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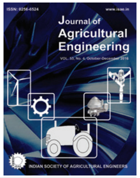

Thin Layer Drying Kinetics of Indian Blackberry (*Syzygium cumini* L.) Pulp

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ABSTRACT

Drying kinetics of fruit has importance in estimating optimum nutritional retainability, preservation requisites and process economy while processing into useful products. Drying kinetics of pulp of local variety of Indian blackberry was studied in a cabinet dryer. The drying experiment was conducted at 50 ºC, 60 ºC and 70 ºC, and moisture losses were recorded at 30-min intervals. Drying took place in two falling rate periods. Shift of first to second falling rate period was found to be irrespective of temperature, and started from 1.08 g water.g^{-1} dry matter. The drying data of Indian blackberry pulp was fitted into five commonly used Newton, Page, Peleg, Henderson and Pabis, and Logarithmic thin layer drying models. The logarithmic model adequately described the drying of Indian blackberry pulp. The activation energy values in first and second falling rate periods were 42.20 kJ.mol^{-1} and 61.62 kJ.mol^{-1}, respectively.

Indian blackberry (*Syzygium cumini* L.), commonly known as Indian blackberry, is an under-utilized fruit of the Indian subcontinent. The edible pulp is 75 % of the whole fruit. It is a good source of vitamins and minerals with medicinal values. Indian blackberry pulp was found to be effective in preventing paracetamol-induced hepatotoxicity, induce cytotoxic effects against human cervical cancer cell (Barh and Viswanathan, 2008). Like all perishable fruits, Indian blackberry cannot be stored for more than two days, and all physical (Jha and Kachru, 1998) and biochemical properties (Rai *et al.*, 2008) change rapidly under ambient conditions. Fruits packed in perforated polyethylene bags can be stored for 21 days at 8-10 ºC and 85-95 % relative humidity (Rai *et al.*, 2011). Thus, reduction of moisture content of the Indian blackberry pulp up to a safe storage limit is one of the options to ensure availability in off-seasons. This can be achieved by drying the pulp in a way that nutrient quality is affected to a minimum level. Drying is one of the oldest methods of food preservation, and it represents an important aspect of food processing. Advantages of drying include reduction in water activity, enhancement of shelf life, maintenance of flavour and nutritive value, and reduction in packaging and transportation costs (Okos *et al.*, 1992). Dried pulp of Indian blackberry is expected to have potential in confectionery and fruit beverage industry for preparation of soft drinks, fruit juices, jams, jellies, milk-based drinks etc.

Traditionally, Indian blackberry fruits are dried under the sun. However, slow drying process, exposure to environmental contamination, insect infestation and labour requirements limit its use for quality produce (Aghbashlo *et al.*, 2008a). Industrial dryers provide uniform dried hygienic products, and the process is rapid. The industrial drying process may be economical with optimal nutritional properties with information on the drying kinetics of the fruit (Gupta *et al.*, 2014). Drying kinetics of food is a complex phenomenon, and requires dependable models to predict drying behaviour. Many studies on drying behaviour of various fruits, nuts, spices, and vegetables are reported in literature (Arora *et al.*, 2003; Doymaz, 2004; Guine and Fernandes, 2006; Kingsly and Singh, 2007; Chong *et al.*, 2008; Gupta *et al.*, 2014). However, studies on the drying kinetics of Indian blackberry pulp are scarce in the literature. This work was, therefore, carried out with the objective to study the drying kinetics of Indian blackberry pulp. A suitable drying model was identified to describe the drying kinetics and the changes in physico-chemical properties of the pulp.

MATERIALS AND METHODS

Material

Fifty kg of fully ripened Indian blackberry fruits of locally grown desi variety were harvested from the orchard of ICAR-Central Institute of Post-Harvest Engineering and Technology (ICAR-CIPHET), Abohar, Punjab, India, using a blackberry harvester developed by ICAR-CIPHET (capacity: 10 kg.min^{-1}). Unripe fruits were separated manually, and the ripe ones washed using tap-water to remove dust and foreign particles, if any. The surface water of the fruits was removed using blotting paper. Pulp from the fruits was extracted using pulp extracting machine (M/s Agrosaw, Ambala, India, capacity: 50 kg.h^{-1}). The pulp was separated using sieve of 0.5 mm opening. The pulp was filled in a stainless steel can, sealed and stored in a deep freezer (M/s Macro Scientific Works Pvt. Ltd., New Delhi, India, accuracy (±) 1°C) at (-)10 ºC. Required quantity of pulp was taken out from the can and kept at room temperature for 2 h before starting experimental trials. The drying experiment was completed within 15 days of pulp extraction. A pictorial flow chart of the conducted experiment is shown in Fig. 1.

