



Effect of Temperature on Drying Kinetics of Vegetable Seeds

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ABSTRACT

A study was conducted to investigate the effect of temperature on drying kinetics of onion, carrot and tomato seed. The seeds were dried at drying temperatures of 30°C, 35°C and 40°C in a laboratory hot-air oven dryer. Drying rate was faster at higher temperature (40°C) than at lower temperatures. Drying of the seeds occurred in falling rate periods of drying. Drying data were fitted into Newton, Page, Modified Page, Henderson-Pabis, Logarithmic, two-term exponential, and Wang and Singh models. Based on highest R^2 and lowest χ^2 , RMSE and mean error values, Page model ($R^2 > 0.9$) was found to be the best fit for drying of all selected seeds at the selected temperatures. However, two-term exponential model was the best fit for onion seed at 35°C and carrot seed at 30°C, and was comparable with Page model in the selected temperature range. Effective moisture diffusivity of onion, carrot and tomato seed ranged between $1.59 \times 10^{-10} \text{ m}^2 \cdot \text{s}^{-1}$ and $3.18 \times 10^{-10} \text{ m}^2 \cdot \text{s}^{-1}$, $3.55 \times 10^{-10} \text{ m}^2 \cdot \text{s}^{-1}$ and $7.10 \times 10^{-11} \text{ m}^2 \cdot \text{s}^{-1}$, $2.65 \times 10^{-10} \text{ m}^2 \cdot \text{s}^{-1}$ and $5.31 \times 10^{-11} \text{ m}^2 \cdot \text{s}^{-1}$, respectively, at above drying temperatures. Activation energies of onion, carrot, and tomato seed were $56.85 \text{ kJ} \cdot \text{mol}^{-1}$, $60.69 \text{ kJ} \cdot \text{mol}^{-1}$, and $61.44 \text{ kJ} \cdot \text{mol}^{-1}$, respectively.

India is next to China in vegetable production with an annual production of 184.3 Mt from 10.25 Mha area (Anon., 2018). Among all vegetables cultivated in India, onion and tomato are important being the common ingredients in Indian foods. Onion, with annual production of 21.4 Mt from 1.27 Mha in India, is mostly consumed for its unique flavour and high content of polyphenolic flavonoids (Rao *et al.*, 1998); and shortages of the crop can cause price escalation and consumers' unrest. Similarly, carrot a good source of beta carotene, fibre, vitamin K₁, potassium and antioxidants, is cultivated in almost 22 states of India in 0.06 Mha area with average productivity of 17.2 Mt.ha⁻¹ (Anon., 2018). Tomato is another important protective food because of its special nutritive value. It is a versatile vegetable with wide usage in traditional Indian culinary, and has few competitors in the value-addition processing chain. In India, tomato is cultivated in an area of 0.81 Mha with annual production of 19.69 Mt (Anon., 2018).

The major challenge, therefore, is to make quality seed available at the time of sowing. Increasing trends

in demand of these vegetables require support to strengthen indigenous seed production and maintenance of seed quality. Seed being living organism; its quality need to be maintained from harvest till the time of sowing to ensure viability. Also, vegetable seeds are sensitive and tender unlike cereal crops. It is important to investigate how various unit operations in vegetable seed processing affect the longevity and vigor of seed (McCormack, 2004). Vegetable seed processing involves operations like extraction, cleaning, grading, washing, drying, transportation and storage. Best seed quality is attained at physiological maturity. It is observed that normally the moisture content of vegetable seeds at the time of harvest is non-uniform and higher than the recommended storage moisture (Justice and Bass, 1978; Siddique and Wright, 2003). Drying is an important and sensitive unit operation in vegetable seed processing. Drying of seed involves removing moisture to a safe moisture level for storage till the time of sowing without losing its quality. It is necessary to dry seed to reduce excess moisture content using controlled drying method. Selection of appropriate temperature for seed drying is necessary

to maintain its quality. The maximum temperature that can be tolerated by seed without causing physical and chemical damage has been reported to be in the range of 40.5°C to 43.3°C (Krzyzanowski *et al.*, 2006).

