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Thin layer drying of millet and effect of temperature on drying characteristics

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Abstract: Thin layer drying characteristics of two varieties of millet EX-BORNO and SOSAT C88 at air temperatures of 40, 50, 60 and 70oC was investigated. The drying data were applied to five moisture ratio models, namely, exponential, Henderson and Pabis, page, modified page and Logarithmic. The models performance was evaluated by comparing the coefficient of determination (r^2) and root mean square error (RMSE) relating the experimental and predicted moisture ratios through nonlinear regression analysis. The main factor controlling the drying rate was temperature and falling rate period characterised the entire drying process. The r^2 and RMSE vary between 0.969 - 0.997, 0.961 - 0.993 and 0.021 - 0.064, 0.024 - 0.0535 for SOSAT C88 and EX-BORNO respectively for the five models. The modified Page and Page drying models satisfactorily describe the drying behaviour with highest R^2 and lowest RMSE and gave best fitting curves. The effective moisture diffusivity ranged between 2.86 x 10^{-9} - 5.72 x 10^{-9}m2/s and 1.17 x 10^{-9} - 2.98 x 10^{-9} while the activation energy values were respectively 36.19 and 43.94 kJ/mol for SOSAT C88 and EX-BORNO varieties respectively showing that EX-BORNO requires more energy to trigger the diffusion process.

Keywords: thin layer drying, millet, SOSAT-C88, ex-BORNO

Introduction

Drying is one of the oldest and most widely used methods of food preservation. It is an important unit operation in the food processing industry. The basic objective in drying agricultural products is the removal of water in the solid up to a certain level at which microbial spoilage, deterioration and chemical reactions are greatly minimized (Krokida and Marinos-Kouris, 2003). When a wet solid is subjected to thermal drying, two processes occur simultaneously; transfer of energy (most as heat) from the surrounding environment to evaporate the surface moisture and transfer of internal moisture to the surface of the solid and its subsequent evaporation due to the first process (Sahin and Dincer, 2005).

Pearl millet (*Pennisetum glaucum*) is ranked the most important cereal in the Southern Sudan and Northern Guinea regions of Africa and has a lot of uses both for traditional food preparations for majority of people of Africa (Nkama, 1998) and in such industrial applications as starch production. Millet serves as the all-year-round food for very low income peasant farmers in the savanna region of the western and northern Africa. The crop when harvested is stored in rhombus and prepared in different forms with additions of condiments and seasonings to obtain varieties for the three square meals. These include food in the form of porridge produced from flour called *tuwo* as lunch, refreshing drink *kunu* and *fura* for tea time, dessert *dan-wake* and palp, *ogi*, *koko* or *akamu* for breakfast and dinner. For all these, drying plays a key role in their processing. The grain may also be cooked, baked or fermented in various ways as nutritious food and the remaining parts can be used for animal feed, building material and fuel.

The traditional open air-sun drying technique commonly employed in the tropics for this crop and other fruits and vegetables has some disadvantages which includes the slow speed of the process, contamination from exposure to environmental conditions and the hard labour requirement (Doymaz, 2005). Furthermore, direct exposure to solar radiation results in undesirable colour changes, lowering quality of the dried products significantly. Therefore, the use of solar and hot air dryers, which are far more rapid and which provide uniformity and hygiene for industrial food drying processes become inevitable (Karathanos and Bellesiotis, 1997; Doymaz and Pala, 2002).

Drying as one layer of sample particles or slices is referred to as thin layer drying. There have been many studies on thin layer drying of grains (Misra and Brooker, 1980; Tagawa *et al.,* 1996), apple (Sun and Woods, 1994; Akpinar *et al.,* 2003), leaves and grasses (Gunhan *et al.,* 2005), fruits (Doymaz, 2004a; Karim and Hawlader, 2005), vegetables (Doymaz, 2004b; Doymaz, 2005; Tunde-Akintunde *et al.,* 2005; Akanbi *et al.,* 2006). Thin layer drying process of food products has been described by many mathematical models, which fall into three categories, namely

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theoretical, semi-theoretical and empirical (Midilli *et al.,* 2002; Panchariya *et al.,* 2002). Among semi theoretical thin layer drying models, the exponential (Newton) model, Page model, the modified Page model (I and II), the Hendersen and Pabis model, the Thomson model and the Wang and Singh model are the frequently used (Akpinar and Bicer, 2006).