Drying Experiment

Initial moisture content of Indian blackberry pulp was determined using hot air oven drying method at 70±1°C (AOAC, 2000), and expressed in % (d.b.). Laboratory model cabinet tray dryer (M/s Macro Scientific Works Pvt. Ltd., New Delhi; 0-300 ºC, accuracy: (±) 1ºC) was used to conduct the drying experiment. The dryer consisted of three stainless steel trays of 800×400×30 mm with a centrifugal fan for airflow. Drying of the pulp was done at 50 °C, 60 °C and 70 °C as suggested by Aghbashlo *et al.* (2008a) and Gupta *et al.* (2014) for drying studies on fruit pulps.

During the experiment, relative humidity of air varied between 20-40 % at room temperature (30-35 °C). The initial moisture content of Indian blackberry pulp was 597.9±9.6 % (d.b.). Indian blackberry pulp weighing 350 g was spread uniformly on steel trays. Initial bed thickness of the sample was maintained at 3.5 mm by taking measured volume of pulp, which was calculated by multiplying the thickness of pulp with plate base area. The trays were taken out from the cabinet dryer, weighed, and quickly kept back in the dryer. Mass of the tray along with samples was recorded at 30-min intervals using an electronic balance (M/s Citizen Inc, Japan; least count: 0.001 g). Drying was continued until the moisture content of the pulp did not decrease significantly in consecutive mass recordings. The dried pulp was subsequently cooled to room temperature for 10 min, packed in 75 micron thick LDPE bags, and sealed. The final moisture content of dried pulp was measured using standard oven drying method (AOAC, 2000). Each experiment was replicated three times, and the average values were reported.

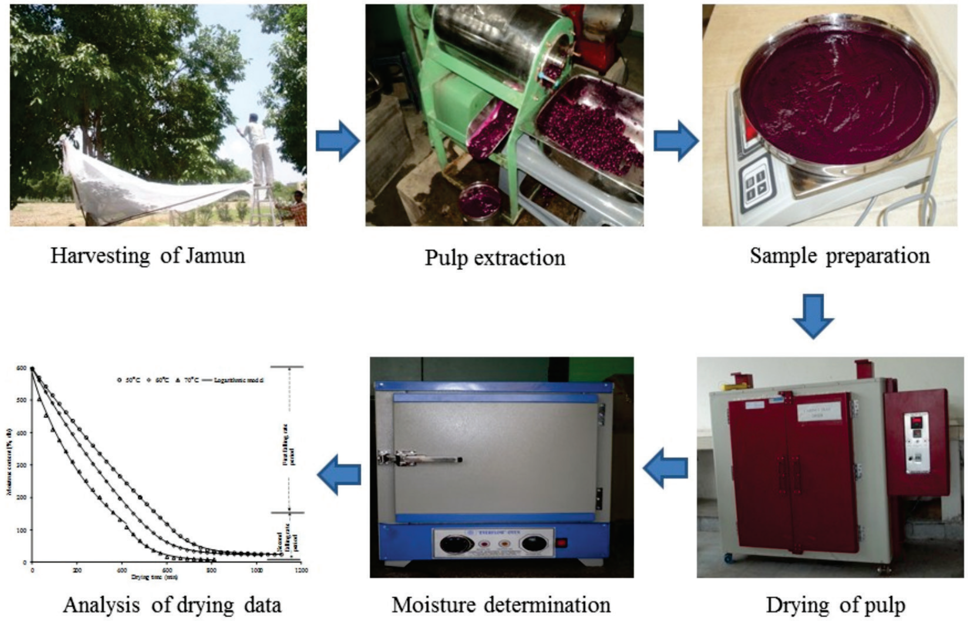

Fig. 1: Experimental flow chart

Modelling of Drying Kinetics

Lagrangian differentiation technique (Kelly, 1967; Vishwakarma *et al.*, 2013) was used to compute the drying rate using five data points. For equally spaced time intervals, the five-point equations are represented as:

$$\frac{dm_1}{dt} = \frac{\left[-25m_1 + 48m_2 - 36m_3 + 16m_4 - 3m_5\right]}{1200\,\Delta t} \qquad ...(1)$$

$$\frac{dm_2}{dt} = \frac{\left[-3m_1 - 10m_2 + 18m_3 - 6m_4 + m_5\right]}{1200\,\Delta t} \qquad ...(2)$$

$$\frac{dm_3}{dt} = \frac{\left[m_1 - 8m_2 + 8m_4 - m_5\right]}{1200\,\Delta t} \qquad ...(3)$$

$$\frac{dm_4}{dt} = \frac{\left[-m_1 + 6m_2 - 18m_3 + 10m_4 + 3m_5\right]}{1200\,\Delta t} \qquad ...(4)$$

$$\frac{dm_5}{dt} = \frac{\left[3m_1 - 16m_2 + 36m_3 - 48m_4 + 25m_5\right]}{1200\,\Delta t} \qquad ...(5)$$

Where,

dm_i/dt = Drying rate at ith time, g moisture.g^{-1}.dry matter.h^{-1},

m_i = Moisture content at ith time, %, (d.b.), and

Δt = Magnitude of equally spaced time interval, h.

Drying rate values at extreme points were computed using Eqs. (1) and (2) for the first two data points. Equation (3) was used to calculate the drying rates at central points. Equations (4) and (5) were used to compute the drying rates for the last two data points.

Drying rate was plotted against drying time. Drying in falling rate period was decided by the change in slope of the curve. Five thin-layer drying models were investigated to find the appropriate model to describe drying kinetics of Indian blackberry pulp (Table 1).

Statistical Analysis

Drying rate data were fitted to all models for the temperature range under study. Non-linear least square regression analysis was done using Statistica version-6 software to compute the regression coefficients of the models. The quantitative error estimates and residual plot were used to ascertain the ability of the models to describe drying behaviours.

Standard Error of Estimate (SEE) indicates the fitting ability of a model to a set of data. The SEE represents the deviation of the dependent variable M_t.

$$SEE = \sqrt{\frac{\sum_{i=1}^{n} (M_t - M_p)^2}{d_f}} \qquad ...(6)$$

Where,

M_p = Predicted value of moisture content, % (d.b.),

M_t = Observed value of moisture content, % (d.b.),

n = Sample population, and

d_f = Degree of freedom.

However, the SEE indicates the fitting ability of an equation only and cannot provide goodness of fit of the equation. The mean relative deviation modulus (MRD) was, therefore, used to describe the goodness of fit of equations. The MRD gives mean deviation of the measured data from the predicted data. Thus, the smaller the MRD value, the better the goodness of fit.

$$MRD = \frac{100}{n} \sum_{i=1}^{n} \frac{\left|(M_t - M_p)\right|}{M_t} \qquad ...(7)$$

Plotting of the residuals (M_t–M_p) against the drying time was used as a measure of the distribution of errors. The residuals should be only random independent errors with a zero mean, constant variance and arranged in a

Table 1. Thin-layer drying models used for fitting drying kinetics data

Sl. No.	Model	Model equation	Reference
1.	Newton	$MR=\exp(-kt)$	Akpinar (2006)
2.	Page	$MR=\exp(-kt^n)$	Bruce (1985)
3.	Henderson and Pabis	$MR= \alpha \times \exp(-\beta t)$	Doymaz (2005)
4.	Peleg	$M_t = M_0 + t/(k_1+k_2 t)$	Planinic *et al.* (2005)
5.	Logarithmic	$MR= \alpha \times \exp(-\beta t)+c$	Akpinar (2006)

normal distribution. If the residual plots indicate a clear pattern, the model should not be accepted (Basu *et al.*, 2006; Vishwakarma *et al.*, 2013).

