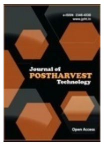

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RESEARCH ARTICLE

Mathematical modelling of drying kinetics of kachri (*Cucumis callosus*) dried in heat pump dryer

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ABSTRACT

Drying kinetics of pretreated Kachri (*Cucumis callosus*) slices of thickness 5 and 10 mm were carried out at temperatures of 40, 50 and 60ºC in a heat pump dryer. Mass transfer in kachri slices during drying was described using Fick's model of diffusion with drying taking place in a falling rate period. The drying data obtained were fit to three different semi-theoretical mathematical thin layer drying models to determine the best fit model for drying kachri slices by non-linear regression analysis. The goodness of fit was evaluated based on the highest value of the coefficient of determination (R^2) and the lower value of root mean square error (RMSE). The experimental results found that the drying rate and effective diffusivity increased with an increase in temperature whereas decreased with the increase in slice thickness. The value of effective diffusivity ranged from 2.14×10^{-07} to 9.41×10^{-08} m^2/s. Page model was found a best fit model for describing the drying behaviour of kachri slices dried in a heat pump dryer.

Keywords: Cucumis callosus, Diffusivity, Heat pump drying, Kachri, Modelling.

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INTRODUCTION

Kachri is an underutilized green fast growing climber plant belongs to family cucurbitaceae (Nathawat et al., 2013). It is harsh, drought tolerant crop grown in arid and semiarid regions of Rajasthan particularly in Nagaur, Churu, Jaisalmer, Jodhpur, and Barmer districts. The availability of arid vegetables is limited to a period of short duration only. During this period, a little part of the total produce is used in the form of vegetables. The remaining produce spoils either through over ripening or from unawareness of various processing and value addition methods. Due to its perishable nature and overproduction during harvest, kachri has post-harvest losses that range from 30 to 40 per cent and lower the market value of the fruits (Nathawat et al., 2013).

Drying is one of the most commonly used preservation method to extend the shelf life of foods by lowering the moisture content (Deng et al., 2019). It is a complex process involves transient heat and mass transfer process. The problem of post-harvest

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losses can be solved by dehydrating the produce, which can also offer significant economic returns to the growers and the availability of fruits throughout the year.

The convective drying application is widely followed in dehydrating foods (Castro et al., 2019). There are many thin-layered drying mathematical models available to determine drying times. The thickness of the material as well as temperature and air velocity of the drying have a good impact on drying kinetics. The design of an ideal dryer depends on physical and thermal characteristics of product like moisture diffusivity and heat and mass transfer data (Kohli et al., 2022). Numerous studies have been already investigated on drying kinetics and mathematical modelling for variety of fruits and vegetables.

Mathematical modelling plays important role in designing dryers and optimizing the process. Theoretical and empirical modelling can be used to define drying characteristics. Theoretical models are commonly based on Fick's law of diffusion (Brasiello et al., 2013, Kohli et al., 2022). Empirical models are derived from theoretical models or on pure kinetic formulas depending on process conditions, these models are simple to use but do not provide any physical information and their use is restricted to specific process conditions (Brasiello et al., 2013). The objective of this study was to evaluate the effect of drying air temperature and slice thickness on the drying characteristics and to choose suitable model that best describe the drying kinetics of pretreated kachri samples using thin layer drying models.

MATERIALS AND METHODS

Fresh, matured, raw kachri cultivar AHK 200 were collected from Central Arid Zone Research Institute, Jodhpur, Rajasthan. Then, the fruits were immediately transported to the lab within 6 h to preserve the freshness of the fruit. Care was taken to procure a sample of uniform size, colour, defect free on visual inspection, and maturity for drying. Before conducting experiment the kachri were washed, cut into thin slices of 5 and 10 mm manually by using a sharp stainless steel knife. The slices were pre-treated with 0.1 per cent potassium metabisulphite (KMS) at 80 ºC for 3 min (Prajapati et al., 2011) and cooled immedietly n cold water to remove the excess heat.

