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Thin-layer drying characteristics of *Kachkal* banana peel (*Musa* ABB) of Assam, India

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Abstract

The present study investigated the thin-layer drying characteristics of *kachkal* (*Musa* ABB) peel in a convective tray dryer with four different drying temperatures of 40, 50, 60 and 70°C, which exhibited falling rate period. The initial moisture content of sample was 85.47% wet basis which was reduced to 7.02 to 10.59%. In order to select suitable form of drying curve nine different thin-layer drying models were fitted to experimental data. Among all the models fitted modified Page model was found to be the best fitted model to describe the drying behaviour of *kachkal* peel with lowest χ^2 value of 2.236 x 10^{-4} and highest R^2 value of 0.998. The effective moisture diffusivity was 2.05 x10^{-9} m^2/s and 7.80 x10^{-9} m^2/s at 40 and 70°C respectively. The result indicates that effective diffusion coefficient increased with increase in temperature. The value of activation energy (E_a) was found to be 27.22 kJ/mol.

Introduction

Culinary banana (*Musa* ABB) which is known as *kachkal* in local language of Assam is the only cooking banana found in entire North Eastern region and Assam. It is popular in Assam and it has high commercial value and high demand on market due to its high culinary purpose. The peel of banana represents 40% of the total weight of fresh banana (Tchobanoglous *et al*., 1993) and has been underutilized and discarded as waste.

Like its pulp flour counterpart, banana peel flour can potentially be used in new products with standardized composition for various industrial and domestic uses (Emaga *et al*., 2007). Peels are the major by-products of all fruits and vegetables obtained during processing; some studies show that these are good sources of polyphenols, carotenoids and other bioactive compounds which possess various beneficial effects on human health (Rodriguez De-Sotillo *et al*., 1994; Zhang *et al*., 2005). Various studies have been conducted to investigate banana peel, including the effect of ripening stage on the dietary fibre components and pectin (Emaga *et al*., 2008) and the chemical compositions of peel, as influenced by the maturation stage and varieties of banana (Emaga *et al*., 2007). As reported by Mohapatra *et al.* (2010), banana peel is rich source of starch (3%) and crude protein (6-9%), crude fat (3.8-11%), dietary fibre (43.2-49.7%), banana peels are good source of lignin (6-12%), pectin (10-12%), cellulose (7.6-9.6%), hemicellulose (6.4-9.4%). Emaga *et al.* (2008) and Davey *et al.* (2009) found in their study that micronutrients such as iron and zinc were found in higher concentration in banana peels compared to pulps. Therefore, peels could be good feed material for cattle and poultry (Dormond *et al*., 1998; Emaga *et al*., 2007; Adeniji *et al*., 2008). Fatemeh *et al.* (2012) in their study have also reported that the total phenolic content (TPC) and total flavonoids content (TFC) of banana peel was higher than that of pulp.

According to Archibald (1949) skin of banana peel can be used for extraction of banana oil (amyl acetate) that can be used for food flavourings. Pectin extracted from banana peel also contains glucose, galactose, arabinose, rhamnose and xylose. Faturoti *et al*. (2006) reported that banana peels can also be used in making wines, ethanol production (Tewari *et al*., 1986; Castro-Gomez *et al.*, 1988), as substrate for biogas production (Ilori *et al*., 2007) and as base material for pectin extraction.

Drying, the process of unit operation is applied to reduce the water content of various agricultural products. The purpose of reducing water content is to prolong the shelf life of the products of bio-origin by reducing water activity to a level low enough where growth of microorganisms, enzymatic reactions and other deteriorative reactions are inhibited (Majumdar and Law, 2010). Tahmasebi *et al*. (2011) stated that information on the physical and thermal properties of the agricultural products, such as heat and mass transfer, diffusion, thermal conductivity and specific heat required for designing an ideal dryer. The quality of final dried product depends on the entire

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drying conditions; therefore it is very important to understand the drying process and to determine the drying characteristics of the sample (Diamante and Yamaguchi, 2012). Thin layer drying refers to the drying process in which food materials are fully exposed to the drying air under constant drying conditions of temperature and humidity. Thus, thin-layer drying simulation is the best criterion to model the food drying process (Chakraverty and Singh, 1988).

