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RESEARCH PAPER

Mathematical Modelling of the Thin Layer Drying of Tender Palm Shoots *(Borassus flabellifer L.)*

Naveen Kumar. M*, Edukondalu. L, Sai Supraja. Ch, Jyothi. B, Maheendra Reddy. J

College of Agriculture Engineering, Bapatla, Andhra Pradesh, India

*Corresponding author: naveen09006@gmail.com

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Abstract

In this study, the influence of air temperature on thin layer drying of different pre-treated (Baking, Steam boiling and boiling) tender palm shoots has been reported. Drying experiments were performed in a tray dryer at temperatures of 50°C, 60°C and 70°C. Results showed that drying takes place in falling rate period. The experimental moisture loss data were fitted to the selected semi-theoretical and empirical thin-layer drying models. The mathematical models were compared according to the three statistical parameters such as the coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (RMSE). Except Wang and Singh model all the remaining models gave the best fitting results. The effective diffusivity coefficient of moisture transfer varied from 2.19 to 4.21×10^{-8} m^2/s for all the pre-treated samples over the temperature range, while the activation energy values varied from 11.4816 to 30.2131 kJ/mol for all the pre-treated samples.

Keywords: Activation energy, diffusion coefficient, drying, mathematical modelling, palm shoots

Palmyrah (*Borassus flabellifer L.*) is a palm tree belonging to the family Palmae and the sub-family Boracidae (Jeyaratnam, 1986). The three most economically important species of Borassus are *Borassus aethiopum Mart, B. flabellifer Linn*, and *Borassus sundaicus* Becc. (Mohanadas, 2002). The species *B. flabellifer L.* is abundant in the arid tropics of South America, West Africa, India, Sri Lanka and Southeast Asia (Mohanadas, 2002, Morton, 1988). These palms grow abundantly in sandy plains just above the sea level, having annual rainfall of 620 to 650 mm (Ghosh *et al.* 1998). There are about 140 million palmyrah palms distributed worldwide with over 11 million in Sri Lanka (Mohanadas, 2002).

Palmyrah provides a variety of edible and non-edible products. Foremost edibles of the palmyrah include the inflorescence sap, the sweet fruit pulp, the peeled seed-shoots (seedlings), and the kernel from both the very young and mature nuts (Barminas *et al.* 2008, Morton, 1988). During germination of palmyrah seeds, the excess carbohydrate is stored in the form of starch in the scale leaf of the seedling (Fig. 1). The scale leaf becomes the edible part of the seedling (shoot) and is colloquially known as "palmyrah tuber" (Jeyaratnam, 1986). The palmyrah seed-shoot is high in starch and it is widely utilised in the preparation of starch based products such as porridge and soups (Sumudunie *et al.* 2004). The palm tuber however is a neglected crop, the availability of the tuber is seasonal during the months of November to February every year. The tender palm shoots, because of there high moisture content has a self-life limited to 4-5 days only after harvesting. In Sri Lanka, the palmyrah seed shoots as dried, powdered and locally made into gruel with rice, herbs, chilli peppers, fish, or other ingredients added. In India, these tender palm shoots are processed before consumption by traditional baking in clay pot, boiling in hot water and steam boiling. Keeping in view the importance of tender palm shoots, the study was to determine the effect of drying air temperature on drying time of different pre-treated tender palm shoots, to determine a suitable thin-layer drying model for describing the drying process, and to calculate the effective moisture diffusivity and activation energy for different pre-treated tender palm shoots.