Temperature and moisture content, for both seed and its ambience are important factors affecting seed quality during storage (Pradhan and Badola, 2012). It is, therefore, necessary to study the drying kinetics of vegetable seeds to understand the best drying temperature and safe moisture content (Zamariola *et al.*, 2014). Mathematical modelling and simulation of drying curve can be used to study drying variables, and to optimize drying parameters and conditions. Modelling of drying curve can satisfactorily describe the drying behaviour and non-linear regression analysis can compare different thin layer mathematical drying models according to R² values, Root Mean Square Error (RMSE), χ^2 and Error fraction. The statistical analysis could be employed to study the effect of drying air temperature on the model constants and coefficients (Roberts *et al.*, 2008; Sandeepa *et al.*, 2013; Rosa *et al.*, 2015).

In addition, information on the thermal properties as moisture diffusivity and activation energy with respect to vegetable seed drying are important for proper design, modelling and optimization of mass transfer process during drying or moisture absorption phenomenon (Chayjan *et al.*, 2013). Sufficient information on drying kinetics, moisture diffusivity and activation energy of important vegetable seeds like onion, tomato and carrot are not available to work out design values of appropriate dryers.

Thus, the aim of this study was to investigate the effect of temperature on drying behaviour, determination of moisture diffusivity, activation energy of selected vegetable seeds; and examine suitability of drying models for corresponding characteristic drying curve.

MATERIALS AND METHODS

Sample Preparation

Seeds of onion, carrot and tomato, all closely related and small in size, were selected for experimental purpose. Freshly harvested 500 g seeds each of onion (*P. madhvi*), carrot (*P. vasudha*), and tomato (*P. rohini*) were collected from the Vegetable Science Division and Seed Processing Unit of ICAR-IARI by random selection method during 2015-16. The seeds were manually cleaned from dust and foreign materials,

and stored for further use in experimentation. The seeds were brought to normal initial moisture content by required moistening. The moisture content of each seed type was determined according to the standard of International Seed Testing Association (2015).

Experimental Setup

Drying experiment was conducted using a convective hot air oven dryer (Model-ASEW; SHIVAKI, T-701) at the Division of Agricultural Engineering, ICAR-IARI, New Delhi. Drying experiment on the three vegetable seed types was studied at three different levels of temperature (30°C, 35°C and 40°C). The range of temperature for seed drying was selected from literature to ensure uniform drying without quality deterioration, and to check drying behaviour at high temperature (Justice and Bass, 1978; Jayas and Ghosh, 2006). The upper limits of moisture content were selected based on usually observed moisture content during harvesting of these vegetables (26.6 % for carrot, 26.37 % for onion, 25.88 % (d.b.) for tomato), and the lower limit of moisture content as the safe storage moisture value of 8-9 % (Delouche, 1968). The response parameters studied were equilibrium moisture content (% d.b.), rate of drying (kg.min⁻¹) and moisture ratio (%).

Experimental procedure for drying

Fresh samples (5±1g each) of all three vegetable seeds, were dried at constant temperature of 30°C, 35°C and 40°C in a convective hot air oven dryer (Make-METTLER TOLEDO, Model: ML503/Z, least count: 1 mg). The samples of all vegetable seeds were dried upto a safe moisture level of 8.7±1% (d.b.) at the three above said selected constant temperatures. The change in moisture were recorded at every 15-minute intervals till the latter reached a constant value. Each experimental trial was replicated three times, and the average values reported.

Mathematical Modelling of Drying Curves

Drying curves describing the drying rate of seed with drying time, moisture content versus drying time and moisture ratio versus drying time were studied and evaluated.

During the experiment, the equilibrium moisture content of each sample was taken as one per cent less than the final moisture content (Tiwari and Pandey, 2009). The final moisture content in case of all sets of experiments was recorded when the mass of a sample became almost constant with respect to time.

Drying rate was calculated using the following equation (Abano *et al.*, 2011):

$$\text{Drying rate, DR} = \frac{M_{t+dt} - M_t}{dt} \quad \dots(1)$$

Where,

M_{t+dt} = Moisture content at t+dt, kg water.kg⁻¹ dry matter, and

t = Drying time, min.

Moisture ratio (MR) of a sample during drying was expressed by the following equation:

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad \dots(2)$$

Where,

M_t = Moisture content at any time (t), % (d.b.),

M_o = Initial moisture content, % (d.b.), and

M_e = Equilibrium moisture content, % (d.b.).

Drying kinetics of the selected vegetable seeds were expressed in terms of empirical models. Second falling rate was not considered in this study due to small seed size and better diffusion properties. The experimental data of moisture content obtained at different temperatures (30°C, 35°C and 40°C) were plotted in the form of dimensionless moisture ratio (MR). Different empirical drying models (Togrul and Pehlivan, 2003) mentioned in Table 1 were employed to find the drying kinetics of the seeds.