Drying procedure

Drying experiment was performed in a convective heat pump dryer. The dryer was allowed to run before starting experiment to enhance steady state condition. Blanched kachri samples were uniformly placed in thin layer on the solid tray and the drying of samples were conducted at a different temperatures of 40, 50 and 60ºC. The experiments were conducted in three replications. The drying process starts when the required drying conditions were achieved. Weight of the samples were recorded constantly with an interval of one hour for both tray and heat pump dryer to determine the drying characteristics at different time interval. The drying was carried until two to three consecutive constant weights were recorded. The data were used to analyse the drying characteristics.

Drying kinetics

To study the drying characteristics of kachri and to represents drying behaviour graphically it is need to calculate the moisture ratio at different time interval. The moisture ratio curves at different drying conditions can better describe the drying behaviour as compared to moisture content curve, as the initial value for all the experiment is one. The Moisture Ratio (MR) was calculated by using the following Eq. 1 (Gomez-Daza and Ochoa-Martinez, 2015)

$$\mathrm{MR} = \frac{\mathrm{M} - \mathrm{M_e}}{\mathrm{M_0} - \mathrm{M_e}} \qquad \ldots(1)$$

Where,

M = Moisture content at time t (min) during drying (% d.b.)

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

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

The values of M_e were neglected because when compared to M_o and M the values of Me (equilibrium moisture content) were very small for long drying time. Therefore the following Eq. 2 was used to calculate the MR

$$\mathrm{MR} = \frac{\mathrm{M}}{\mathrm{M_0}} \qquad \ldots(2)$$

The moisture content data recorded during experiments will be analysed to determine the moisture lost from the sample of kachri in particular time interval. The drying rate of sample will be calculated by using the following Eq. 3 (Erol, 2022).

$$\text{Drying rate} = \frac{\mathrm{M_{t+dt}} - \mathrm{M_t}}{\mathrm{dt}} \qquad \ldots(3)$$

Where,

M_{t+dt}= Moisture content at t + dt (g water/g dry matter)

dt = Time between two sample weighing (min)

Effective moisture diffusivity D_{eff} is an important property of food during drying and it indicates the rapidness of removal of moisture from the food. In falling rate period of drying, moisture is mainly removed by molecular diffusion. Fick's diffusion equation was used for the diffusivity calculation for infinite slab or cylindrical geometry biological products. The fresh cut kachri fruits were assumed to similar as slab shape and for calculation of moisture ratio the following equation was used (Kalyanamitra and Assawarachan, 2022).

$$\mathrm{MR} = \frac{8}{\pi^2}\exp\left(\frac{\pi^2 \mathrm{D_{eff}} \mathrm{t}}{4\mathrm{L}^2}\right) \qquad \ldots(4)$$

The above equation can also written as:

$$\ln \mathrm{MR} = \mathrm{tk_0} + \ln\frac{8}{\pi^2} \qquad \ldots(5)$$

Where,

D_{eff} = Effective moisture diffusivity, m^2/s

L = Slice thickness, m

Experimental values of moisture diffusivity were determined by plotting values of ln (MR) versus drying time. It gives a straight line and slope (k_0) of the line is used to calculate the effective moisture diffusivity (Kalyanamitra and Assawarachan, 2022).

$$\mathrm{k_0} = \frac{\pi^2 \mathrm{D_{eff}}}{4\mathrm{L}^2} \qquad \ldots(6)$$

$$\mathrm{D_{eff}} = \frac{4\mathrm{L}^2 \mathrm{k_0}}{\pi^2} \qquad \ldots(7)$$

Mathematical modelling of drying kinetics

Various researchers have proposed several thin-layered drying models for drying of food materials, perishable foods, and these proposed models may be describe the drying behaviour of kachri fruits. Drying curve data i.e. moisture ratio calculated at different times obtained from drying were fitted in widely used three thin layered drying models as mentioned in Table 1 for obtaining the best model to describe the drying kinetics of kachri. Non-linear regression analysis was carried out by using curve fitting Toolbox in curve expert and MATLAB software to determine the coefficients of models. The model was selected on the basis of value of correlation coefficient (R^2) and other parameter such as root mean square error (RMSE). The best fit model was evaluated based on highest value of R^2 and lowest values of RMSE (Akpinar, 2010; Silva et al., 2014). These statistical significant values were calculated as (Bishnoi, et al., 2020; Komonsng et al., 2021):