Mathematical modelling of the convective drying process employing diffusion theory can adequately described the profile of water distribution within the particular agricultural products to a solid of perfect geometry. Establishment of functional relationship between the diffusion coefficient and the moisture content is also required (Parry, 1985). Studies on drying kinetics provide parameters as experimental diffusion coefficients, which can be used to predict the drying time and thus define the basic design characteristics of drying equipment. The aim of present study was the investigation of the thin layer convective drying behaviour of kachkal peel at different drying air temperatures to select the suitable mathematical model for describing the drying kinetics of kachkal peel and also to calculate the effective diffusivity and activation energy by adopting appropriate mathematical model to the experimental data. The aim of the present study is to investigate the thin-layer drying behaviour of kachkal peel at different drying temperatures to select the suitable mathematical model for describing the drying characteristics of kachkal peel and also to calculate the effective moisture diffusivity and activation energy.

Materials and Methods

Sample preparation

Freshly harvested *Musa* ABB the culinary banana (*kachkal*) of Assam was procured from local vegetable market of Tezpur. The fruits were washed and separated into pulp and peel. Peel which constitutes 40% of the fruit was taken for the drying study. The peels were cut into small pieces and grounded into fine paste by using mechanical grinder and paste were spread into approximately 4 mm thickness in stainless steel trays. Before starting the drying experiment, the initial moisture content of the peel was determined by following hot air oven method which was found to be 85.47% wet basis. The drying kinetics of peel was studied at 40, 50, 60 and 70°C. A laboratory scale convective tray dryer (Model No. IK-112, Make IKON Instruments, Delhi) was set at the desired temperature prior to experiment. The sample trays which was previously weighed were loaded to pre heated drying chamber and the loss in weight was recorded at every 30 min interval till the sample attains constant weight. Each experiment was replicated thrice and the average values were taken for further analysis.

Table 1. Mathematical models used for thin-layer drying of *kachkal* peel

Model	Mathematical Equation	References
Lewis	$MR = \exp(-kt)$	Doymaz (2005)
Page	$MR = \exp(-kt^n)$	Page (1949)
Modified Page	$MR = \exp(-kt)^n$	Yaldiz *et al.* (2001)
Henderson and Pabis	$MR = a\exp(-kt)$	Doymaz (2004c)
Logarithmic	$MR = a\exp(-kt) + c$	Togrul and Pehlivan (2002)
Two-Term Model	$MR = a\exp(-k_0t) + b\exp(-k_1t)$	Rahman *et al.* (1997)
Approximation of Diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	Lahsasni *et al.* (2004)
Wang and Singh	$MR = 1 + at + bt^2$	Wang and Singh (1978)
Modified Page Equation II	$MR = \exp[-c(t/L_c^2)^n]$	Doymaz (2005)

Drying kinetics experiments

The moisture content of *kachkal* peels were expressed in dimensionless form as moisture ratio (MR) obtained by following Equation (Midilli *et al.*, 1999; Midilli, 2001; Erenturk *et al*., 2004).

$$MR = Mt - Me/Mi - Me \qquad (1)$$

Where, Moisture Ratio = MR, M_i = initial moisture content, M_t = moisture content at time t, M_e = equilibrium moisture content. The M_e values were neglected because the values were very small comparing to those values of M_i and M_t, therefore moisture ratio can be reduced to the following Equation (Jena and Das, 2007; Goyal *et al*., 2007).

$$MR = Mt/Mi \qquad (2)$$

The drying data of MR versus drying time was analysed for nine thin-layer drying models given in Table 1 to select the best model to describe the thin layer drying curve of *kachkal* peel. Software ORIGIN 8.5 was employed for nonlinear regression analysis of drying data. The coefficient of determination (R^2) was considered as one of the main criteria for selecting best drying model (Ozdemir and Devers, 1999; Yaldiz *et al.*, 2001; Erenturk *et al.*, 2004). In addition to coefficient of determination, the goodness of fit was characterised by determining reduced chi-square (χ^2), (Pangavhane *et al.*, 1999; Demir *et al.*, 2004; Erenturk *et al*., 2004; Goyal *et al.*, 2007).

Effective moisture diffusivity

Fick's second law for unsteady state diffusion Equation was used to model the moisture diffusivity of *kachkal* peel. The *kachkal* peel was considered as slab geometry (Doymaz, 2006). Assuming a uniform initial moisture content and negligible external resistance, the solution of Fick's diffusion Equation is as follows (Crank, 1975). Following are the assumptions made for the effective moisture diffusivity for an infinite slab in this study:

(i) Moisture distribution inside *kachkal* peel paste was uniform at the beginning of drying.