There appears to be little information in the literature on the drying characteristics of millet and the combined effect of temperature and variety. To properly model and improve the efficiency of the drying process of this crop and improve the efficiency of the drying systems, there is the need to study the drying characteristics with a view to providing useful information which will enhance the drying process. This study therefore investigates the thin layer drying characteristics of millet in a convective dryer and fits the experimental data to five mathematical models.

Materials and Methods

Sample preparation

Two millet varieties (SOSAT C88 and EX-BORNO) grown in the Lake Chad Research Institute, Borno State, Nigeria were used in this study. Millet samples were soaked in water, decanted to remove dirts, chaff and other foreign materials. They were then conditioned to initial moisture contents of between 31.5 - 31.7% (w.b) and 22.5 - 23.0% (w.b.) for SOSAT C88 and EX-BORNO varieties respectively. This was achieved using the method of Ezeike (1986) by soaking the millet and castor seeds in water for a period of 16 - 18hours, the seeds were then spread out in thin layer to dry in natural air for about four hours. They were then sealed in polyethylene bags and stored in that condition for a further twenty four hours. This allowed the achievement of a stable and uniform moisture content of the bulk seeds. Moisture content of this crop was determined by placing samples of known weight (using a top loading compact digital weighing balance EK-H6000i, A and D Company Ltd, Japan) in a vacuum oven at 130°C for 16 - 18hrs using the ASAE standards, ASAE S352.1 (ASAE, 1983) and the weights noted at intervals until a constant weight was obtained. The procedure employed by Syraief *et al.* (1984) and Ajibola (1989) for thin layer drying experiments of sunflower and melon seeds was adopted with modifications to suit the laboratory and experimental conditions.

The drying system

A laboratory model tray dryer fitted with a temperature control system, designed and fabricated at the Department of Agricultural and Environmental Engineering, University of Ibadan, Ibadan, Nigeria was used for the experiments. It consists of a 0.374kW axial flow fan blowing air at a rate of 0.238m^3/s over a heating element into a drying chamber with perforated trays arranged vertically and placed horizontally in the plenum chamber. The entire dryer casing is lagged, thus enclosing the functional units. A door is provided in front of the drying chamber for loading and unloading the sample tray.

Drying studies were carried out at drying air temperatures of 40, 50, 60 and 70°C. Triplicate samples of millet grains of known weight in thin-layer, were used for each drying experiment and the drying process was monitored by weighing the samples every 10 mins for the first one hour; then every 30 mins for the next three hours and every 1hr for the next three hours till the end of drying. The time intervals were chosen based on outcome of preliminary investigations. Weighing continued until constant weights were obtained being the period that equilibrium with environment was assumed to have been reached and the test was terminated. Moisture content determined at this point is the dynamic equilibrium moisture content. With the initial moisture already known, weight loss was used to calculate the moisture content using the equation of Silayo (1995) and Kajuna *et al*. (2001) given as:

$$M_t = \frac{M_i m_i - w_i}{m_i - w_i}$$

where, M_t is the moisture content (m.c.) at time t, (% w.b.), M_i the initial m.c. (%w.b), m_i the initial weight, (g) and w_i is the weight loss at time, t (g). The moisture content was converted to moisture ratio (MR) using the non-exponential part of the thin-layer equations being considered. The moisture content obtained at different drying air temperature were converted to moisture ratio (MR) using

$$MR = \frac{M - M_e}{M_o - M_e}$$

where, MR is the moisture ratio, M_o the initial moisture content (% db), M_e the equilibrium moisture content (% db), M the moisture content at time t (% db), t the drying time (hr), k and N are drying constants. The drying curve for each experiment was obtained by plotting the dimensionless moisture ratio of the sample against the drying time.