$$\mathrm{R}^2=\frac{\sum_{\mathrm{i}=1}^{\mathrm{N}}\left(\mathrm{MR}_{\mathrm{exp,i}}-\mathrm{MR}_{\mathrm{exp}_{\mathrm{mean,i}}}\right)^2-\left(\mathrm{MR}_{\mathrm{pre,i}}-\mathrm{MR}_{\mathrm{exp,i}}\right)^2}{\sum_{\mathrm{i}=1}^{\mathrm{N}}\left(\mathrm{MR}_{\mathrm{exp,i}}-\mathrm{MR}_{\mathrm{exp}_{\mathrm{mean,i}}}\right)^2} \quad \ldots(8)$$

$$\mathrm{RMSE}=\left[\frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}}\left(\mathrm{MR}_{\mathrm{exp,i}}-\mathrm{MR}_{\mathrm{pre,i}}\right)^2\right]^{1/2} \quad \ldots(9)$$

Table 1: Selected drying models

Model Name	equations	References
Page	$MR = e^{-kt^n}$	Akpinar (2010)
Logarithmic	$MR = ae^{-kt} + c$	Patel *et al.,* 2022
Henderson and Pabis	$MR = ae^{-kt}$	Gomez-Daza and Ochoa-Martinez (2016)

Where,

MR = Moisture ratio, $\frac{\mathrm{M}-\mathrm{M_e}}{\mathrm{M_0}-\mathrm{M_e}}$

t = Time, min

k = Drying constant

a, b, c, n = Drying parameters

RESULTS AND DISCUSSION

Drying curves

The effect of drying air temperature on moisture profile as shown in Fig 1 and 2. It shows that as the drying proceeds moisture content of product decreases continuously with increase of temperature. The loss in moisture content with of drying time followed almost similar pattern for all thickness and drying air temperatures. Initial moisture removal rate was higher due to high moisture content, and then decreased with drying time. Falling rate period was observed during the whole drying process and constant rate period was completely absent for all the experiments, it showed that there was no surface moisture present on the kachri fruit slices. The increasing drying temperatures also fasten the drying process within temperature range (40 – 60 ºC). Similar results were also obtained by Kohli et al., 2022; Kannan et al., 2021. For the different slice thicknesses the moisture content versus drying time is shown in Fig 3. Furthermore, it can be found that for the samples of less thickness, the moisture removal rate was faster