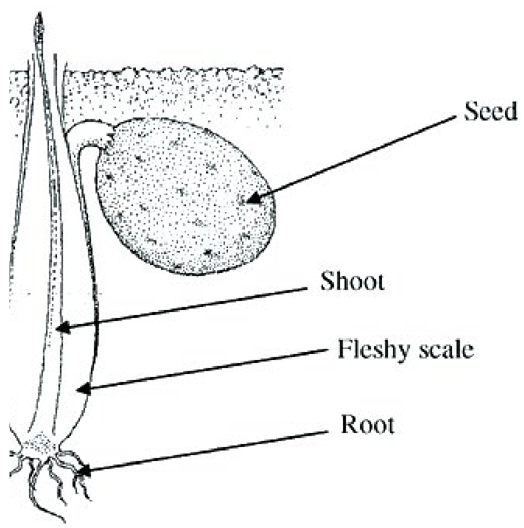

Fig. 1: Germinating palmyrah seed (Naguleswaran *et al.* 2010)

Materials and Methods

Experimental material and drying procedure

Fresh tender palm shoots (*Borassus flabellifer L.)* were collected from local farmers Bapatla, Guntur district, Andhra Pradesh, India. They were washed thoroughly with cold water to remove soil adhering to the shoots. Cleaned palm shoots were pre-treated namely baking, steam boiling and water boiling. In baking process, cleaned palm shoots were kept in clay pot then, the clay pot was exposed to open fire uniformly throughout the pot until palm shoots get cooked completely, for steam boiling process cleaned palm shoots were cooked with steam in autoclave and in boiling process palm shoots were boiled in hot water until they reached their boiling stage.

After these pre-treatments palm shoots were sliced up to 5±1 mm thickness with stainless steel knife. These sliced samples (raw, baked, steam boil and water boil) were kept in a tray dryer for drying at a temperature of 50°C, 60°C and 70°C. Moisture loss was recorded at every 60 min interval. The drying was continued until two consecutive moisture readings were obtained. Moisture content of these pre-treated samples was measured by oven drying method (AOAC, 2000).

Mathematical modelling

In thin-layer drying, the moisture ratio during drying was calculated as follows:

$$\text{MR} = \frac{M - M_e}{M_0 - M_e} \tag{1}$$

Where MR is the dimensionless moisture ratio, M the moisture content (% d.b) at time t, and M_o and M_e the initial and equilibrium moisture contents, respectively, on dry weight basis. The experimental tender palm shoot drying data at three different temperatures were fitted using ten thin layer drying models listed in Table 1. The non linear regression analysis in the present study was performed using the software Origin 8.5 Statistical parameters such as the correlation coefficient (R^2), the reduced chi-square (χ^2) and the root mean square error (RMSE) were used to assess the goodness of the fitting. The best fit was that which resulted in higher R^2 and the lowest reduced chi-square (χ^2) and RMSE (Duc *et al.* 2011, Janjaia *et al.* 2011, Radhika *et al.* 2011, Shen *et al.* 2011). The reduced chi-square (χ^2) and RMSE were evaluated as:

$$\chi^2 = \sum_{i=1}^{n} \frac{\left(MR_{\exp,i} - MR_{pre,x}\right)^2}{N - z} \tag{2}$$

Table 1: Mathematical models applied to drying curves

Model	Equation	References
Newton	MR = exp (-kt)	Ayensu (1997)
Modified Page	MR = exp $(-kt)^n$	White *et al*. (1981)
Henderson and Pabis	MR = a exp (-kt)	Kashaninejad *et al.* (2007)
Modified Henderson and Pabis	MR = a exp(-kt) + b exp(-gt) + c exp(-ht)	Yaldiz and Ertekin (2001)
Logarithmic	MR = a exp(-kt) + c	Togrul and Pehlivan (2002)
Two term	MR = a exp $(-k_o t)$ + b exp $(-k_i t)$	Wang *et al.* (2007)
Two term exponential	MR = a exp (-kt) + (1-a) exp (-kat)	Sacilik *et al.* (2006)
Verma *et al.*	MR = a exp (-kt) + (1-a) exp (-gt)	Vega-Galvez *et al*. (2008)
Wang and Singh	MR = 1 + at + bt^2	Wang and Singh (1978)
Midilli *et al.*	MR = a exp (-kt) + bt	Karaaslan *et al*. (2013)

$$\text{Reduced chi-square } (\chi^2) = \frac{\chi^2}{D.F} \quad (3)$$

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{n}\left(MR_{pre,n} - MR_{\exp,n}\right)^2\right]^{1/2} \quad (4)$$

Where, $MR_{exp,}$ i is the i^{th} experimentally observed moisture ratio, $MR_{pre,}$ i is the i^{th} predicted moisture ratio, N is the number of observations and Z, the number of constants in models.