Mathematical modelling of the drying process

Moisture ratio data obtained from the drying experiment were fitted to five of the most commonly used thin layer drying models (Table 1) using the non-linear regression procedure in SPSS for Windows 14.0 released in 2005. In order to estimate and select the appropriate drying model between five of the commonly used thin layer drying models for grains and legumes were tested the fit was statistically determined by fitting experimental data to the model equation.

Table 1. Mathematical models used for drying characteristics

Model	Equation
Exponential (Newton)	MR = exp(-kt)
Henderson and Pabis	MR = a.exp(-kt)
Page	MR = exp(-kt^n)
Modified Page	MR = exp[-(kt)^n]
Logarithmic	MR = a. exp(-kt)+c

Source: Akpinar and Bicer (2006)

The initial parameter estimates were obtained by linearization of the models through logarithmic transformation and application of linear regression analysis. The least-squares estimates or coefficients of the terms were used as initial parameter estimates in the non-linear regression procedure. Model parameters were estimated by taking the moisture ratio (MR) to be the dependent variable.

The Coefficient of determination (r^2) and Root Mean Square Error (RMSE) were used as criteria for adequacy of fit. The best model describing the thin layer drying characteristics of millet samples was chosen as the one with the highest r^2 and the least RMSE (Ozdemir and Devres, 1999; Doymaz *et al*., 2004; Ertekin and Yaldiz, 2004).The RMSE was calculated using

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

where subscript *pre* and *exp* indicate predicted and experimental.

The experimental drying data for the determination of effective diffusivity coefficient (D_{eff}) were interpreted using Fick's second law for spherical bodies according to Geankoplis (1983) and Doymaz (2004a). This is because the shape of the seeds are closer to being spherical than the commonly used flat object (slab assumption). The diffusivity coefficient (D_{eff}) was obtained from the equation for spherical bodies and the moisture diffusivity coefficient (D_{eff}) was calculated at different temperatures using Equation 4 as the slope derived from the linear regression of *ln*(MR) against time data.

$$MR = \frac{6}{\pi^2}\exp\left(\frac{-\pi^2 D_{eff}}{R^2}t\right)$$

The effective radius (R) was calculated using the equation given by Aseogwu *et al*. (2006). The activation energy is a measure of the temperature sensitivity of D_{eff} and it is the energy needed to initiate the moisture diffusion within the seed. It was obtained by linearising Equation (5) and *ln*D_{eff} was plotted against $\left(-\frac{1}{R_g(T+273.15)}\right)$

$$D_{eff} = D_o e^{-\frac{Ea}{R_g(T+273.15)}}$$

Where, D_{eff} is the effective diffusivity coefficient m^2/s, D_o is the maximum diffusion coefficient (at infinite temperature), E_a is the activation energy for diffusion (J/mol), T is the temperature (^{o}C) and R_g is the gas constant.

Results and Discussion

Drying curves

The drying curves showing the variation of moisture content with drying time at different temperatures are as presented in Figures 1 and 2 for SOSAT C88 and EX-BORNO millet varieties, respectively. Within the temperature range used, the time to reach the dynamic equilibrium moisture in both varieties reduced with increasing temperature. Also, the higher the drying rate, described as the amount of water removed per time (Doymaz, 2005) the shorter the time taken to dry the product. This drying rate is higher at higher temperatures as evident by the steeper slopes in both varieties (Figures 1 and 2). The slopes became steeper with temperature indicating increasing drying rate. In all the cases, at the beginning of the drying process, drying rate was higher, but decreased continuously with decreasing moisture content as the drying time progresses.

