

Effect of temperature on drying rate constant and effective moisture diffusivity

The Arrhenius law can be used to relate 'k' and 'D' with drying air temperature and to calculate the activation energy:

$$k = k_o \exp(-E_a / RT) \quad (3)$$
$$D = D_o \exp(-E_a / RT) \quad (4)$$

where k_o- frequency factor (l/h); D_o – Reference diffusion coefficient at infinitely high temperature; E_a- activation energy (kJ/mol); R- Universal gas constant (8.314 kJ/mol.K); T - Absolute temperature (K).

Lycopene retention and visual color

Sample (2 g) was extracted with acetone in a pestle and mortar till residues became colorless. Lycopene was transferred into petroleum ether phase by diluting acetone extract in a separating funnel, passed through sodium sulfate, volume made to 50 ml and absorbance was measured at 503 nm using UV visible spectrophotometer (Shimadzu, Kyoto, Japan) (Sadler et al. 1990). The extinction coefficient (17.2×10^4 mol cm^{-1}) was verified with standard lycopene solution (Sigma Chemical Co, St. Louis, U.S.A.) and used to determine lycopene in the sample.

Visual color was measured using a Hunter colorimeter (Hunter Associates Laboratory, Virginia, U.S.A.) in terms of L (lightness), a (redness and greenness) and b (yellowness and blueness). $\Delta E = \sqrt{L^2 + a^2 + b^2}$ indicates the magnitude of color difference between fresh vacuum dried sample and dried samples of different dryers at different temperatures.

Statistical analysis

The parameters were estimated by fitting the mathematical model to experimental data, using nonlinear regression. The adequacy of models was evaluated by the R^2, standard error (SE) and the pattern of residual plots. The data on drying and effective moisture diffusivity were analyzed following one way analysis of variance (ANOVA) using Microsoft Excel (Microsoft Inc., Redmond, USA).

Results and discussion

Watermelon processing

On processing, the 'Namdhari' cultivar of watermelon yielded 55.28 % juice, 31.47 % rind and 10.44 % pomace (including seeds). The previous studies on processing of watermelon state that watermelon yields 41.5–60 % juice, 31–49.55 % rind and 8.9–23.59 % pomace (Shin et al. 1978; Crandall

and Kesterson 1981; Uddin and Nanjundaswamy 1982; Hayoglu and Fenercioglu 1990; Sogi 2003). The present findings are in agreement with the previous results.

Drying characteristics

The initial moisture content of watermelon pomace was found to be 925.41 % dry basis (db). The moisture content was