Results and Discussion

Drying characteristics

The initial moisture content (% d.b) of water boiled, baked, raw, steam boil sample was 129.4%, 104.1%, 112.3%, and 124.2% respectively on dry basis. These ware compared with moisture contents obtained by Bradbury and Holloway (1998) method. The kinetics of water uptake, however, was different for boiling and steam-cooking. Boiling and steam-cooking had a very rapid water-uptake (Food and Agriculture Organization of the United Nations), whereas in the baked sample loss of moisture took place**.**

Effects of drying air temperature on drying time of different pre-treated samples were determine (Fig. 2 to Fig. 5). It was observed that with increase in temperature the drying rates of samples increased therefore, decreasing the drying time. Drying time for all pre-treated samples was 540, 480, 420 min at different drying temperatures of 50°C, 60°C and 70°C, respectively. It is observed that there was no constant rate drying period for all the pre-treated samples, where as the drying takes place in falling rate period for all the pre-treated samples. In all samples, drying was carried out until two consecutive constant moisture contents were obtained. After drying, the moisture content of water boiled sample was more as compared to remaining at all the drying temperatures, followed by steam boil, baked, and raw sample, respectively. This might be due to the effect of starch gelatinization, structural changes, and water content absorbed during blanching. Higher degree of starch gelatinization might affect the cell structure and increase the internal resistance to moisture movement, which resulted in lower diffusivity (1988). However, drying time for the sample was decreased with increasing drying air temperature.

Evaluation of models

Thin layer drying models namely, Newton, Modified Page, Henderson and Pabis, Modified Henderson and Pabis, Logarithmic, Two term, Two term exponential, Verma *et al.* Wang and Singh and Midilli *et al.* empirical models were fitted to the experimental drying data (Table 1). The mathematical model constants of different pre-treated samples dried at different drying temperatures are listed in Table 2. The values of coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) with estimated parameters for proposed models of different pre-treated samples dried at different drying temperatures are presented in Tables 3-6. The maximum R^2 value (0.999), least RMSE value (0.003) and least reduced- χ^2 value (7.663×10^{-6}) ware found in Verma *et al.* and least R^2 value 0.654, maximum RMSE value 0.219 and maximum reduced- χ^2 value 0.048 ware found in Wang and Singh model. The highest R^2 value and lowest RMSE and χ^2 values were obtained from Verma *et al.* Amongest all the model, Verma *et al.* model explains the best relationship between MR and drying time. Similar results have been obtained by other authors on drying of various fruits and vegetables (Doymaz, 2005[b], Togrul and Pehlivan, 2002). Except Wang and Singh model, almost all models had R^2 value more than 0.970. This indicated that all the models could satisfactorily describe the air drying of different pre-treated tender palm shoot slices.

Table 2: Model constants of different pre-treated tender palm shoots fitted with ten models.