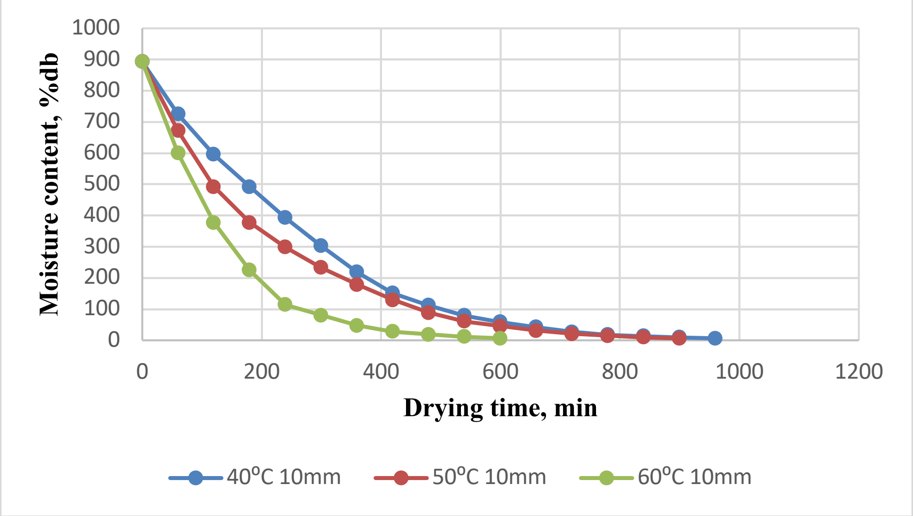

Fig.1: Variation in moisture content of kachri fruit of 10 mm thickness dried at various temperatures in heat pump dryer

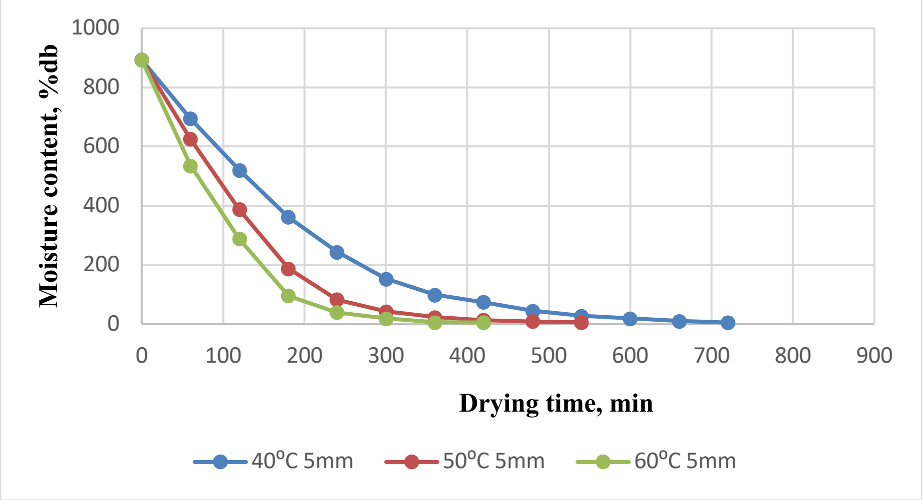

Fig.2: Variation in moisture content of kachri fruit of 5 mm thickness dried at various temperatures in heat pump dryer

The variation in drying rate versus time of blanched samples of different thicknesses dried in the heat pump dryer were illustrated in Figs.3 and 4. It was found that as the drying air temperature increases the drying rate increases for all the experiments and the thickness of slices also affects the drying rate, as the slice thickness decreases the drying rate increases. The increase in drying rate with an increase in temperature might be due to high moisture diffusivity at higher temperatures. The maximum drying rate of 0.05 g-w/g-dm-min was observed initially for a 5 mm thickness sample dried at 60ºC. It was observed from the figures that the drying rate was found maximum during the initial inception of drying and it was reduced with time as the moisture content was reduced towards the end of drying. It can be evident from the Figs. 3 and 4 that constant rate period was absent and complete drying of kachri slices takes place in a falling rate period for all the experiments. These results are in line with the findings of several researchers works on the drying characteristics of fruits and vegetables viz. Kohli et al., 2022 for asparagus roots, Akpinar et al., 2010 for the drying of mint leaves, Al-Amin et al., 2015 for the drying of carrots.