There was no marked constant rate phase as drying in both varieties seems to start and proceed in the falling rate phase. The result suggests that diffusion is the most likely physical mechanism governing the moisture movement in millet and do agree with some past studies on drying of various food products especially grains and legumes the category to which millet belongs (Sun and Woods, 1994; Doymaz, 2005). In addition millets on maturity are hard and have low moisture content hence they are harvested at low moisture content implying very low or no surface and/or capillary water which are responsible for constant rate drying. This is unlike the fruits and vegetables with existence of two drying rate periods namely the constant rate period and the falling rate period as shown by Tunde-Akintunde *et al.* (2005) in artificial drying of bell pepper.

The drying rate at the beginning of the process was generally lower at 40°C with a marked difference between it and the other temperatures. This is because of the nature of millet as stated above i.e. the hard nature requires that the millet be heated to a level before the heat transfer will reach the core water and trigger the diffusion process. At this low temperature the rate of heat transfer is slower compared to others hence the wide gap in the curve of 40°C and the other three temperatures investigated. The paired t-test analysis of the moisture variation during drying showed that there were significant differences ($p<0.05$) between the variation at 40°C and the other temperatures and at 50°C and 60°C and other temperatures within varieties. Cross analysis between varieties also showed that there were significant differences ($p<0.05$) between SOSAT and EX-BORNO at 40 - 60°C while there was no significant difference ($p<0.05$) in the variation at 70°C between the two varieties. This is evident in the plots in Figures 1 and 2 showing similar pattern of drying and attainment of low moisture content below 8% within 150 minutes at this high temperature. This is an indication that higher temperature may be the appropriate for the drying of millet.

The drying data obtained in the experiments were converted to dimensionless moisture ratio (MR) and then plotted against time. Figures 3 and 4 show the variation of moisture ratio with drying time at different temperatures for SOSAT C88 and EX-BORNO respectively. It can be observed from Figures 3 and 4 that moisture ratio decreased exponentially with time. The difference between moisture ratios increased gradually at the commencement of drying and the time required to reach equilibrium moisture content decreases with increasing temperature. Thus, the effect of temperature on drying rate has been established for millet. Similar results were reported by Ozdemir and Derves (1999).

Model fitting

The model constants and the coefficients from the results of statistical analyses undertaken by regression on the five models listed in Table 1 are given in Tables 2 and 3 for 40°C. Moisture ratio data obtained from the drying experiment were fitted to the five thin layer drying models using the non-linear regression procedure in SPSS for Windows 14.0 released in 2005. In order to estimate and select the appropriate drying model between the five models tested, parameters of thin layer drying models were statistically determined by fitting experimental data to the models equations.

The average value of coefficient of determination (r^2) and RMSE values of the five models at 40-70°C are as presented in Tables 4 and 5. The r^2 and RMSE vary between 0.969 - 0.997, 0.961 - 0.993 and 0.021 - 0.064, 0.024 - 0.0535 for SOSAT C88 and EX-BORNO, respectively. It is assumed that the model which has the highest r^2 and lowest RMSE is the best-suited one. Consequently, the best fits were obtained for the drying with modified Page and Page models with the highest r^2 and least RMSE at all the temperatures. This shows that in line with the reports of the works of Yaldiz and Ertekin (2001), SOSAT-C88 and EX-BORNO millet varieties drying behaviours are better predicted by the modified Page and Page models from the five models investigated.

The Page model is an empirical modification and a special case of Henderson and Pabis that has corrected its shortcomings. It has been used to test the experimental data of grains and leguminous crops such as berries, soybean, white bean, green bean and corn (Yaldiz and Ertekin, 2001; Aghbashlo *et al*., 2009). Its use as an immediate check is therefore appropriate. Empirical models derive a direct relationship between average moisture content and drying time. They neglect fundamentals of the drying process and their parameters have no physical meaning. Therefore, they cannot give clear accurate view of the important processes occurring during drying although they may describe the drying curve for the conditions of the experiments (Ozdemir and Devres, 1999).