Non-linear regression analysis was performed to find each model constants. The expected and predicted values of MR were used to determine the statistical parameters root mean square error (RMSE), mean error (ME), correlation coefficient (R²) and reduced chi-square (χ²) to evaluate the goodness of fit of the models. The highest R², lowest χ², ME and RMSE values were used to determine the goodness of fit (Togrul and Pehlivan, 2003; Sandeepa *et al.*, 2013; Cantu-Lozan *et al.*, 2013).

The parameters were given by the following formulae.

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N-n} \quad \dots(3)$$

$$ME = \frac{1}{N} \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i}) \quad \dots(4)$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2 \right]^{\frac{1}{2}} \quad \dots(5)$$

The constant values of the models and statistical parameters were obtained using MATLAB-R2012 and Microsoft Office Excel 2010 software.

Effective Moisture Diffusivity and Activation Energy

Effective moisture diffusivity was calculated using Fick's diffusion equation for particles with slab geometry. Assuming the infinite slab as the thickness which was much smaller than length and breadth, Fick's equation for effective moisture diffusivity is given by the following equation (Akpinar and Toraman, 2013; Chayjan *et al.*, 2013):

$$MR = \frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left(\frac{-D_{eff}(2n-1)^2\pi^2 t}{4L^2}\right) \quad \dots(6)$$

Where,

D_{eff} = Effective moisture diffusivity, m².s⁻¹,

L = Average thickness of seed, m,

t = Time of drying, s, and

n = 1, 2, 3, ... number of terms taken into consideration.

Equation (6) can be simplified for long drying time (approximately 3h) as (Akpinar and Toraman, 2013; Chayjan *et al.*, 2013):

$$MR = \frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 D_{eff} t}{4L^2}\right) \quad \dots(7)$$

The linearized form of the above equation (7) is:

$$\ln(MR) = \left(\frac{M - M_e}{M_o - M_e}\right) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad \dots(8)$$

Effective diffusivity can be calculated from the slope (K) of the straight line obtained by plotting ln (MR) versus drying time, given by the Eq. (9).

$$K = \left(\frac{\pi^2 D_{eff}}{4L^2}\right) \quad \dots(9)$$

The temperature dependence of moisture diffusivity can be expressed by Arrhenius type equation (Gowda *et al.*, 2015) as:

$$D = D_o \exp\left(\frac{-E_a}{RT_a}\right) \quad \dots(10)$$

Where,

E_a = Activation energy, kJ.mol⁻¹,

R = Universal gas constant, 8.3143J.mol⁻¹,

T_a = Absolute air temperature, K, and

D_o = Pre-exponential factor of Arrhenius equation, m².s⁻¹.

From the slope (K₁) obtained from the Arrhenius plot of ln (D_{eff}) versus 1/T_a, the activation energy was

determined (Gowda *et al.*, 2015) as:

$$K_1 = \left(\frac{10^{-3} \times E_a}{R} \right) \dots(11)$$

RESULTS AND DISCUSSION

The effects of different drying temperatures on selected vegetable seeds were evaluated. The initial moisture content of the selected vegetable seeds was in the range of 25±1% (d.b.) with 26.6 % for carrot, 26.37 % for onion, and 25.88 % (d.b.) for tomato, respectively. The seeds of all three vegetables were dried to the safe moisture level of 8.7±1 % (d. b.). Drying characteristics of the selected vegetable seeds at different temperatures are presented below.

Drying Characteristics of Different Seeds

Effect of temperature

The variations in moisture content with drying time, drying rates with drying time and moisture ratios with drying time obtained at different temperatures were plotted for onion (Figs. 1 (a), 2 (a), 3 (a)), carrot [Figs. 1 (b), 2 (b), 3 (b)] and tomato [Figs. 1 (c), 2 (c), 3 (c)]. It was observed that the moisture content decreased with drying time. Seeds exposed to air temperature of 40°C required 75 min less time than that at 35°C to be dried to the safe moisture content. Similarly, seeds exposed to air temperature of 35 °C took 45 min less than that at 30°C to reach to the same moisture content.

Onion seed took 315 min to reach 10.56 % (d.b.) moisture content when exposed to 30°C air temperature, but it took 195 min to reach 9.00 % (d.b.) moisture content when exposed to 40°C air temperature. Similarly, carrot and tomato seed required 315 min to reach 9.84 % (d.b.) and 9.23 % (d.b.) moisture content, respectively, when exposed to 30°C air temperature; and 195 min to reach 8.53 % (d.b.) and 8.59 % (d.b.), respectively, at 40°C air temperature. This difference in the drying rate among selected seeds might be due to variation in moisture diffusion attributed to the differences in nature and structure of the materials (Sobukola *et al.*, 2007). Similar results were obtained in fluidized and convective drying kinetics of onion slices (Doharey *et al.*, 2009).