Models		Raw sample			Baked sample			Steam boil sample			Boil sample		
		50°C	60°C	70°C	50°C	60°C	70°C	50°C	60°C	70°C	50°C	60°C	70°C
Newton	K	0.018	0.021	0.034	0.014	0.016	0.022	0.011	0.014	0.018	0.014	0.015	0.016
Modified Page	K	0.136	0.143	0.185	0.120	0.125	0.147	0.106	0.116	0.136	0.120	0.122	0.125
	N	0.136	0.143	0.185	0.120	0.125	0.147	0.106	0.116	0.136	0.120	0.122	0.125
Henderson and Pabis	A	0.997	0.997	0.999	0.981	0.987	0.996	0.955	0.972	0.992	0.983	0.986	0.998
	K	0.018	0.020	0.034	0.014	0.015	0.022	0.011	0.013	0.018	0.014	0.015	0.016
Modified Henderson and Pabis	A	0.740	0.631	0.293	0.575	0.619	0.556	0.571	0.553	0.579	0.622	0.626	0.900
	B	0.185	0.239	0.409	0.268	0.245	0.277	0.269	0.278	0.265	0.244	0.242	0.105
	C	0.075	0.129	0.299	0.158	0.135	0.167	0.159	0.168	0.155	0.134	0.132	-0.005
	G	0.760	0.760	0.760	0.760	0.760	0.760	0.760	0.760	0.760	0.760	0.760	0.760
	H	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800
	K	0.014	0.014	0.015	0.008	0.010	0.014	0.006	0.008	0.012	0.009	0.010	0.014
Logarithamic	A	0.982	0.983	0.988	0.958	0.967	0.982	0.929	0.945	0.974	0.965	0.966	0.988
	K	0.019	0.022	0.036	0.016	0.017	0.023	0.013	0.016	0.020	0.016	0.016	0.016
	C	0.017	0.015	0.011	0.032	0.027	0.015	0.047	0.040	0.022	0.025	0.026	0.012
Two term	A	0.740	0.632	0.293	0.575	0.619	0.556	0.571	0.553	0.579	0.622	0.626	0.900
	Ko	0.014	0.014	0.015	0.008	0.010	0.014	0.006	0.008	0.012	0.009	0.010	0.014
	B	0.260	0.368	0.707	0.425	0.381	0.444	0.429	0.447	0.421	0.378	0.374	0.100
	Ki	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000
Two term exponential	A	0.416	0.353	0.413	0.296	0.302	0.333	0.261	0.280	0.313	0.284	0.300	0.101
	K	0.032	0.044	0.064	0.037	0.039	0.050	0.033	0.037	0.045	0.039	0.038	0.143
Verma *et al.*	A	0.260	0.369	0.707	0.425	0.381	0.444	0.429	0.447	0.421	0.378	0.374	0.100
	K	9.900	9.900	9.900	9.900	9.900	9.900	9.900	9.900	9.900	9.900	9.900	9.900
	G	0.014	0.014	0.015	0.008	0.010	0.014	0.006	0.008	0.012	0.009	0.010	0.014
Wang and Singh	A	-0.006	-0.007	-0.008	-0.006	-0.007	-0.008	-0.005	-0.006	-0.008	-0.006	-0.007	-0.007
	$b(\times10^{-6})$	8.791	11.042	15.231	7.976	10.014	13.962	7.092	9.218	13.170	8.091	9.829	12.672
Midilli *et al.*	A	0.998	0.997	1.000	0.985	0.990	0.997	0.965	0.978	0.994	0.986	0.989	0.999
	$b(\times10^{-5})$	3.263	2.910	2.416	5.323	5.083	3.175	6.918	6.787	4.611	4.027	4.614	2.698
	K	0.019	0.021	0.034	0.015	0.016	0.022	0.011	0.014	0.019	0.015	0.015	0.016