RESULTS AND DISCUSSION

Drying Kinetics of Indian blackberry Pulp

Change in moisture content of Indian blackberry pulp with drying time is shown in Fig. 2. The pulp dried from average initial moisture content of 597.9±9.6 % (d.b.) to the final moisture content of about 9.4-22.6 % (d.b.) or until the reduction in the mass of dried pulp was found to be less than 1 % in the preceding 60 min of drying period. The moisture content of pulp decreased continuously with drying time. Indian blackberry pulp exhibited the characteristic exponential drying behaviour, whereby an initial high rate of drying was followed by a slower rate of drying in later stages (Fig. 2). Similar behaviour of drying for plums and pomegrane have been reported by Matteo *et al.* (2002) and Kingsly and Singh (2007), respectively.

The drying curve consisted of a fast reduction in moisture (first phase), followed by a very slow drying rate period at the end (relaxation phase). Drying process took nearly two-third of the total drying time to remove the second half of the moisture present in pulp due to slowing down of diffusion process (Fig. 2). The reduction in moisture content of pulp during drying led to increase in the concentration of sugars, which bind water. Thus, the moisture removal in the second phase of drying required more time (Gujral *et al.*, 2013). As expected, drying temperature had affected the drying time of the pulp. At 50 ºC air temperature, the time to reach the moisture content of 19.8 % was 1110 min. The same moisture content of pulp was achieved in less than 600 min at 70 ºC air temperature. Thus, the drying time was reduced by about 46 % with an increase in air temperature by 20 ºC. The decrease in drying time with the increase of drying temperature was attributed to increase in water vapour pressure within the pulp, which increased the migration of moisture. The moisture loss rate of Indian blackberry pulp was faster at the beginning than that at the end. Similar behaviour has been reported on thin-layer drying of pineapple and mango (Alaguselvi *et al.*, 2009; Gujral *et al.*, 2013).

The variations of the computed drying rates with pulp moisture content are reported in Fig. 3. Drying of the pulp occurred in falling rate period, and no constant rate period was observed indicating internal moisture diffusion. The drying rate decreased continuously with decrease in pulp moisture content and with decrease in air temperature. The initial drying rate moderately increased from 0.57 g moisture.g^{-1}dry matter.h^{-1} to 0.74 g moisture.g^{-1}dry matter.h^{-1} with 10 ºC increase in air temperature from 50 ºC, whereas with another 10 ºC rise (i.e. at 70 ºC) the drying rate had significantly increased to 2.80 g moisture.g^{-1} dry matter.h^{-1}. Further, the drying rate values were mostly higher for higher temperatures at all pulp moisture contents. At higher drying temperature, drying rate increased and the possible reasons might be the increased temperature

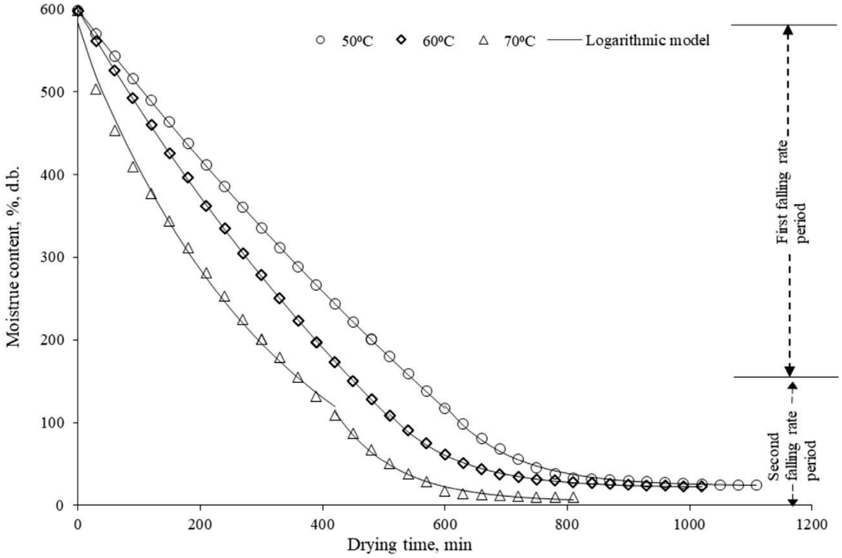

Fig. 2: Drying characteristics of Indian blackberry pulp at different temperatures