Moisture ratio decreased as the drying proceeded at all temperatures for the selected vegetable crop seeds. However, the trends in reduction of moisture ratio for the selected seed types were observed to be same.

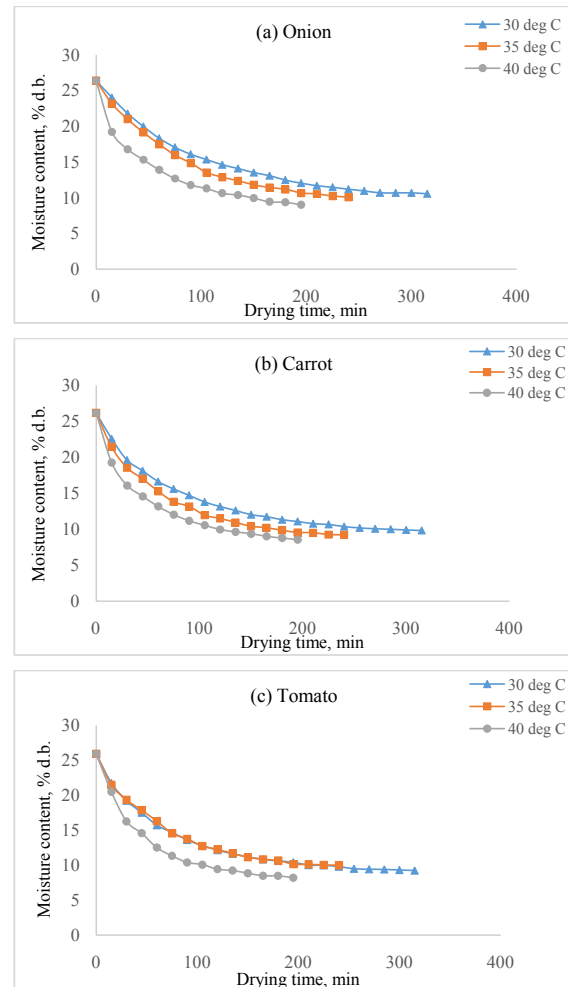


Fig. 1: Variations in moisture content with drying time at different drying air temperature for selected vegetable seeds

Drying rate patterns of the vegetable seeds with time indicated that there was no constant rate period of drying. In fact, drying occurred in falling rate period, which was governed by diffusion of water in solid (Fig. 2). This might be due to low initial moisture content, and absence of surface moisture resulting in capillary migration of water from the core to the surfaces. This required more heat to vaporize the water (Motri *et al.*, 2013). Previous studies also revealed that drying of biomaterials is a diffusion-controlled process, and mostly fell in the falling rate period (Khazaei and Daneshmandi, 2007; Raol *et al.*, 2013). Drying rate increased with increase in drying air temperature. Air temperature of 40°C caused higher drying rate than those at lower temperatures of 35°C and 30°C. As drying continued, the seed moisture continued reducing. More energy was required to drive the