(ii) The moisture transfer occurs only in the thickness direction and the external resistance to moisture transfer was negligible.

(iii) The shrinkage effect should be taken into account for determining the effective moisture diffusivity, particularly when the material shrinkage is high. This is because the mean diffusion path of moisture which travels from the inside to outside is shorter.

$$MR = Mt - Me/Mi - Me = \sum_{n=0}^{\infty} 8/\pi^2\{\exp[(2n+1)^2\,\pi^2/4\,D_{eff}\,(t)/L^2]\} \quad (3)$$

Neglecting the higher order terms Eq. (3), it can be written as

$$Mt - Me/Mi - Me = 8/\pi^2 \exp(-\pi^2\, Deff\, t\,/L^2) \quad (4)$$

n = 1, 2, 3, . . . the number of terms taken into consideration, D_{eff} is the effective moisture diffusivity (m^2/s), L is the sample thickness (mm) and t is the drying time (s). The effective moisture diffusivity was calculated using the method of slopes when plotting logarithm of MR values versus the drying time. Linear regression analysis was used to obtain values of diffusion coefficients for different drying conditions.

Activation energy

The activation energy is known as the energy barrier in order to activate moisture diffusion (Hii *et al.*, 2009). The effective moisture diffusivity can be related with temperature by Arrhenius relation given in Eq. 5. (Akpinar *et al.*, 2003; Lopez *et al.*, 2000)

$$Deff = Do\exp[-Ea/R(T+273.15)] \quad (5)$$

Where D_0 is the Arrhenius factor (m^2/s), E_a is the activation energy (kJ/g mol), R is the ideal gas constant (8.314 kJ/kg) and T is the drying temperature. Eq. 5 can be arranged in the form of

$$ln\,(Deff) = ln\,(Do)[-Ea/R(T+273.15)] \quad (6)$$

The activation energy can be obtained from the slope of the Arrhenius plot, ln (D_{eff}) versus $1/T_{abs}$, from Eq. (7) a plot of ln (D_{eff}) versus $1/T_{abs}$ gives a straight slope of k.

$$K = Ea/R \quad (7)$$

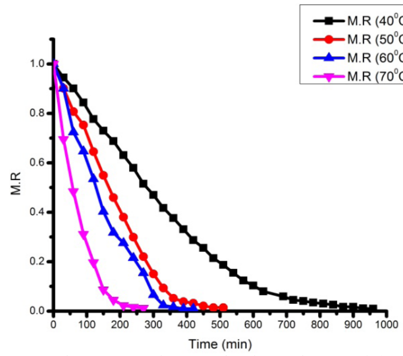

Figure 1. Moisture ratio vs drying time of *kachkal* peel

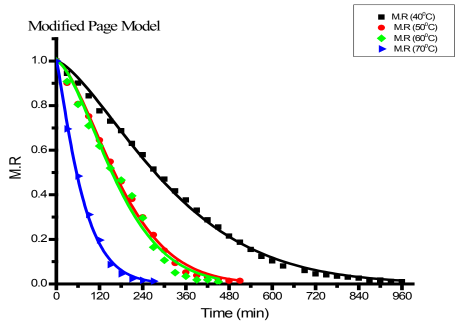

Figure 2. Moisture ratio vs drying time in modified Page model

Results and discussion

Drying characteristics

Kachkal peel paste approximately 4 mm thickness was dried in a convective dryer at 40, 50, 60 and 70°C in a thin-layer. The initial moisture content of the sample was 85.47% wet basis which was reduced to 7.02-10.59% wet basis. Drying of *kachkal* peel predominantly followed falling rate profile. Mass transfer during drying is caused by moisture diffusion at constant relative humidity which used to describe the drying behaviour in the falling rate period of *kachkal* peel. The decrease in weight was measured at each 30 min interval.