reduced to about 6 % (db) at 50–70 °C using 2–6 kg/m² feed rate in a fluidized bed or cabinet dryer. Drying curves of watermelon pomace at 50–70 °C with feed rates of 2–6 kg/m² for fluidized bed dryer (Fig. 1 a-c) and for cabinet dryer (Fig. 1 d-f) showed that moisture content decreased continuously with increase in the time indicating that drying of watermelon pomace took place in the falling rate period. Sogi and Bawa (1998) reported that drying of tomato pomace followed the falling
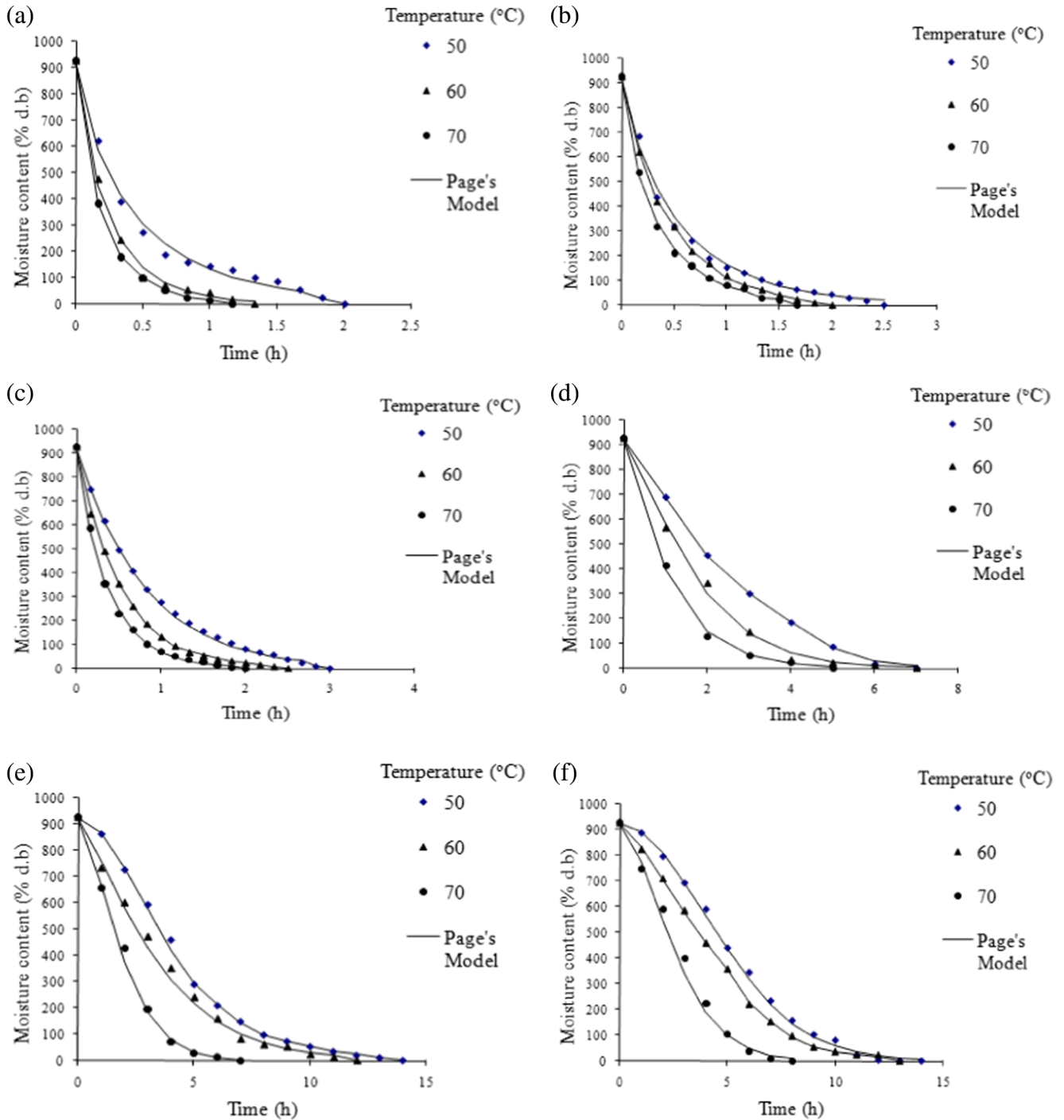

Fig. 1 Drying curves of watermelon pomace dried in a fluidized bed dryer (**a**, **b**, **c**) and cabinet dryer (**d**, **e**, **f**) with 2, 4 and 6 kg/m² tray load respectively at 50–70 °C

rate period pattern during cabinet and sun drying. Kaur et al. (2006) studied drying characteristics of peel isolated from tomato pomace in cabinet and fluidized bed dryer and concluded similar findings.

It took 7–12 h for drying the pomace in cabinet dryer while 2–2.5 h in fluidized bed dryer with tray load of 4 kg/m^2 at 50–70 °C. With decrease in tray load to 2 kg/m^2, the drying process got completed in 5–7 h in cabinet dryer and 1.2–2 h in fluidized bed dryer at 50–70 °C. With increase in tray load to 6 kg/m^2, the drying of watermelon pomace took 8–14 h in cabinet dryer and 2–3 h in fluidized bed dryer at selected temperatures. Hence, fluidized-bed dryer took less time for drying than cabinet dryer. Dehydration of tomato peel in cabinet and fluidized bed dryer revealed that the latter gave good quality product in minimum time (Kaur et al. 2006).

Regression analysis was carried out using Page's model and the coefficients were determined (Table 1). The drying rate constant (k) varied from 1.244 to 3.705 1/h for fluidized bed dryer and from 0.036 to 0.848 1/h for cabinet dryer respectively. Dimensionless constant (n) varied from 0.806–1.043 to 1.102–1.976 for fluidized-bed dryer and cabinet dryer respectively. The values for the R^2 between experimental and predicted values were greater than 0.964 while the SE was less than 0.03 for given temperatures and tray loads. The residual plots showed scattered pattern for both the dryers for given feed rates and drying temperatures. The Page's model adequately describes the drying behavior of watermelon pomace over the range of temperature used in the study. Two way

ANOVA indicated that the drying rate constant (k) significantly (p≤0.05) increased with increased drying air temperature and decreased tray loads for both dryers. This means as the drying air temperature increased, the drying time of watermelon pomace decreased. Similar reports are available on tomato seeds and mushrooms (Sogi et al. 2003; Shivhare et al. 2004).