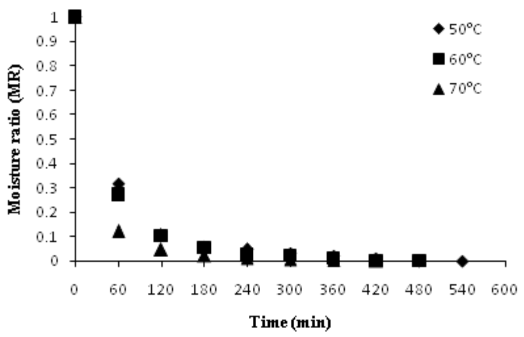

Fig. 2: Effect of drying air temperature on drying time of raw sample

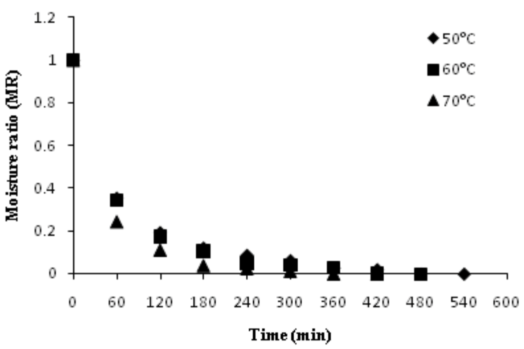

Fig. 3: Effect of drying air temperature on drying time of baked sample

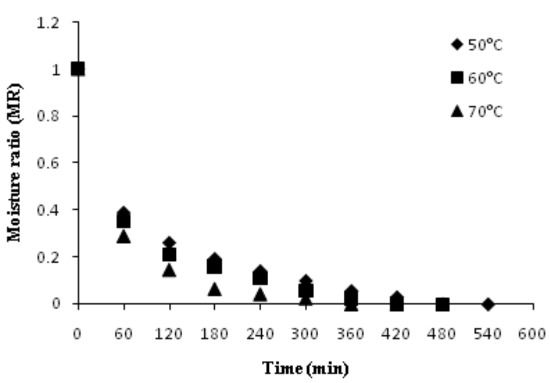

Fig. 4: Effect of drying air temperature on drying time of steam boil sample.

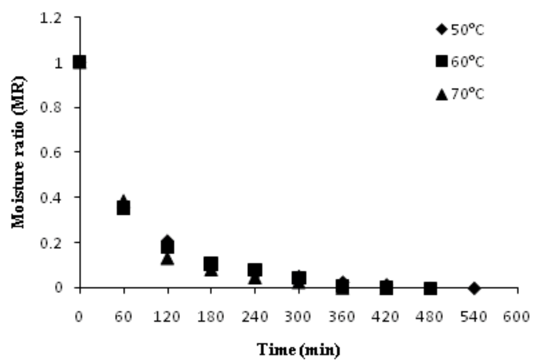

Fig. 5: Effect of drying air temperature on drying time of boil sample.

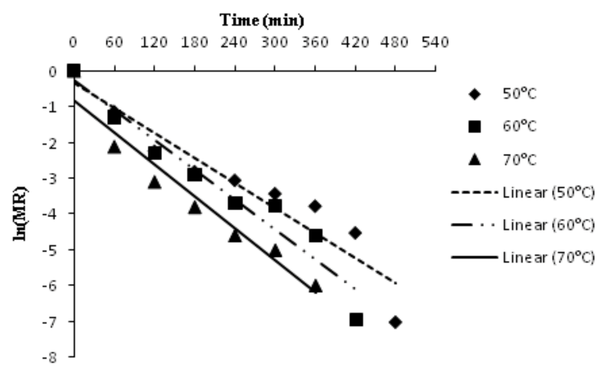

Fig. 6: Plot between logarithm of moisture ratio and drying time for raw sample.

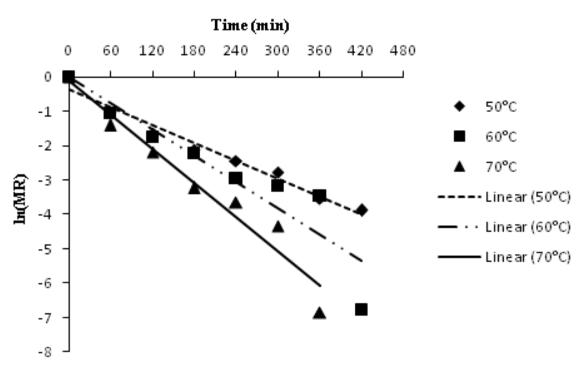

Fig. 7: Plot between logarithm of moisture ratio and drying time for baked sample