The moisture ratio profile of *kachkal* peel paste with respect to drying time is shown in Figure 1. From the Figure it can be seen that moisture ratio decreased with increase in drying time. The moisture content rapidly dropped at the initial stage and then it gradually decreased till it reached an equilibrium point. The effect of drying air temperature on drying time showed that increase in drying air temperature resulted in decrease in drying time (Figure 1). At 40°C it took approximately 15 hours to reach the safe final moisture content and the same sample required only 3 hours at 70°C to reach the same moisture value. Therefore, from the drying curve (Figure 1) it can be concluded that drying rate decreased continuously with decreasing moisture content or increasing drying time. All the drying process occurred in falling rate period, starting from the initial moisture content reaching to the final moisture content; the

Table 2. Values of model constants for thin-layer drying of *kachkal* peel

Model name	Coefficients and constants	χ^2	R^2
Drying temperature 40^{0}C			
Lewis/Newton	k = 0.0029	3.7 x 10^{-2}	0.9640
Page			0.9063
Modified Page	**k = 0.0028, n =1.4390**	**2.236 x 10^{-4}**	**0.9986**
Henderson and Pabis	a=1.1060, k = 0.0032	2.61 x 10^{-2}	0.9748
Logarithmic	a= 1.2293, c= -0.1735, k = 0.0022	8.659 x 10^{-4}	0.9917
Two-Term	a= 0.5530, b = 0.5530, m = 0.0032, n = 0.0032	2.842 x 10^{-2}	0.973
Approximation of Diffusion	a= 5.47 x 10^{-8}, k = -53798.89, m =2.212	4.0 x 10^{-3}	0.9615
Wang and Singh	a= -0.0021 b = 1.175 x 10^{-6}	3.431 x 10^{-4}	0.9967
Modified Page Equation II	c= 0.0146, m = -4.3223, n = 1.4354	2.815 x 10^{-4}	0.9947
Drying temperature 50^{0}C			
Model name	**Coefficients and constants**	**χ^2**	**R^2**
Lewis/Newton	k = 0.0051	5.95 x 10^{-2}	0.9489
Page			0.9248
Modified Page	**k = 0.0049, n = 1.5612**	**2.654 x 10^{-4}**	**0.9982**
Henderson and Pabis	a= 1.1020, k = 0.0056	4.9 x 10^{-2}	0.9580
Logarithmic	a= 1.3291, c= -0.2825, k =0.0034	1.675 x 10^{-2}	0.9855
Two-Term	a= 0.5510, b = 0.5510, m = 0.0056, n = 0.0056	5.6 x 10^{-2}	0.9520
Approximation of Diffusion	a= -0.2020, k = 0.0304, m= 2.2683	3.8 x 10^{-3}	0.9667
Wang and Singh	a= -0.0037 , b = 3.421 x 10^{-6} ,	9.929 x 10^{-4}	0.9914
Modified Page Equation II	c= 0.0049, m = -2.5886, n = 1.5567	7.10 x 10^{-4}	0.9939
Drying temperature 60^{0}C			
Model name	**Coefficients and constants**	**χ^2**	**R^2**
Lewis/Newton	k = 0.0053	7.30 x 10^{-2}	0.9387
Page			0.9500
Modified Page	**k = 0.0051, n = 1.5781**	**2.657 x 10^{-4}**	**0.9966**
Henderson and Pabis	a= 1.1006, k = 0.0059	6.354 x 10^{-3}	0.947
Logarithmic	a= 1.4944, c=-0.45974, k = 0.0029	1.7 x 10^{-2}	0.9850
Two-Term	a= 0.5502, b = 0.8761, m = 0.0059, n = 0.0453	7.31 x 10^{-4}	0.9382
Approximation of Diffusion	a= 1.262 x 10^{-8}, k = -426903.57, m = 2.1312	8.422 x 10^{-2}	0.9292
Wang and Singh	a= -0.0037, b = 3.281 x 10^{-6}	1.38 x 10^{-3}	0.9885
Modified Page Equation II	c= 0.0051, m = -2.6155, n = 1.5730	1.7 x 10^{-2}	0.9856
Drying temperature 70^{0}C			
Model name	**Coefficients and constants**	**χ^2**	**R^2**
Lewis/Newton	k = 0.0136	9.305 x 10^{-4}	0.9919
Page			0.8068
Modified Page	**k = 0.0131, n = 1.1895**	**2.642 x 10^{-4}**	**0.9977**
Henderson and Pabis	a= 1.0246, k = 0.0138	9.495 x 10^{-4}	0.9917
Logarithmic	a= 1.0659, c= -0.0553, k = 0.0120	4.435 x 10^{-4}	0.9961
Two-Term	a= 0.5123, b = 0.5123, m = 0.0138, n = 0.0138	1.272 x 10^{-3}	0.9890
Approximation of Diffusion	a= -0.1302, k = 0.1165, m = 3.0879	6.404 x 10^{-4}	0.9944
Wang and Singh	a= -0.0093, b = 2.159 x 10^{-5}	8.991 x 10^{-4}	0.9922
Modified Page Equation II	c= 0.0032, m = 0.7797, n = 1.1841	3.026 x 10^{-4}	0.9973