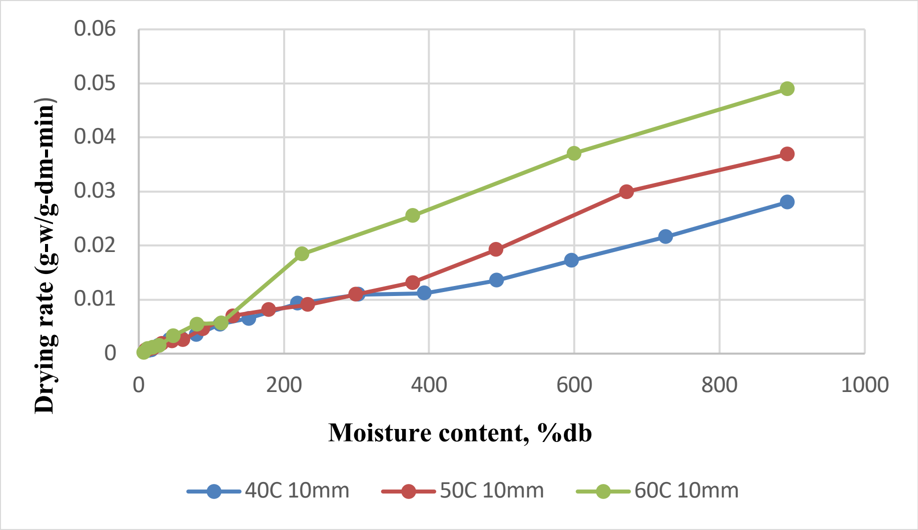

Fig. 3: Variation in drying rate with moisture content of kachri fruit of 10 mm thickness dried at various temperatures in heat pump dryer

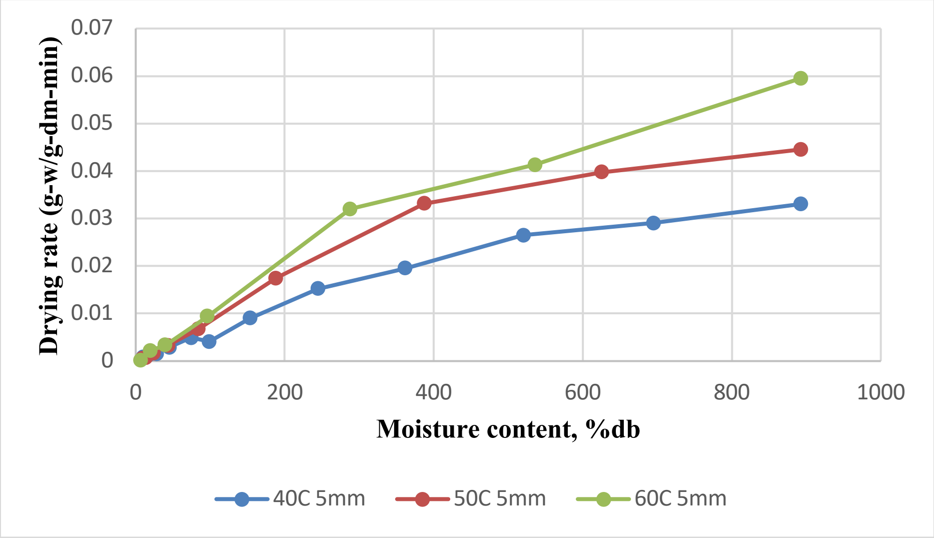

Fig. 4: Variation in drying rate with moisture content of kachri fruit of 5 mm thickness dried at various temperatures in heat pump dryer

The drying rate data was further analysed to find out the effective moisture diffusivity using Eq.7. For the estimation of diffusion coefficients (D_{eff}) slope of (MR) versus time was used (Figs. 5 and 6). The values of effective moisture diffusivity are shown in Table 2. From Figs. 5 and 6; it can be observed that a linear relationship existed between the ln(MR) versus time for all the drying temperatures and thicknesses. As the time increases the moisture ratio of the sample decreased. Due to this for different air temperatures with drying time the values of ln(MR) decreased (Srinivas et al., 2018).

The values of effective moisture diffusivity for different temperatures and thickness ranged from 2.14×10^{-07} to 9.41×10^{-08} m^2/s. From Table 2 it is shown that the values of effective moisture diffusivity increase with the increase in the temperature and slice thickness (Jiang et al., 2021). Trends obtained in this study are in line with the results reported for papaya cubes (Srinivas et al., 2018) and turmeric (Komonsing et al., 2021) .