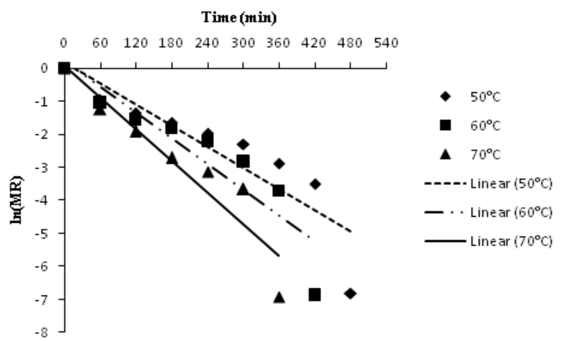

Fig. 8: Plot between logarithm of moisture ratio and drying time for steam boil sample

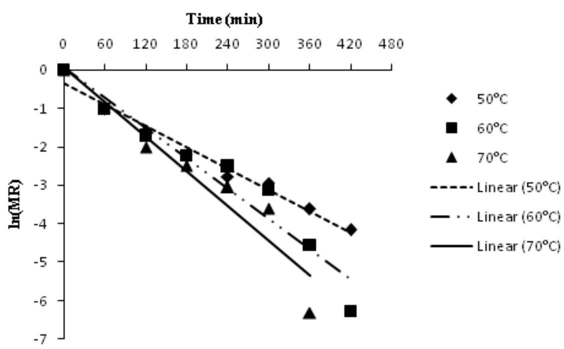

Fig. 9: Plot between logarithm of moisture ratio and drying time for boil sample

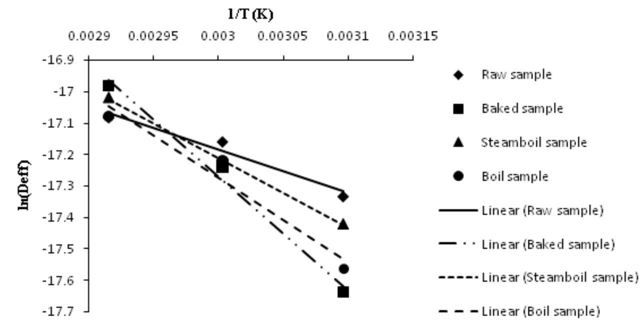

Fig. 10: Effect of air temperature on effective diffusivity of different pre-treated samples

Calculation of Effective diffusivity

The drying data in the falling rate period are usually analysed by Fick's second law of diffusion equation. The solution of this equation developed by Crank (1975), and the form of Eqn. (5) can be applicable for slab geometry by assuming uniform initial moisture distribution, constant diffusivity and negligible shrinkage.

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(\frac{-(2n+1)^2\pi^2 D_{aee}t}{4L^2}\right) \quad (5)$$

Table 3: Statistical results obtained with different models for raw sample at different temperatures

Models	R^2			RMSE			Reduced-χ^2 (10^{-4})		
	50°C	60°C	70°C	50°C	60°C	70°C	50°C	60°C	70°C
Newton	0.996	0.997	0.998	0.019	0.017	0.014	3.615	2.988	2.085
Modified page	0.996	0.997	0.998	0.020	0.018	0.016	4.067	3.415	2.432
Henderson and Pabis	0.996	0.997	0.998	0.020	0.018	0.016	4.055	3.398	2.431
Modified Henderson and Pabis	0.997	0.999	1.000	0.024	0.013	0.004	5.551	1.628	0.192
Logarithmic	0.998	0.999	0.999	0.014	0.014	0.012	2.018	2.015	1.556
Two term	0.997	0.999	1.000	0.019	0.010	0.003	3.701	0.977	0.096
Two term exponential	0.998	0.999	0.999	0.015	0.010	0.012	2.301	1.043	1.547
Verma *et al.*	0.997	0.999	1.000	0.018	0.009	0.003	3.172	0.814	0.077
Wang and Singh	0.688	0.726	0.655	0.184	0.182	0.219	337.700	330.500	480.500
Midilli *et al.*	0.997	0.998	0.999	0.018	0.017	0.015	3.147	2.978	2.341

Table 4: Statistical results obtained with different models for baked sample at different temperatures.