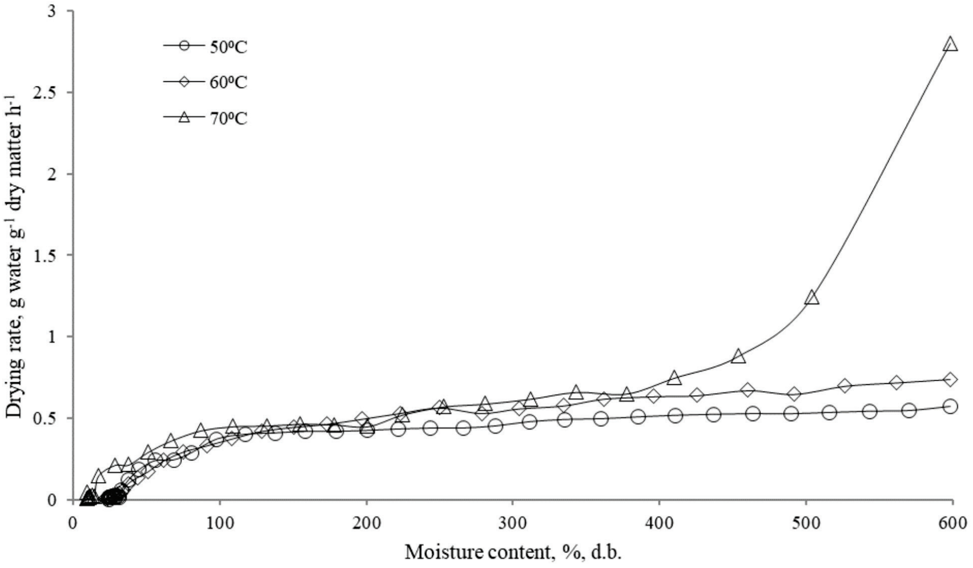

Fig. 3: Variation in drying rate of Indian blackberry pulp with moisture content at different temperatures

gradient, which resulted rapid removal of moisture from the sample (Gagare *et al*., 2017). Appreciable decrease in drying time at 70 ºC drying temperature was possibly due to increase in water vapour pressure inside the pulp. The other probable reason could be the higher moisture carrying capacity of the drying air at higher temperature (Kumar and Shrivastava, 2017).

The change in drying rate with drying time of pulp is reported in Fig. 4. Drying rate decreased linearly with drying time till the pulp moisture content reached near 108.99 % (d.b.). Thereafter, the drying rate decreased rapidly and finally ceased at the end of drying. If the initial drying rate value (0 time drying rate) is ignored, it may be inferred from Fig. 3 and 4 that the constant drying rate period was absent. Drying took place in two falling rate periods, and the shift from first to second falling rate period was found to be irrespective of air

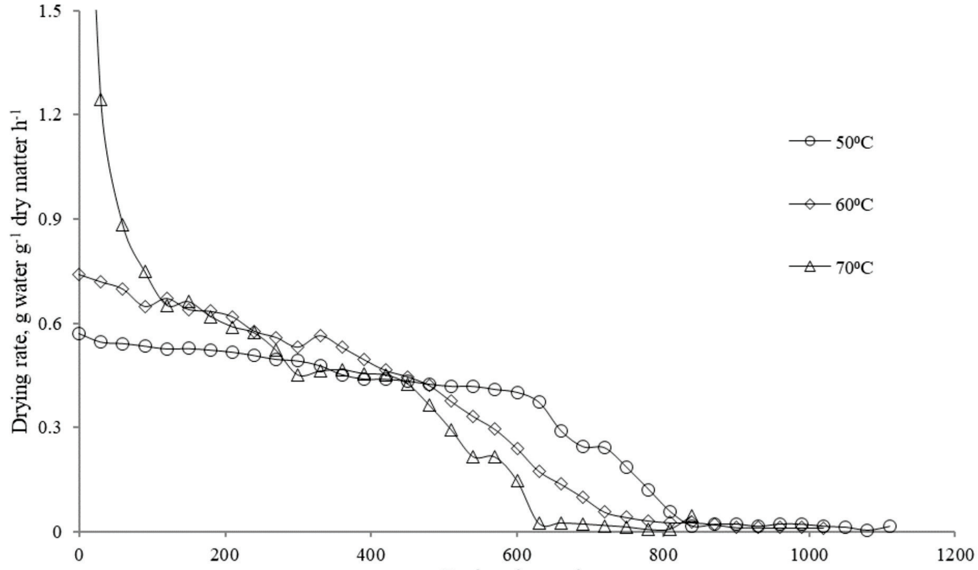

Fig. 4: Variation in drying rate of Indian blackberry pulp with drying time at different temperatures

temperature range studied (50-70 °C). The shift of first to second falling rate period started from approximately 108.99 % (d.b.) moisture content for Indian blackberry pulp at all drying temperatures.