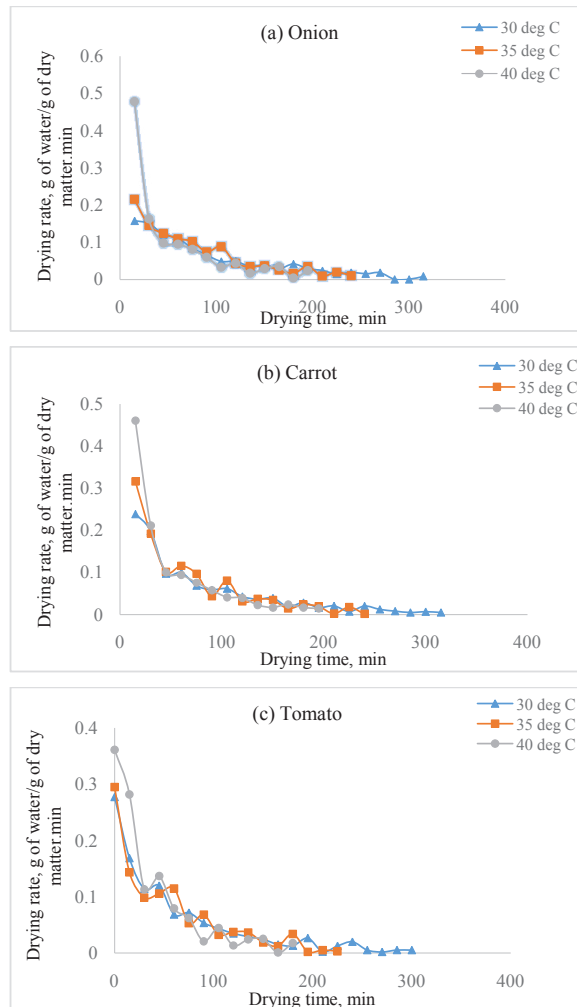


Fig. 2: Variations in drying rate with drying time at different drying air temperature for selected vegetable seeds

remaining moisture by breaking the molecular bond of water. The energy supplied was constant, resulting in longer time to break the bond and also resulted in decrease in drying rate (Prabhanjan *et al.*, 1995). Thus, higher temperature implied larger drying force than lower temperature for heat transfer (Methakhup *et al.*, 2005; Nimmol *et al.*, 2007). Higher temperature also provided larger vapour pressure difference between the partial pressure and saturated pressure of water vapour in the drying air. Thus, it could be concluded that drying air temperature was the main parameter influencing the drying rate of agricultural products (Touil *et al.*, 2010; Mohamed *et al.*, 2005). Also, there was little difference in final moisture content of all selected seed types at same drying temperature and time (Fig. 1). However, the difference in final moisture might be due to predominant chemistry of seeds that influenced its isotherm (McDonald, 2007).

Analysis of drying curves

The experimental data of moisture content obtained with time were converted into dimensionless ratio to compare various models. There was decrease in moisture ratio of selected vegetable seeds with time at the three air temperatures. Moisture ratio decreased at a higher rate in the beginning of drying, and reduced as the moisture content decreased (Fig. 3). Thus, exponential decrease of moisture content with time and absence of constant drying rate were observed. Similar observations were made by Gazor and Mohsenimanesh (2010), Abano *et al.* (2011) in canola and tomato slices, respectively.

The dimensionless moisture ratios against drying time for the vegetable seeds at different drying temperatures were fitted to different models listed in Table 1. Similar

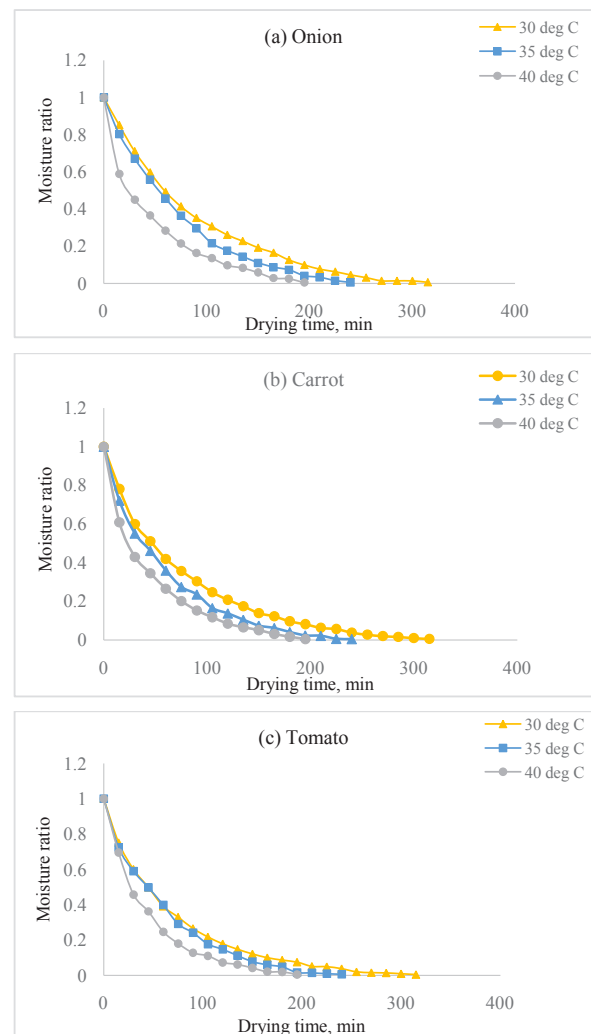


Fig. 3: Variations in moisture ratio with drying time at different drying air temperature for selected vegetable seeds