Models	R^2			RMSE			Reduced-χ^2($\times 10^{-4}$)		
	50°C	60°C	70°C	50°C	60°C	70°C	50°C	60°C	70°C
Newton	0.984	0.991	0.996	0.038	0.031	0.021	14.800	9.535	4.470
Modified page	0.984	0.991	0.996	0.041	0.033	0.023	16.700	10.900	5.215
Henderson and Pabis	0.985	0.991	0.996	0.040	0.033	0.023	16.200	10.700	5.188
Modified Henderson and Pabis	0.999	0.999	1.000	0.015	0.015	0.008	2.255	2.153	0.649
Logarithmic	0.991	0.995	0.997	0.033	0.027	0.020	11.100	7.292	4.177
Two term	0.999	0.999	1.000	0.012	0.011	0.006	1.504	1.292	0.324
Two term exponential	0.994	0.997	0.999	0.026	0.019	0.013	6.762	3.532	1.730
Verma *et al.*	0.999	0.999	1.000	0.011	0.010	0.005	1.289	1.076	0.260
Wang and Singh	0.750	0.795	0.778	0.162	0.155	0.174	262.800	241.000	302.600
Midilli *et al.*	0.988	0.993	0.997	0.039	0.031	0.023	14.800	9.643	5.273

Table 5: Statistical results obtained with different models for steam boil sample at different temperatures

Models	R^2			RMSE			Reduced-χ^2($\times 10^{-4}$)		
	50°C	60°C	70°C	50°C	60°C	70°C	50°C	60°C	70°C
Newton	0.963	0.974	0.993	0.058	0.051	0.028	33.300	26.200	7.704
Modified page	0.963	0.974	0.993	0.061	0.055	0.030	37.400	29.900	8.988
Henderson and Pabis	0.966	0.975	0.993	0.059	0.054	0.030	34.900	28.800	8.888
Modified Henderson and Pabis	0.998	0.998	1.000	0.021	0.024	0.011	4.303	5.666	1.208
Logarithmic	0.975	0.982	0.996	0.054	0.049	0.026	28.700	23.800	6.842
Two term	0.998	0.998	1.000	0.017	0.018	0.008	2.869	3.400	6.042
Two term exponential	0.983	0.988	0.998	0.042	0.038	0.017	17.500	14.100	3.020
Verma *et al.*	0.998	0.998	1.000	0.016	0.017	0.007	2.459	2.833	4.834
Wang and Singh	0.787	0.800	0.811	0.148	0.152	0.159	218.300	229.600	25.330
Midilli *et al.*	0.971	0.978	0.995	0.059	0.054	0.030	34.400	29.000	8.731

Table 6: Statistical results obtained with different models for boil sample at different temperatures

Models	R^2			RMSE			Reduced-χ^2(10^{-4})		
	50°C	60°C	70°C	50°C	60°C	70°C	50°C	60°C	70°C
Newton	0.989	0.990	0.998	0.032	0.033	0.016	10.500	10.700	2.654
Modified page	0.989	0.990	0.998	0.034	0.035	0.018	11.900	12.200	3.096
Henderson and Pabis	0.989	0.990	0.998	0.034	0.035	0.018	11.500	11.900	3.088
Modified Henderson and Pabis	1.000	0.999	0.998	0.010	0.018	0.028	0.954	3.173	8.073
Logarithmic	0.993	0.993	0.998	0.030	0.030	0.016	8.868	9.259	2.681
Two term	1.000	0.999	0.998	0.008	0.014	0.020	0.636	1.904	4.036
Two term exponential	0.996	0.997	0.998	0.020	0.020	0.016	3.807	4.120	2.691
Verma *et al.*	1.000	0.999	0.998	0.007	0.013	0.018	0.545	1.586	3.229
Wang and Singh	0.768	0.806	0.869	0.157	0.151	0.134	247.500	229.200	180.100
Midilli *et al.*	0.991	0.992	0.998	0.033	0.034	0.018	11.000	11.600	3.074