Fitting of Drying Models

The observed moisture content data of the drying experiment were fitted to five thin-layer drying models (Table 1) for both drying rate periods. Statistical results of the different models, including the drying model coefficients and the comparison criterion used to evaluate the goodness of fit (SEE, MRD values and pattern of the residual plot) are presented in Table 2.

It may be observed from Table 2 that the Newton model, Page model, and Henderson and Pabis model did not adequately describe drying behaviour of Indian blackberry pulp in both falling rate periods as the values of SEE and MRD were high and the residual plots showed pattern. Further, the Peleg model described the drying kinetics of Indian blackberry pulp only in the first falling rate period because of lower values of SEE and MRD and random pattern of residuals (Table 2). However, in the second falling rate period, the Peleg's model did not predict drying kinetics. This observation supported the results of a previous study that the Peleg's model was suitable for describing curvilinear part of the process for short duration drying of carrot slices (Planinic *et al.*, 2005). However, Gujral *et al.* (2013) reported that the Peleg's model adequately described the drying kinetics of pineapple and mango pulp when the concept of different falling rate periods was not considered.

The SEE and MRD values for the Logarithmic model were less than 9.84 and 4.97, respectively, for all drying temperatures in both falling rate periods, and plot of residuals revealed random pattern (Table 2). It could, therefore, be inferred that Logarithmic model adequately described the drying kinetics of Indian blackberry pulp in both falling rate periods (Fig. 2).

The value of parameter α for the Logarithmic model decreased with increasing drying temperature in both falling rate periods, whereas the variation of β and c with temperature was not consistent. Therefore, the temperature dependence of parameter α was analysed using Arrhenius relationship and described as below:

$$\alpha = \alpha_o \exp(-E/RT) \quad (R^2 > 0.89) \qquad ...(8)$$

Where,

E = Activation energy, kJ. mole^{-1},
R = Universal gas constant, 8.314 $\text{kJ.mol}^{-1}.\text{K}^{-1}$,
T = Absolute temperature, kelvin, and
α_o = Frequency factor, minute.

Activation Energy

Activation energy is defined as the energy needed to initiate the moisture diffusion from the internal regions of the material (Torki-Harchegani *et al.*, 2016).

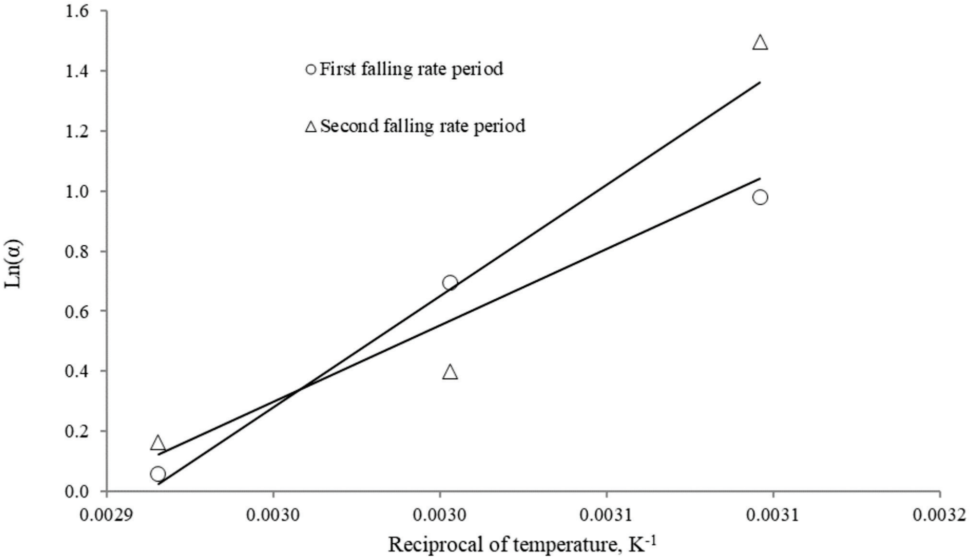

Fig. 5: Arrhenius plots of lograthemic model constant (α) for Indian blackberry pulp of (a) First falling rate period (R^2: 0.95); (b) second falling rate period (R^2: 0.89)