Table 1. Drying kinetics models under consideration

Sl. No.	Model	Equation
1.	Newton	MR= exp (-kt)
2.	Page	MR= exp (-kt ⁿ)
3.	Modified Page	MR= exp (-(kt) ⁿ)
4.	Henderson and Pabis	MR= a exp (-kt)
5.	Logarithmic	MR= a exp (-kt)+c
6.	Two term exponential	MR= a exp (-kt) + b exp (-kt)
7.	Wang and Singh	MR=1+at+bt ²

(Ref: Togrul and Pehlivan, 2003)

models were reported by different researchers for different vegetables (Mehta *et al.*, 2005; Gupta and Sehgal, 2011). The goodness of fit of the models were selected according to statistical parameters with highest R² value and lowest χ^2 , RMSE and ME value. Different model parameters along with statistical parameters for onion, carrot and tomato were compared. All models had R² values greater than 0.9, except for logarithmic model, Wang and Singh model at 40°C air temperature for onion and carrot (Table 2, 3). Page model was found to be the best model to describe the drying kinetics of onion at 40°C with R² of 0.995. However, for onion seed, two-term exponential model was the best fit for air temperatures of 30°C and 35°C with R² of 0.998 and 0.998, respectively, (Table 2). In a study on drying of different varieties of onion bulbs, the whole process

Table 2. Parameters of different models for onion seed

Drying temperature, °C	Model	Parameter value					R ²	ME	RMSE	χ^2
		a	b	c	k	n				
30	Newton				0.0116		0.9975	0.0144	0.0141	0.0002
	Page				0.0100	1.0306	0.9978	0.0139	0.0132	0.0002
	Modified page				0.1075	0.1075	0.9975	0.0147	0.0140	0.0002
	Henderson and Pabis	1.0074			0.0116		0.9976	0.0146	0.0139	0.0002
	Logarithmic	0.7585		0.2415	1394.14		0.3889	0.2237	0.2357	0.0643
	Two-term exponential	1.3838			0.0129		0.9979	0.0136	0.0129	0.0002
	Wang and Singh	(-)0.0079	0.00002				0.9724	0.0495	0.1930	0.0410
35	Newton				0.0140		0.9965	0.0180	0.0172	0.0003
	Page				0.0098	1.0805	0.9981	0.0135	0.0125	0.0002
	Modified page				0.1184	0.1183	0.9965	0.0186	1.8110	3.7162
	Henderson and Pabis	1.0130			0.0142		0.9974	0.0180	0.0331	0.0003
	Logarithmic	0.7464		0.2536	112.39		0.3591	0.2586	0.2345	0.0668
	Two-term exponential	1.5366			0.0169		0.9984	0.0123	0.0298	0.0001
	Wang and Singh			(-) 0.009	0.00003				0.9855	0.0376
40	Newton				0.0225		0.9740	0.0012	0.0432	0.0020
	Page				0.0603	0.7582	0.9951	0.0202	0.0188	0.0004
	Modified page				0.1510	0.1487	0.9740	0.0465	0.0432	0.0022
	Henderson and Pabis	0.9279			0.0207		0.9808	0.0400	0.0371	0.0016
	Logarithmic	0.8073		0.1927	11394.2		0.6047	0.1897	0.1681	0.0360
	Two-term exponential	0.1962			0.0940		0.9929	0.0244	0.0473	0.0026
	Wang and Singh	(-) 0.0138	0.00005				0.8747	0.1022	0.1021	0.0122