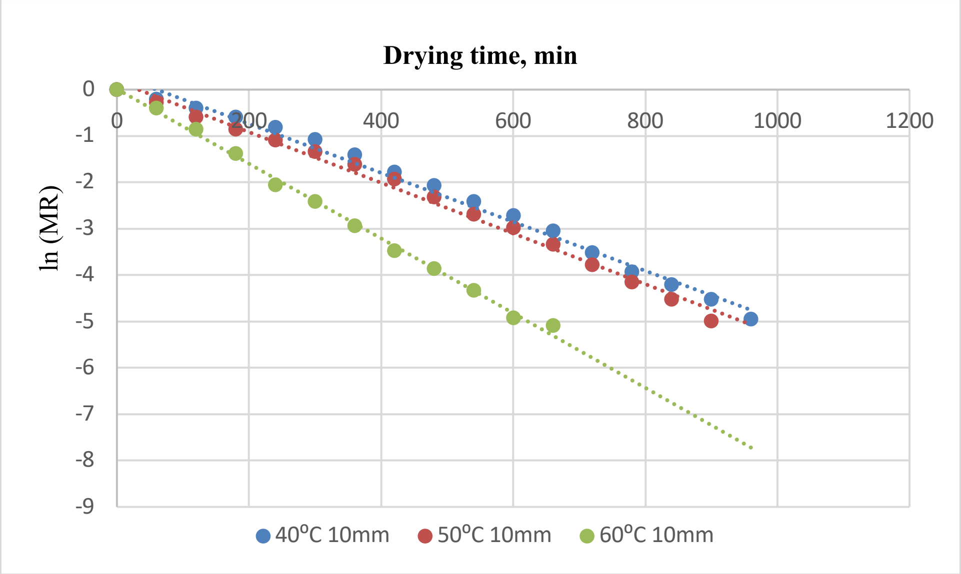

Fig. 5: Variation in ln(MR) with time of kachri fruit of 10 mm thickness dried at various temperatures in heat pump dryer

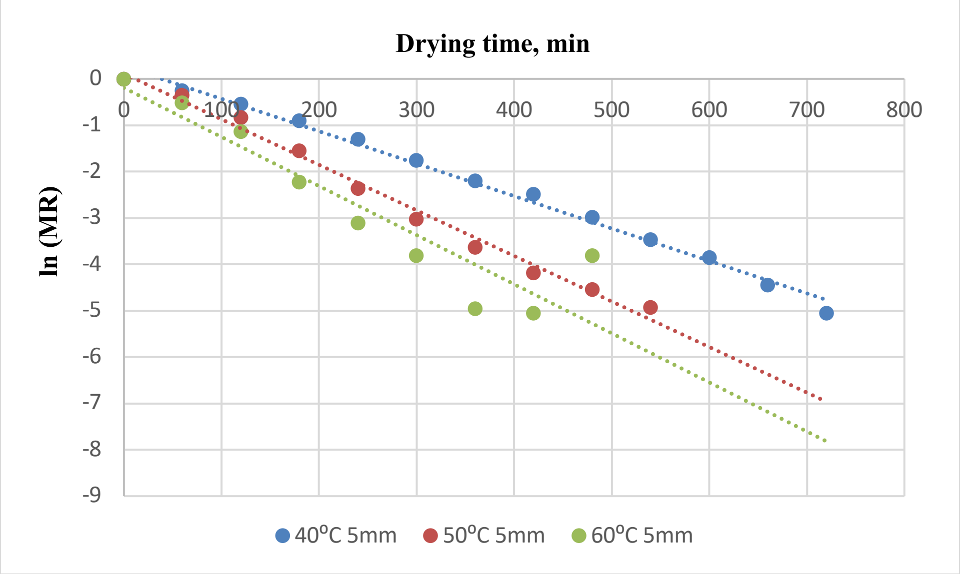

Fig. 6: Variation in ln(MR) with time of kachri fruit of 5 mm thickness dried at various temperatures in heat pump dryer