Effective moisture diffusivity

The effective moisture diffusivity (D) for watermelon pomace varied from 0.880×10^{-8} to 3.541×10^{-8} m^2/s for fluidized bed dryer and from 0.347×10^{-8} to 0.868×10^{-8} m^2/s for cabinet dryer respectively (Table 2). It was observed that effective moisture diffusivity increased with increase in temperature as well as tray load for both fluidized bed and cabinet dryer. It may be due to increase in vapor pressure inside the pomace at higher temperature. The highest value of diffusivity was found to be 3.541×10^{-8} m^2/s and 0.868×10^{-8} m^2/s for fluidized bed dryer and cabinet dryer at higher temperature 70 °C and 6 kg/m^2 tray load.

Falade et al. (2007) studied kinetics of mass transfer during osmotic dehydration of watermelon slices and concluded that water diffusivities for variable thickness of watermelon slices at different temperatures was in the range between 0.1030×10^{-9} and 3.549×10^{-9} m^2/s. Thus water diffusivity of watermelon slices increased with the temperature but decreased by increasing the thickness of the samples.

Table 1 Coefficients of page's model [Eq. (1)] for watermelon pomace at 50–70 °C (n=3)

Drying system	Temperature (°C)	Feed Rate (kg/m^2)	Drying rate constant (k) (1/h)	Dimensionless number (n)	R^2	SE	Residual Pattern
Fluidized-bed dryer	50	2	1.941	0.806	0.969	0.016	Scattered
		4	1.729	0.871	0.980	0.011	Scattered
		6	1.244	1.019	0.991	0.008	Scattered
	60	2	3.467	0.877	0.976	0.017	Scattered
		4	2.624	0.977	0.969	0.016	Scattered
		6	2.344	1.043	0.992	0.019	Scattered
	70	2	3.705	0.897	0.992	0.025	Scattered
		4	2.779	0.817	0.995	0.030	Scattered
		6	2.601	0.954	0.991	0.024	Scattered
Cabinet dryer	50	2	0.103	1.976	0.997	0.007	Scattered
		4	0.066	1.795	0.988	0.003	Scattered
		6	0.036	1.893	0.974	0.014	Scattered
	60	2	0.468	1.277	0.983	0.011	Scattered
		4	0.195	1.249	0.987	0.011	Scattered
		6	0.102	1.399	0.964	0.024	Scattered
	70	2	0.848	1.102	0.990	0.007	Scattered
		4	0.322	1.481	0.984	0.009	Scattered
		6	0.176	1.586	0.979	0.018	Scattered

R^2 - Coefficient of determination; S.E.-Standard error

Table 2 Effective moisture diffusivity (Eq. 2) of watermelon pomace dried at 50–70 °C in different drying system

Drying system	Temperature (°C)	Feed Rate (kg/m²)	Effective Moisture Diffusivity, D (m²/s) x 10⁻⁸	R²	SE	Residual Pattern
Fluidized-bed dryer	50	2	0.880	0.951	0.04	Scattered
		4	1.348	0.974	0.08	Scattered
		6	1.887	0.957	0.09	Scattered
	60	2	1.768	0.967	0.01	Scattered
		4	2.554	0.934	0.03	Scattered
		6	3.460	0.973	0.05	Scattered
	70	2	1.951	0.989	0.07	Scattered
		4	1.967	0.990	0.012	Scattered
		6	3.541	0.972	0.09	Scattered
Cabinet dryer	50	2	0.347	0.882	0.08	Scattered
		4	0.399	0.862	0.04	Scattered
		6	0.648	0.969	0.03	Scattered
	60	2	0.422	0.974	0.02	Scattered
		4	0.438	0.972	0.06	Scattered
		6	0.459	0.941	0.05	Scattered
	70	2	0.523	0.995	0.03	Scattered
		4	0.697	0.966	0.07	Scattered
		6	0.868	0.907	0.01	Scattered

R^2 - CoR2 : Coefficient of determination; S.E.-Standard error

Akpinar and Toraman (2013) estimated the moisture diffusivity in thin layer drying of ginger slices and found the average effective moisture diffusivity values varied from 2.807×10^{-10} to 6.977×10^{-10} m²/s over the temperature range of 40–70 °C and velocity range 0.8–3 m/s. Similar trend for temperature has been observed in hot air drying but the diffusivity increased with increase in tray load indicating that the thickness of the watermelon pomace did not affect the diffusivity.