drying process was mainly controlled by diffusion mechanism. Similar results have been reported by various researchers in potato slices (Akpinar *et al.*, 2003), ripe banana (Nguyen and Price, 2007), pomegranate arils (Motevali *et a*l., 2010), Mulberry (Doymaz, 2004a), eggplant (Erketin and Yaldiz, 2004), peach slices (Kingsly *et al.*, 2007), cassava chips (Tunde-Akinthunde and Afon, 2010).

Mathematical modelling for fitting drying curves

In order to describe the drying behaviour of *kachkal* peel paste and predict it under different drying temperature of 40, 50, 60 and 70°C for 4 mm slab thickness were compared by fitting different thin-layer drying models given in Table 1. The models were evaluated on the basis of coefficient of determination (R^2) and the reduced chi-square (χ^2). The selection of best model to describe the drying behaviour of *kachkal* peel paste was based on the highest R^2 and lowest χ^2 values. The drying model constants and coefficients from the results of statistical analysis undertaken by regression of all models are given in Table 2. The average value of χ^2 varied from 2.236 x 10^{-4} to 8.44 x 10^{-2} and value of R^2 varied between 0.806 to 0.998. For all mentioned thin-layer drying models, R^2 values were greater than 0.924 except Page model, which

Table 3. Effective moisture diffusivity, activation energy of *kachkal* peel

Temp (°C)	D_{eff} (m^2/s)	1/Tabs
40	2.05 x10^{-9}	0.003195
50	3.85 x 10^{-9}	0.003096
60	4.05 x 10^{-9}	0.003003
70	7.80 x 10^{-9}	0.002915

Table 4. Progressive parameters of Arrhenius relationship between affective diffusivity and absolute temperature

Regression parameters	Values
Slope (E_a/R)	327.48
Activation energy (E_a)	27.22 kJ/mol
Intercept (ln D_0)	8.9 x 10^{-2}
R^2	0.9998

Table 5. Comparison of activation energy values with literature values

Study material	Activation energy (E_a) (kJ/mol)	References
Kachkal peel	27.22	Present study
Black tea	406.02	Panchariya *et al.* (2002)
Carrot	82.93	Doymaz (2004b)
Green peas	24.70	Simal *et al.* (1996)
Grapes	40.14	Roberts *et al.* (2008)

showed the minimum R^2 =value of 0.806. Therefore, from Table 2 it can be concluded that modified Page model was found to be the best fitted model with least X^2 value of 2.236 x 10^{-4} and highest R^2 value of 0.998, thus modified Page model was selected as suitable model to represent the thin-layer drying behaviour of kachkal peel (Figure 2). The coefficients of all the models applied and fitted are given in Table 2. The values of moisture diffusion coefficient or drying constant rates which are obtained from modified Page model will be useful to explain the effects of different drying conditions on drying behaviour of kachkal peel. Similar findings have been reported for thin layer drying of fresh ripe banana (Sankat *et al.*, 1996), semi-dried fruits (Karathanos and Belessiotis, 1999), apricots (Togrul and Pehlivan, 2002), plum (Goyal *et al.*, 2007), cassava (Tunde-Akinthunde and Afon, 2010).

Effective moisture diffusivity

Drying of most of the food materials occur in the falling rate period (Wang and Brennan, 1992) and moisture transfer during drying is controlled by internal diffusion (Saravacos and Charm, 1962). An analysis of falling rate period was carried out to understand the drying kinetics by determination of effective moisture diffusivity (D_{eff}). To determine the effective moisture diffusivity, slope method was used (Eq.4). The calculated values of D_{eff} for all the four temperatures are presented in Table 3 and Figure 3. The highest diffusivity value of 7.80 x10^{-9} m^2/s was observed at 70°C and the lowest D_{eff} value of 2.05 x10^{-9} m^2/s was observed at 40°C. From the study it can be concluded that effective moisture diffusivity declined sharply with moisture content in the first