Table 3. Parameters of different models for carrot seed

Drying temperature, °C	Model Name	Parameter value					R ²	ME	RMSE	χ^2
		a	b	c	k	n				
30	Newton				0.0138		0.9949	0.0195	0.0191	0.0004
	Page				0.0218	0.8993	0.9983	0.0115	0.0110	0.0001
	Modified page				(-) 0.1181	(-) 0.1169	0.9949	0.0200	0.0191	0.0004
	Henderson and Pabis	0.9623			0.0133		0.9965	0.0166	0.3225	0.1144
	Logarithmic	0.7960		0.2040	672.95		0.3889	0.2237	0.2078	0.0500
	Two-term exponential	0.1105			0.1114		0.9988	0.0095	0.0090	8.9E-05
	Wang and Singh	(-) 0.008	0.00002				0.9216	0.0781	0.0951	0.0099
35	Newton				0.0175		0.9956	0.0190	0.0184	0.0004
	Page				0.0242	0.9245	0.9973	0.0153	0.0143	0.0002
	Modified page				(-) 0.1321	(-) 0.1322	0.9956	0.0196	0.0383	0.0004
	Henderson and Pabis	0.9706			0.0170		0.9966	0.0172	0.1387	0.0003
	Logarithmic	0.7969		0.2031	4075.16		0.4579	0.2248	0.2040	0.0505
	Two-term exponential	0.5649			0.0229		0.9961	0.0184	0.0287	0.0003
	Wang and Singh	(-) 0.011	0.00003				0.9397	0.0724	0.1049	0.0061
40	Newton				0.0237		0.9824	0.0373	0.0359	0.0014
	Page				0.0562	0.7853	0.9975	0.0146	0.0135	0.0002
	Modified page				0.1489	0.1591	0.9824	0.0388	0.0359	0.0015
	Henderson and Pabis	0.9424			0.0222		0.9865	0.0340	0.0314	0.0012
	Logarithmic	0.8174		0.1826	10173.3		0.6054	0.1917	0.1700	0.0368
	Two-term exponential	0.2080			0.0925		0.9968	0.0165	0.0387	0.0018
	Wang and Singh	(-) 0.014	0.00005				0.8795	0.1014	0.0940	0.0103

of drying occurred in 2-3 falling rate drying period (Gupta *et al.*, 2010).

Similarly, Page model described the best fit for drying air temperature of 35°C and 40°C with R² of 0.997 and 0.998, respectively for carrot. However, two-term exponential models described the best fit for drying at 30°C having R² of 0.999 with minimum value of ME (0.0095), RMSE (0.090) and χ^2 (8.9E-05), Table 3. Srinivasakannan (2008) reported Page model as a best fit for mustard seed drying, and found to match the experimental data very closely with the maximum RMSE of less the 2 per cent. Similar results were observed while studying drying characteristics of rose flowers (Raol *et al.*, 2013).

Page model described the best for tomato seed in the selected temperature range (Table 4). The coefficient of determination (R²) at 30°C, 35°C and 40°C were 0.999, 0.996 and 0.999, respectively. Hence, it was noted that drying kinetics of the selected vegetable seeds at different temperatures could be best described by either Page model or two-term exponential model. Similar patterns were observed by Cantu-Lozano *et al.* (2013) for grape seed and by Sogi *et al.* (2003) for tomato seed. However, logarithmic model was found to be the best fit for canola seed dried in fluidized bed dryer (Gazor and Mohsenimanesh, 2010).

Effective moisture diffusivity and activation energy

Both heat and mass transfer occur during drying.

Table 4. Parameters of different models for tomato seed

Drying temperature, °C	Model Name	Parameter values					R ²	ME	RMSE	χ ²
		a	b	c	k	n				
30	Newton				0.0149		0.9958	0.0174	0.0171	0.0003
	Page				0.0237	0.8959	0.9993	0.0074	0.0072	0.0001
	Modified page				(-) 0.1217	(-) 0.1225	0.9958	0.0179	0.0171	0.0003
	Henderson and Pabis	0.9628			0.0143		0.9973	0.0143	0.3125	0.1074
	Logarithmic	0.8105		0.1895	2172.76		0.4101	0.2179	0.2025	0.0475
	Two-term exponential	0.4025			0.0272		0.9985	0.0105	0.0102	0.0001
	Wang and Singh	(-) 0.009	0.00002				0.9059	0.0848	0.0811	0.0072
35	Newton				0.0165		0.9953	0.0201	0.0195	0.0004
	Page				0.0185	0.9737	0.9958	0.0196	0.0185	0.0004
	Modified page				(-) 0.1301	(-) 0.1270	0.9953	0.0207	0.0195	0.0004
	Henderson and Pabis	0.9794			0.0162		0.9955	0.0203	0.0191	0.0004
	Logarithmic	0.7871		0.2129	4052.78		0.4300	0.2350	0.2132	0.0552
	Two-term exponential	1.1860			0.0170		0.9953	0.0207	0.0313	0.0004
	Wang and Singh	(-) 0.010	0.00003				0.9582	0.0615	0.2612	0.0773
40	Newton				0.0232		0.9972	0.0155	0.0149	0.0002
	Page				0.0312	0.9264	0.9986	0.0114	0.0106	0.0001
	Modified page				(-) 0.1509	(-) 0.1540	0.9972	0.0161	0.0149	0.0003
	Henderson and Pabis	0.9855			0.0229	0.9855	0.9975	0.0154	0.0142	0.0002
	Logarithmic	0.8154		0.1846		5234.3	0.5460	0.2160	0.1916	0.0467
	Two-term exponential	0.4971				0.0341	0.9986	0.0116	0.0152	0.0003
	Wang and Singh	(-) 0.014	0.00005				0.9270	0.0829	0.0768	0.0069

Drying of most agricultural products occur in falling rate period. Internal diffusion is responsible for moisture transfer during drying. Fick’s second law of diffusion described the drying process during falling rate period (Roberts *et al.*, 2008).