Correlation between drying rate constant and effective moisture diffusivity

Different models such as linear, exponential and power were fitted to find out the correlation between 'k' and 'D'. The R^2 was maximum using exponential model (0.920) followed by power (0.869) and linear (0.758). The exponential model for 'k' and 'D' is as follows:

$$k = -0.078 * e^{1.082D} \tag{5}$$

This model can be used for the prediction of 'D' for any value of 'k' and vice-versa with good level of confidence.

Effect of temperature on drying rate constant and effective moisture diffusivity

Dependence of both 'k' and 'D' on temperature for fluidized-bed and cabinet dryer was evaluated using Arrhenius
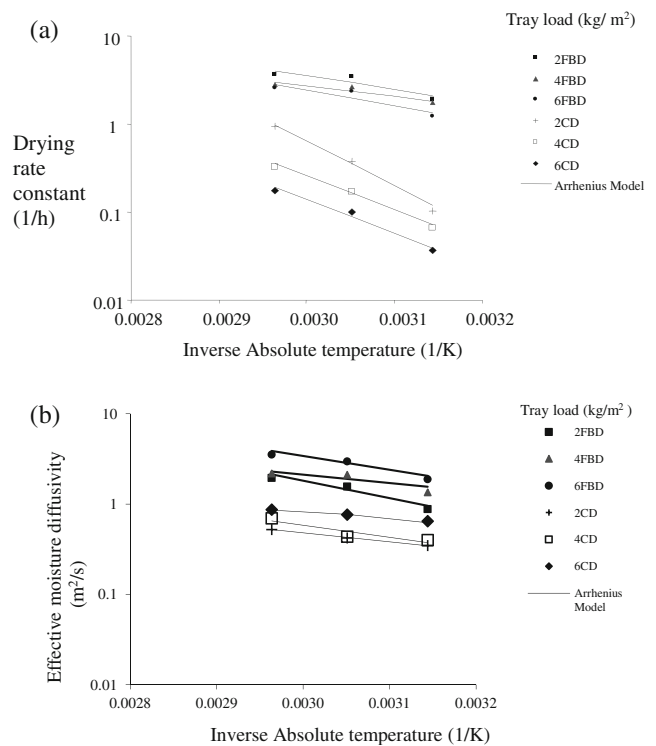

Fig. 2 The Arrhenius relationship between drying rate constant (k) and drying air temperature (1/K) (**a**) and between effective moisture diffusivity and drying air temperature (1/K) (**b**) for watermelon pomace dried in a fluidized bed and cabinet dryer (2, 4 and 6 kg/m² tray load)

Table 3 Coefficients of Arrhenius law (Eqs. 3 and 4) for watermelon pomace dried at 50-70 °C

Drying System	Feed rate (kg/m²)	Activation energy (E) (kJ/mol)	R^2	SE	Residual pattern
Drying rate constant (k)					
Fluidized-bed dryer	2	22.05	0.839	0.006	Scattered
	4	29.61	0.851	0.003	Patterned
	6	32.20	0.865	0.003	Scattered
Cabinet dryer	2	19.25	0.925	0.04	Scattered
	4	26.22	0.856	0.08	Scattered
	6	36.66	0.906	0.03	Scattered
Diffusivity coefficient (D)					
Fluidized-bed dryer	2	15.67	0.939	0.002	Scattered
	4	17.81	0.951	0.005	Scattered
	6	29.34	0.965	0.009	Scattered
Cabinet dryer	2	18.87	0.948	0.05	Scattered
	4	25.51	0.964	0.07	Scattered
	6	31.21	0.975	0.08	Scattered

R^2 - Coefficient of determination; S.E.-Standard error

Eqs. (3 and 4). Results obtained are presented in Fig. 2 a, b. The activation energy obtained from the slope of plot for 'k' were varied from 22.05–32.20 to 19.25–36.66 kJ/mol for fluidized bed and cabinet dryer respectively (Table 3). The activation energy obtained from 'D' value varied between 15.67–29.34 and 18.87–31.21 kJ/mol for fluidized bed and cabinet dryer respectively (Table 3). Kaur et al. (2006) found the activation

energy was 36.80 kJ/mol in cabinet dryer and 20.59 kJ/ mol in fluidized bed dryer for tomato peel at 4 kg/m² feed rate. Relation between drying temperature and moisture diffusivity was satisfactorily described by an Arrhenius type relationship in thin layer drying of ginger slices (Akpinar and Toraman 2013). An activation energy value of 19.3 kJ/mol was obtained with temperature range of 40–70 °C and air velocity of 0.8–3 m/s

Table 4 Lycopene retention and color values of watermelon pomace at different drying ($n=3$)