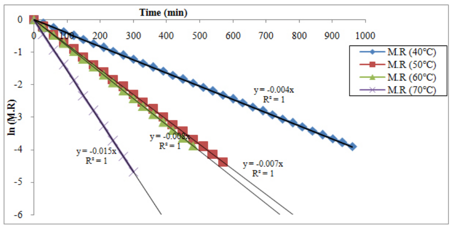

Figure 3. Variation in ln (MR) with time (T) of kachkal peel

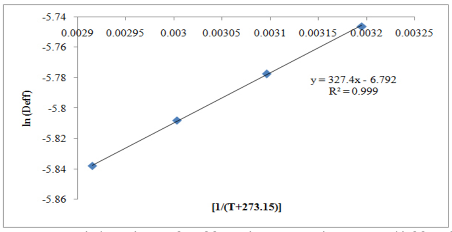

Figure 4. Logarithmic of effective moisture diffusivity vs function of the inverse of absolute Temperature in K

falling rate period and when drying entered into the second falling rate period the diffusivity changed slightly with moisture content. The values of D_{eff} found in this study were in the range of 10^{-9} to 10^{-8} m^2/s which is typical value for drying of agricultural products (Maskan *et al.*, 2002). The obtained values of diffusivity are within the suitable range of various food products (10^{-11} to 10^{-9} m^2/s) reported in the literature like tomato (Taheri-Garavand *et al.*, 2011a), cassava crackers (Lertworasirikul, 2008), ginger (Alakali and Satimehin, 2004), bell-pepper (Taheri-Garavand *et al.*, 2011b), ripe banana slices (Thuwapanichayanan *et al.*, 2011). The values of D_{eff} obtained in our finding are in accordance to that of ripe banana slices by Thuwapanichayanan *et al.* (2011). The moisture diffusivity increased with air drying temperature. Kadam *et al.* (2011) also reported that moisture diffusivity increased with the increase in drying air temperature for vegetables.

Activation energy

The minimum energy required to initiate moisture diffusion from the food products is known as activation energy. Figure 4 shows the logarithmic of effective moisture diffusivity values (D_{eff}) obtained at different temperatures plotted against the corresponding absolute temperature [1/ (T+273)] to obtain the constants of Arrhenius Equation. The values of activation energy lie from 12.7 to 110 kJ/mol for most food material (Zogzaz *et al.*, 1996). The plots in Figure 4 showed the straight line in the temperature range investigated, indication Arrhenius dependence. From the slope of the straight line described by the Arrhenius Equation the activation energy was found to be 27.22 kJ/mol which was calculated by using Eq. 6. The value of activation energy compared with literature values of different agricultural products are given in Table 5.

Conclusion

Thin-layer drying of *kachkal* (*Musa* ABB) peel paste was carried out to determine the effect of different drying temperature which took place in falling rate period. This implies that the moisture removal from the product was governed by diffusion phenomenon. Using a simple solution of Fick's diffusion Equation for an infinite slab it was possible to model the drying kinetics of drying *kachkal* peel slabs. Nine different models were applied and fitted to the experimental data. According to the statistical analysis applied to all the models, modified Page model gave the best result with minimum χ^2 value of 2.236 x 10^{-4} and maximum R^2 value of 0.9986. The highest effective moisture diffusivity found was 7.80 x10^{-9} m^2/s at 70°C and lowest value of 2.05 x10^{-9} at 40°C. The activation energy required to initiate moisture diffusion from the *kachkal* peel was found to be 27.22 kJ/mol. Temperature dependence of diffusivity followed an Arrhenius model with high correlation factor (R^2 = 0.99). From the present study it can be concluded that the drying of *kachkal* peel can be accurately predicted using modified Page model. Therefore, this model may be useful in the description of the drying process of *kachkal* characterised by variable properties and drying condition.

Nomenclature

M_e equilibrium moisture content (% wet basis)
M_i initial moisture content (% wet basis)
M_t moisture content at time t (% wet basis)
M average moisture content (% wet basis)
MR moisture ratio
D_{eff} effective moisture diffusivity (m^2/s)
D_0 Arrhenius factor (m^2/s)
E_a activation energy (kJ/mol)
L slab thickness (mm)
t drying time (min)
T drying air temperature (°C)
abs absolute temperature (K)
R ideal gas constant (8.314 J/mol K)
R^2 coefficient of determination
χ^2 chi-square
X independent variable
Y dependent variable
db dry basis
wb wet basis
a, b, c, k, m, n drying model coefficient

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