The best fit was also investigated by plotting the MR against time for the predictive drying models and the experimental data for the lowest and highest temperatures investigated as presented in Figures 5 to 8. A wide variation is observable in the curves for the Henderson and Pabis model and the Exponential models against the experimental data. This shows that these two models are not suitable for the prediction of the drying behaviour of the millet varieties. The statistical fitting reported above is therefore confirmed by these plots which shows the modified Page and Page being the best fit to the experimental curve in that order. The fit was better for all the models at the beginning of drying at higher temperature (70°C, Figures 6 and 8) except for exponential model for EX-BORNO. This indicates that the power index ‘n’ in the equations plays a role in prediction than the constant ‘a’. The findings showing better fit at higher

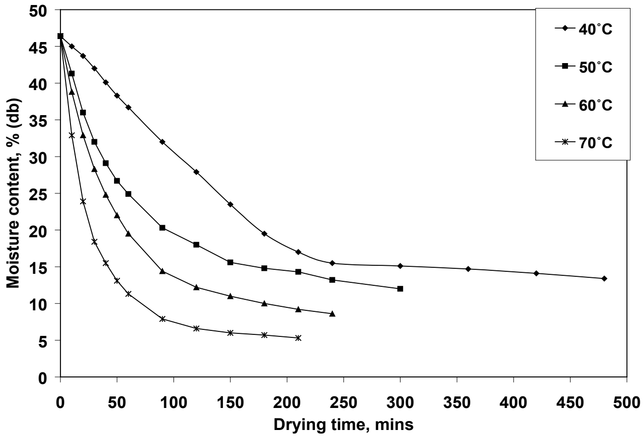

Figure 1. Drying curve for SOSAT-C88 millet

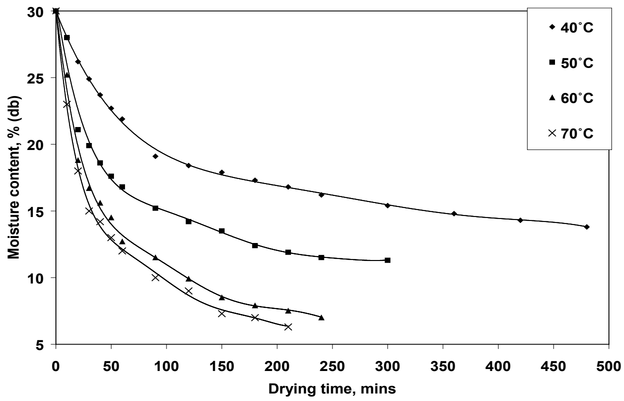

Figure 2. Drying curve for EX-BORNO millet

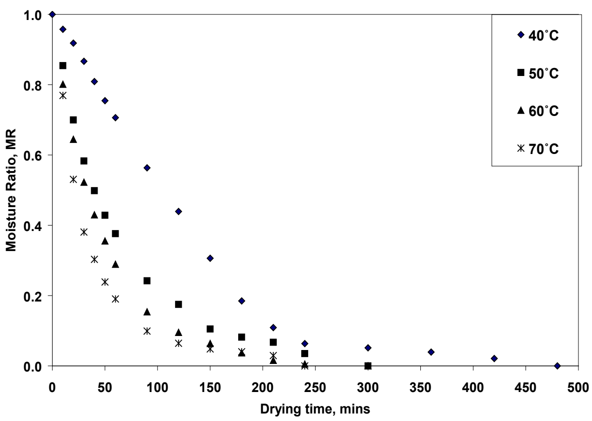

Figure 3. Moisture ratio for SOSAT C88 millet

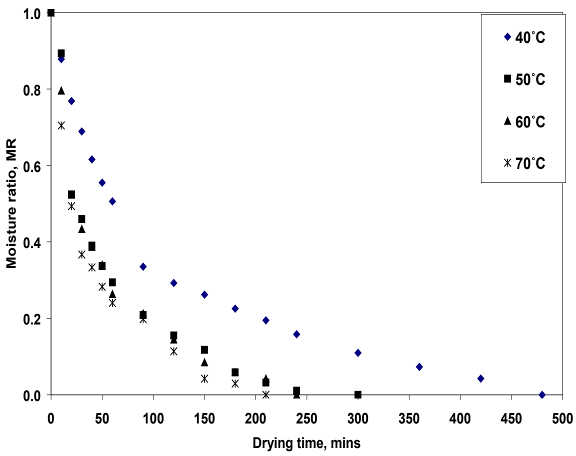