Drying system	Temperature (°C)	Feed Rate (kg/m²)	Lycopene content mg/100 g (d.b.)	'L'	'a'	'b'	$\Delta E = \sqrt{L^2 + a^2 + b^2}$ *
Fluidized-bed dryer	50	2	17.3±0.02	46.23±0.21	6.37±0.08	9.41±0.08	1.54±0.15
		4	16.7±0.05	45.27±0.09	6.29±0.099	8.89±0.071	2.56±0.10
		6	15.3±0.02	44.51±0.14	6.16±0.11	8.53±0.12	3.40±0.09
	60	2	16.7±0.03	44.23±0.70	6.07±0.06	8.52±0.12	3.68±0.19
		4	15.9±0.06	41.48±0.24	5.86±0.07	8.02±0.056	6.41±0.18
		6	14.7±0.04	40.88±0.06	5.76±0.11	7.78±0.09	7.07±0.23
	70	2	13.1±0.08	41.84±0.16	5.59±0.06	7.22±0.11	6.42±0.11
		4	12.2±0.01	40.89±0.09	5.34±0.09	7.04±0.05	7.40±0.22
		6	11.0±0.07	40.6±0.11	4.83±0.07	6.81±0.22	7.88±0.13
Cabinet dryer	50	2	15.4±0.03	46.16±0.36	6.12±0.02	9.36±0.15	1.74±0.19
		4	14.1±0.01	45.23±0.09	5.66±0.07	8.88±0.09	2.86±0.17
		6	13.2±0.02	42.59±0.07	5.03±0.02	8.47±0.04	5.51±0.16
	60	2	14.1±0.02	44.47±0.336	5.76±0.09	9.33±0.07	3.36±0.17
		4	12.8±0.08	43.98±0.29	5.15±0.14	8.62±0.06	4.21±0.26
		6	11.7±0.03	41.41±0.19	4.98±0.11	8.31±0.13	6.64±0.28
	70	2	11.9±0.01	40.67±0.11	5.46±0.15	6.91±0.22	7.61±0.12
		4	10.8±0.01	40.57±0.21	5.11±0.02	6.88±0.09	7.79±0.13
		6	9.3±0.03	39.56±0.13	4.59±0.08	6.59±0.10	8.95±0.18

* compared with the values of vacuum dried pomace ie L-47.614, a-6.874, b-9.839

in ginger slice drying. Thus results obtained in present study are in close agreement with previous studies.

Effect of drying on lycopene retention and visual color

Lycopene content of fresh watermelon pomace was 19.2 mg/100 g dry basis (db). Lycopene retention varied from 11.0 to 17.3 mg/100 g (db) in fluidized bed dried pomace and 9.3–15.4 mg/100 g (db) in cabinet dried pomace at 50–70 °C (Table 4). Increase in temperature and feed rate had a negative effect on the retention of lycopene. It may be attributed to the fact that drying time increased with the increase in feed rate while lycopene gets degraded at high temperature. Maximum retention of lycopene content was in case of watermelon pomace dried in fluidized-bed which might be due to short drying time. Chawla et al. (2008) reported that lycopene retention was higher in fluidized bed dried tomato pulp as compared with cabinet dried pulp. Shi et al. (2002) studied the kinetics of lycopene degradation in tomato puree and found 0.15–3.47 % relative loss in lycopene during treatment at 90–150 °C for 5–60 min.

Visual color of dried watermelon pomace in terms of 'L', 'a', 'b' is given in Table 4. In fluidized bed dried pomace, 'L', 'a' and 'b' value decreased from 46.23–40.60, 6.37–4.83 to 9.41–6.81 respectively with increase in feed rate and temperature. In the case of cabinet dried pomace, 'L', 'a' and 'b' value decreased from 46.16–39.56, 6.12–4.59 to 9.36–6.59 respectively with increase in feed rate and temperature. It indicated the increase in darkness and decrease in redness and yellowness in watermelon pomace on drying. The color difference increased with increase in temperature and feed rate. Previous results on thin layer drying of tomato slices revealed that 'L', 'a', 'b' decreased with increase in temperature from 50 to 70 °C (Purkayastha et al. 2011).

Conclusion

Drying behavior of watermelon pomace followed the falling rate period pattern and adequately described by Page's model over the range of temperatures and tray loads used. The effective moisture diffusivity increased with increase in temperature and tray load for both the dryers. Arrhenius's equation explained well the relationship between the drying rate constant/effective moisture diffusivity and drying air temperature. Effective moisture diffusivity and drying rate constant are correlated by exponential model. Lycopene retention was found to be higher in fluidized dried pomace and can be utilized to make value added products.

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