Effective moisture diffusivity ranged from 1.59 x 10⁻¹⁰ to 3.18 x 10⁻¹⁰ m².s⁻¹ for onion seed, 3.55 x 10⁻¹⁰ to 7.10 x 10⁻¹¹ m².s⁻¹ for carrot seed, and 2.65 x 10⁻¹⁰ to 5.31 x 10⁻¹¹ m².s⁻¹ for tomato seed in the selected temperature range. Effective moisture diffusivity increased when the air temperature was increased from 30°C to 40°C, Table 5. This might be due to the fact that increased heating energy resulted into increased activity of water molecules. Thus, the diffusivity of water molecules increased at higher temperature (Gupta and Sehgal, 2011; Chijioko *et al.*, 2017).

Activation energy was calculated from the slope of the graph (Fig. 4) and as given by Eq. (11). Activation energy of onion, carrot and tomato seeds were 56.85 kJ.mol⁻¹, 60.69 kJ.mol⁻¹ and 61.44 kJ.mol⁻¹, respectively. Linear

regression analysis was done for fitting the data and to determine the coefficient of determination (R²). The R² values for activation energy were 0.991, 0.981 and 0.997 for onion, carrot and tomato, respectively (Table 4). The values were in conformity with the activation energy of most of agricultural products reported between 12kJ.mol⁻¹ and 110kJ.mol⁻¹ (Doharey *et al.*, 2009; Gupta and Sehgal, 2011; Chayjan *et al.*, 2013)

CONCLUSIONS

Tomato, onion and carrot seeds witnessed faster drying rate with increase in drying air temperature, which helped in reduction of drying time. Drying air temperature of 40°C required 45-75 min less time than at lower temperatures of 35°C and 30°C to attain the safe storage moisture level of 9-10% (d.b.). Drying occurred in falling rate period. Page model was found to be the best fit for the three seed types at different selected temperatures. With increase in drying air temperature, the effective moisture diffusivity of the seeds increased. The activation energy values were 56.85 kJ.mol⁻¹, 60.69

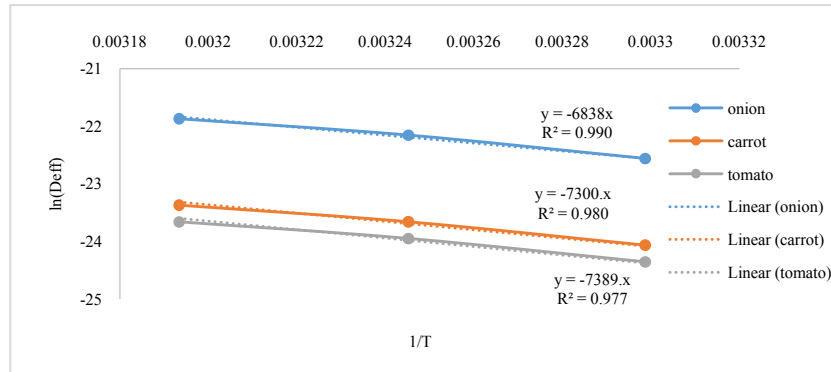


Fig. 4: Relationships between effective moisture diffusivity and reciprocal of absolute temperature by Arrhenius plot

Table 5. Effective diffusivity and activation energy for different types of seed

Type of seed	Temperature, °C	D_{eff} , $m^2 \cdot s^{-1} \times 10^{-11}$	E_a , $kJ \cdot mol^{-1}$	R^2
Onion	30	0.159	56.85	0.9907
	35	0.239		
	40	0.318		
Carrot	30	3.55	60.69	0.9805
	35	5.33		
	40	7.10		
Tomato	30	2.65	61.44	0.9974
	35	3.98		
	40	5.31		

kJ.mol⁻¹ and 61.44 kJ.mol⁻¹ for onion, carrot and tomato seed, respectively. The results on drying kinetics would be helpful in designing precise temperature control and optimum power system for multi-crop seed dryer.

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