Figure 4. Moisture ratio for EX-BORNO millet

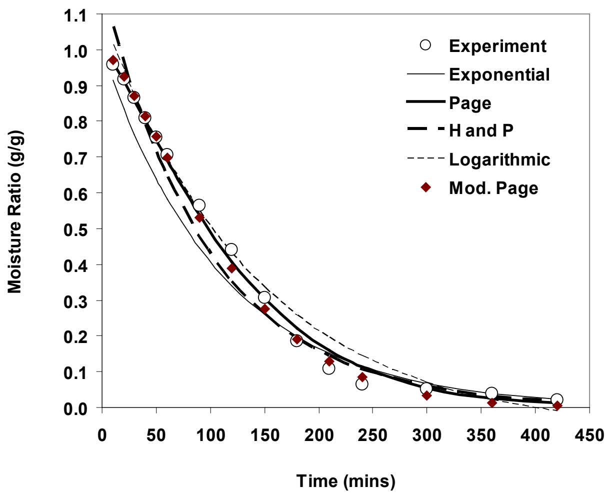

Figure 5. Experimental and predicted moisture ratio for SOSAT C88 at 40°C

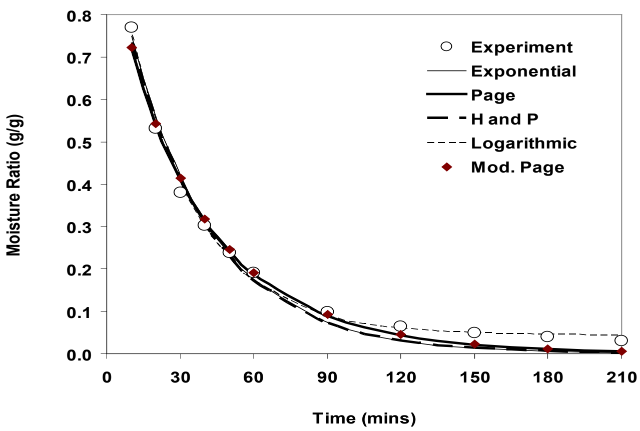

Figure 6. Experimental and predicted moisture ratio for SOSAT C88 at 70°C

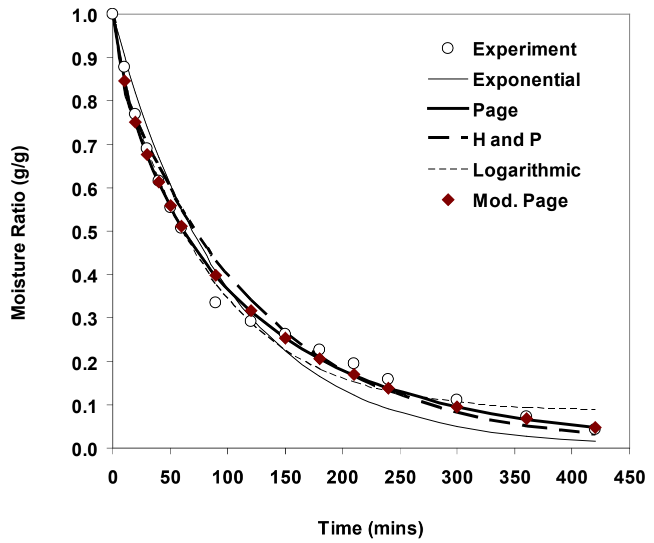

Figure 7. Experimental and predicted moisture ratio for EX-BORNO at 40°C

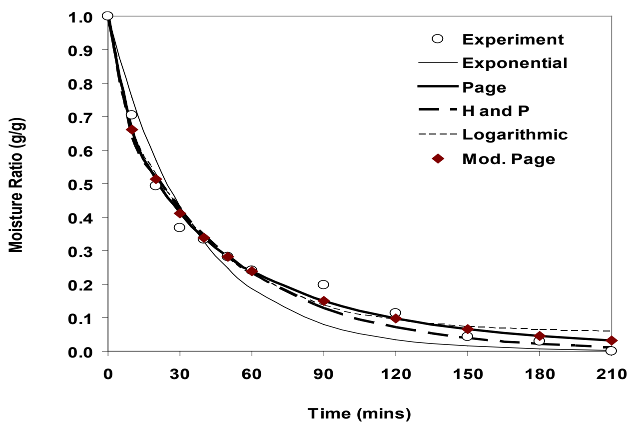

Figure 8. Experimental and predicted moisture ratio for EX-BORNO at 70°C

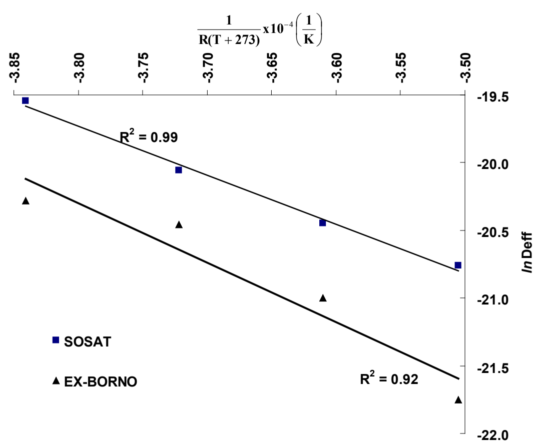

Figure 9. Arrhenius-type relationship between effective diffusivity and temperature.

Table 2. Drying constants and coefficients of the models for SOSAT C88 at 40°C

	Constants and coefficients	Exponential (Newton)	Henderson and Pabis	Page	Modified Page	Logarithmic
Model Constants	k	0.008	0.009	0.001	0.008	0.007
	a	-	1.119	-	-	1.166
	n	-	-	1.392	1.392	-
	c	-	-	-	-	-0.072
	R^2	0.969	0.985	0.996	0.997	0.989
	RMSE	0.064	0.044	0.021	0.021	0.038

Table 3. Drying constants and coefficients of the models EX-BORNO at 40°C

	Constants and coefficients	Exponential (Newton)	Henderson and Pabis	Page	Modified Page	Logarithmic
Model Constants	k	0.010	0.008	0.028	0.010	0.012
	a	-	0.890	-	-	0.865