Table 2. Estimation of parameters and goodness of fit of models for drying of *Indian blackberry* pulp

Model	Soaking temp., °C	Equation parameter in first falling rate period						Equation parameter in second falling rate period					
		k, k_1, α	k_2, n, β	c	SEE	MRD	Residual plot	k, k_1, α	k_2, β, n	c	SEE	MRD	Residual plot
		Moisture content up to 1.09 $g.g^{-1}$dry matter						Moisture content below 1.09 $g.g^{-1}$dry matter					
Newton model	50	2.17×10^{-3}			25.67	8.83	Patterned	3.38×10^{-3}			12.01	19.07	Patterned
	60	2.75×10^{-3}			24.42	9.14		3.96×10^{-3}			8.23	13.67	
	70	3.87×10^{-3}			13.62	3.89		5.17×10^{-3}			16.59	72.31	
Page model	50	3.46×10^{-4}	1.31		9.41	3.00	Patterned	5.31×10^{-5}	1.63		7.63	18.40	Patterned
	60	5.53×10^{-4}	1.28		9.33	3.11		4.09×10^{-4}	1.35		6.09	15.01	
	70	5.30×10^{-3}	0.94		12.98	4.36		2.42×10^{-6}	2.23		2.05	5.44	
Henderson & Pabis model	50	1.06	2.34×10^{-3}		21.98	7.23	Scattered	5.67	5.80×10^{-3}		6.44	16.12	Patterned
	60	1.05	2.94×10^{-3}		21.35	7.58		2.81	5.63×10^{-3}		5.34	13.75	
	70	0.97	3.73×10^{-3}		12.11	3.98		1.99	1.12×10^{-2}		3.74	14.24	
Peleg model	50	(-)1.05	(-)3.29×10^{-4}		1.13	0.28	Scattered	(-)0.35	(-)1.38×10^{-3}		12.59	24.64	Patterned
	60	(-)0.80	(-)4.64×10^{-4}		1.83	0.61		(-)0.26	(-)1.45×10^{-3}		10.24	21.01	
	70	(-)0.40	(-)1.14×10^{-3}		11.77	3.22		(-)0.27	(-)1.33×10^{-3}		12.50	51.80	
Logarithmic model	50	2.66	6.12×10^{-4}	(-)1.66	0.89	0.19	Scattered	4.46	9.33×10^{-3}	0.02	2.21	3.72	Scattered
	60	2.00	1.06×10^{-3}	(-)0.99	1.57	0.50		1.49	9.01×10^{-3}	0.02	1.08	1.69	
	70	1.06	3.11×10^{-3}	(-)0.10	9.84	2.58		1.18	9.93×10^{-3}	(-)0.008	3.03	4.97	

Activation energy values of Indian blackberry pulp were estimated for both falling rate periods. In the first falling rate period, activation energy was 42.20 $kJ.mol^{-1}$, while in the second falling rate period it was 61.62 $kJ.mol^{-1}$. Higher activation energy indicates greater temperature sensitiveness (Arora *et al*., 2003). It could be inferred that drying resulted in higher temperature sensitivity in the second falling rate period of drying Indian blackberry pulp than that in first falling rate period. It also showed that that relatively less energy might be required to initiate moisture diffusion during drying of Indian blackberry pulp, and the energy need might be higher in the second drying phase. The obtained activation energy values were in the range of 1.27-110 $kJ.mol^{-1}$ reported for various potato slices (Aghbashlo *et al.*, 2008b).

CONCLUSIONS

Thin layer drying characteristics of Indian blackberry pulp studied in a hot air cabinet dryer indicated that the rate of drying continuously decreased, and took place in two falling rate periods. The moisture content of the inflexion point where the first period was transformed into the second period was about 1.08 g $water.g^{-1}$dry matter. The logarithmic model described well the drying behaviour of pulp both in first and second falling rate periods. However, the Peleg's model also described well the drying behaviour in first falling rate period. The activation energy for drying of Indian blackberry pulp was 46 % higher in the second falling rate period compared to the first falling rate period.

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