Where, D_{eff} is the effective diffusivity (m^2/s), L is the half thickness of the slab in samples (m), and n is positive integer. Eqn. (5) could be further simplified to a straight line equation as:

$$1n(MR) = 1n\left(\frac{8}{\pi^2}\right) - \pi^2 \frac{D_{eff}}{4L^2} t \quad (6)$$

Effective diffusivities are typically determined by plotting experimental drying data in terms of ln (MR) versus time. From Eqn. (6), a plot of ln (MR) versus time gives a straight line with a slope of k_2 was obtained. The effective diffusivity was calculated from the slope:

$$k_2 = \frac{\pi^2 D_{eff}}{4L^2} \quad (7)$$

The plot of ln (MR) versus time for different pre-treated samples have been shown in Fig 6-9, which were are fitted linearly with R^2 value range of 0.81 to 0.98 at different drying temperatures. The determined values of D_{eff} for different pre-treated samples dried at different drying temperatures are shown in Table 7. It can be seen that the D_{eff} values increased with increasing drying temperature. Similar results were obtained earlier (Swamy Gabriela John *et al.* 2014) for banana, (Doymaz, 2004) for carrot, and (Gogus and Maskan, 1999) for okra.

Table 7: Effective diffusivity of different pre-treated samples at different drying temperatures

	Effective diffusivity (D_{eff}) m^2/s			
Temperature	Raw sample	Baked sample	Steam boil sample	Boil sample
50°C	2.97×10^{-8}	2.19×10^{-8}	2.71×10^{-8}	2.36×10^{-8}
60°C	3.52×10^{-8}	3.25×10^{-8}	3.30×10^{-8}	3.32×10^{-8}
70°C	3.80×10^{-8}	4.21×10^{-8}	4.06×10^{-8}	3.83×10^{-8}

Calculation of activation energy

In order to obtain the influence of temperature on the effective diffusivity ($D_{eff)}$, the values of ln (D_{eff}) versus 1/T are plotted for different pre-treated samples as shown in Fig. 10 which is found to be a straight line. The dependence of D_{eff} can be described by Arrhenius type of relationship (Doymaz, 2007, Simal *et al.* 1996) as given by the equation:

$$D_{eff} = D_o \exp\left(-\frac{E_a}{R(T+273.15)}\right) \quad (8)$$

where D_o is the pre-exponential factor of Arrhenius equation (m^2/s), E_a is the activation energy (kJ/mol), T is the temperature of drying air (°C) and R is the gas constant (kJ/mol K).

The activation energy (E_a) was calculated from the slope of the plot on ln (D_{eff}) versus 1/(T + 273.15). The activation energy of different samples is shown in Table 8. The activation energy for baked sample was more as compared to the remaining samples followed by boil sample, steam boil sample and raw sample. These values however are lower than the activation energy reported for okra (51.26 kJ/mol) (Doymaz, 2005[a]), carrot (28.36 kJ/mol) (Doymaz, 2004), potato (20 kJ/mol) (Bon *et al.* 1997), banana (50.06 kJ/mol) (Swamy Gabriela John *et al.*, 2014).

Table 8: Activation energy of different pre-treated samples

Sample	Activation energy (kJ/mol)
Raw sample	11.4816
Baked sample	30.2131
Steamboil sample	18.5153
Boil sample	22.4062

Conclusion

Drying kinetics of different pre-treated tender palm shoots slices were investigated in a laboratory tray dryer at different temperatures of 50°C, 60°C and 70°C. Drying of tender palm shoots took place in the falling rate period like most food products. All the mathematical models gave the best fitting results except for Wang and Singh model. The Verma *et al.* model gave higher R^2 value and lower χ^2 and RMSE values among all models. Verma *et al.* model considered the best for explaining the relation between MR and drying time of tender palm shoot slices. The values of calculated diffusivity of different pre-treated samples varied from 2.19×10^{-8} to 4.21×10^{-8} m^2/s over drying temperature range. The effective diffusivity increased with increasing temperature. The activation energy for baked sample was however more among all pre-treated samples (30.2131kJ/mol).

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