Table 2: Effective moisture diffusivity values at different conditions

Temperature (ºC)	Slice thickness (mm)	Effective diffusivity, m^2/s
40	10	2.14×10^{-07}
40	5	3.09×10^{-08}
50	10	4.22×10^{-07}
50	5	5.92×10^{-07}
60	10	7.32×10^{-07}
60	5	9.41×10^{-08}

Modelling of the thin layer drying characteristics

Experimental results of moisture ratio with drying were fit for three different models namely Page, Henderson and Pabis and Logarithmic for describing the drying characteristics of blanched kachri samples dried in heat pump dryer. The drying constants and statistical parameter like coefficient of determination (R^2) and root mean square error (RMSE) of the selected mathematical drying models are tabulated in Table 3. The overall values of R^2 ranges from 0.860 to 1.000 and values of RMSE ranges from 0.007 to 0.211, respectively. For drying, the values of R^2 for all selected model was found higher than 0.850 which shows that all model gave an excellent fitting for all the drying data. From the Table 3 among the three thin layer drying model Page model was considered best model since it has high value of coefficient of determination (R^2) and lower values of RMSE for all the temperatures and slice thicknesses combination. For Page model the value of coefficient of determination (R^2) was ranged from 0.999 to 1.000 and RMSE was 0.007 to 0.017 respectively for different treatment combinations. Page model was recommended by the many investigators for describing the drying behaviour of various fruits and vegetables such as for pointed gourd (Sharma and Shrivastava, 2017); crab apple (Jiang et al., 2021); naga chili (Rana et al., 2021).

Table 3: Values of the drying constants and coefficients of mathematical models through non-linear regression analysis for blanched kachri slices of 5 and 10 mm

Model	Temperature (ºC)	Slice thickness (mm)	Drying constants				Statistical parameters	
			k	n	a	c	R^2	RMSE
Page	40	5	0.579	1.223	-	-	1.000	0.007
	40	10	0.527	1.198	-	-	0.999	0.015
	50	5	0.450	1.359	-	-	1.000	0.011
	50	10	6.996	0.999	-	-	0.999	0.011
	60	5	0.363	1.304	-	-	0.999	0.017
	60	10	0.781	1.136	-	-	1.000	0.008
Henderson and Pabis	40	5	2.895	-	1.041	-	0.997	0.030
	40	10	2.898	-	1.038	-	0.996	0.030
	50	5	1.363	-	1.040	-	0.994	0.045
	50	10	2.921	-	0.997	-	0.999	0.011
	60	5	2.802	-	1.023	-	0.995	0.047
	60	10	2.894	-	1.019	-	0.999	0.019
Logarithmic	40	5	2.301		1.069	-0.042	0.998	0.024
	40	10	2.687		1.073	-0.055	0.998	0.021
	50	5	-0.039		-78.887	79.589	0.868	0.211
	50	10	1.977		1.004	-0.012	1.000	0.010
	60	5	-3.261		1.075	-0.062	0.997	0.040
	60	10	0.074		-73.831	74.497	0.860	0.199

CONCLUSION

The drying characteristics of the pretreated kachri sample of slice thickness were dried in heat pump dryer at 40, 50 and 60ºC temperatures were studied and discussed. The moisture ratio, drying rate and effective diffusivities were affected by drying air temperature and slice thicknesses. The moisture content drying rate and effective diffusivity increased with increase in temperature. The increase of slice thickness decreased the drying rate. The Page model gave the highest value of coefficient of determination (R^2) of 1.00 and lowest root mean square error (RMSE) of 0.007 among the three models and considered the best model for describing the drying behaviour of dried kachri. The value of effective diffusivity found ranged from 2.14 × 10^{-07} to 9.41 × 10^{-08} m^2/s.

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