	n	-	-	0.777	0.777	-
	c	-	-	-	-	0.082
	R^2	0.961	0.979	0.992	0.993	0.990
	RMSE	0.054	0.039	0.024	0.024	0.027

Table 4. Coefficient of determination (r^2) for the thin layer drying models

Drying Air Temp. (°C)	Millet Variety	Model				
		Exponential (Newton)	Henderson and Pabis	Page	Modified Page	Logarithmic
40	SOSAT C88	0.969	0.985	0.996	0.997	0.989
	EX-BORNO	0.961	0.979	0.992	0.993	0.990
50	SOSAT C88	0.993	0.995	0.998	0.998	0.998
	EX-BORNO	0.933	0.937	0.954	0.954	0.952
60	SOSAT C88	0.998	0.999	1.000	1.000	0.999
	EX-BORNO	0.929	0.956	0.977	0.977	0.971
70	SOSAT C88	0.989	0.986	0.989	0.989	0.997
	EX-BORNO	0.902	0.959	0.980	0.980	0.968

Table 5. Root Mean Square Error (RMSE) for the thin layer drying models

Drying Air Temp (°C)	Millet Variety	Model				
		Exponential (Newton)	Henderson and Pabis	Page	Modified Page	Logarithmic
40	SOSAT C88	0.06380	0.04391	0.02070	0.02070	0.03779
	EX-BORNO	0.05345	0.03872	0.02390	0.02390	0.02672
50	SOSAT C88	0.02335	0.01906	0.01348	0.01348	0.01348
	EX-BORNO	0.06605	0.06396	0.05477	0.05477	0.05559
60	SOSAT C88	0.00953	0.00953	0.00059	0.00059	0.00953
	EX-BORNO	0.06082	0.04795	0.03464	0.03464	0.03872
70	SOSAT C88	0.02828	0.02828	0.02449	0.02449	0.01414
	EX-BORNO	0.06497	0.04216	0.02981	0.02981	0.03800

Table 6. Effective Moisture Diffusivity (D_{eff}) and Activation Energy (E_a) during

	Effective Diffusivity (x10^{-9}) m^2/s				Activation Energy (kJ/mol)
Temperature (°C)	**40**	**50**	**60**	**70**	
SOSAT C88 (millet)	2.86	3.75	4.55	5.72	36.19
EX-BORNO (millet)	1.17	2.32	2.71	2.98	43.94

temperature corroborate the result of the analysis reported for the moisture variation. Therefore the Modified and the Page models effectively describe the convective drying of the millet at the temperature range used.

The effective mean radii of millet were 1.29x10^{-3} and 1.68x10^{-3} m for EX-BORNO and SOSAT C88 varieties respectively. The effective moisture diffusivity coefficient, D_{eff}, were in the range of 2.86 x 10^{-9} - 5.72 x $10^{-9}m^2s^{-1}$ and 1.17 x 10^{-9} - 2.98 x 10^{-9} for SOSAT C88 and EX-BORNO millet varieties respectively. This is presented in Table 6. Temperature clearly has a marked effect. Statistical analysis showed a significant difference ($p<0.05$) in the means of the diffusivity between the two varieties.These D_{eff} lie within the general range of 10^{-12} - 10^{-8} reported for food materials (Madamba *et al*., 1996; Babalis and Belessiotis, 2004) and several studies reported similar observations on different crops (Ajibola, 1989; Tagawa *et al*., 1996; Yaldiz and Ertekin, 2001; Doymaz, 2005).

It can be seen that the values of D_{eff} increased with increasing temperature. This could be as a result of the fact that water diffusion was mainly due to mass transport mechanism during the first phase of drying. The core moisture replaces the surface and capillary moisture as they evaporated and eventually vapour diffusion of water became the predominant mechanism. The surface water removal was faster at higher temperature especially at 70°C hence most of the drying mechanism was vapour diffusion. This has been reported in many research works such as Falade and Abbo (2007), Orikasa *et al.* (2008), Singh *et al.* (2008) and Doymaz (2009).

The activation energy was found by a semi-log plot (Figure 9) between effective moisture diffusivity and the inverse of the product of the gas constant and absolute air drying temperature as presented in Equation 5. The plot was found to be essentially a straight line in the range of temperatures investigated indicating Arrhenius dependence.

Activation energy is a measure of the temperature sensitivity of D_{eff} and it is the energy needed to initiate the moisture diffusion within the seed. From the slope of the straight line, the activation energy was found to be respectively 36.19 and 43.94 kJ/mol (SOSAT C88 and EX-BORNO), These are within the general range of 12.7 – 110.0 kJ/mol for most agricultural and food materials as presented by several other reports; 27.61 kJ/mol for corn (Tolaba and Suarez, 1988), Green bean 35.43 -39.47 kJ/mol (Senadeera *et al*., 2003), pistachio nut 30.79 kJ/mol (Kashaninejad *et al*., 2007) and spinach leaves (Doymaz, 2009). The activation energy for EX-BORNO is higher than that of SOSAT C88 which indicates that more energy is needed to trigger the diffusion process and for drying to be accomplished in EX-BORNO.

Conclusions

This study has shown that millet dried in the falling rate period and the moisture loss could be described by the diffusion mechanism. The modified Page model has shown a better fit to the experimental drying data as compared to other models. The effect of the drying temperature on the drying model constants and diffusion coefficients has shown that drying of millet is more appropriate at high temperature. Activation energy was higher for EX-BORNO millet variety.

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