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CONVECTIVE THIN-LAYER DRYING AND REWETTING CHARACTERISTICS OF SESAME SEED

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ABSTRACT

Fundamental information on drying and re-wetting characteristics of agricultural seeds is required in the design and aeration systems as well as in the prediction of drying rate using various mathematical models. Thin-layer drying experiments were conducted using air-ventilated oven to simulate the artificial drying and rewetting processes of sesame seed (6.9 to 18.2% w.b) at three drying temperatures of 40, 50 and 60°C. Five drying models were applied to the thin-layer data. The Page equation fitted the data best after comparing the determination of coefficient (R^2), the standard error of moisture content (SEM) and mean relative percent error (e) between the experimental and predicted values. The drying rate of sesame seed under drying and rewetting conditions increased with increased temperature of drying(40 to 60°C) and initial moisture content of seed(6.9, 11.5 and 18.2% w.b). The parameters K and n of the page model was related to the drying temperature and moisture content by two empirical expressions of Page equation for predicting moisture ratio. The coefficient of determination (R^2) for parameters K and n were 0.95 and 0.87 respectively. The effective diffusivity was found to be 2.32 x 10-11 m^2s^{-1}.

Keywords: Sesame seed, Artificial drying, Thin layer, Modeling, Regression, Rewetting

INTRODUCTION

Sesame seed (***Sesamum orientale*. L**) is one of the agricultural crops of growing interest in Nigeria, that a national workshop was organized on the prospect of exploiting the seed by Raw Material Research and Development Council (RMRDC) in December, 2004 at Abuja. Sesame is known as till, gingerly or simsim elsewhere in the world but its local name in Nigeria is benniseed. The seeds are small, ovate, slightly flattened at the bottom and weighs between 2 – 4g per 1000seeds. It is rich in protein content (19-25%), oil content (44%) and a good source of high quality edible oil (Weiss, 1983). The seed is usually harvested at moisture contents of between 15 -20 % (w.b), this has to be reduced significantly before further processing through drying. Bulk drying or aeration are usually carried out in deep beds, however simulation models used assume series of thin-layer drying for proper dryer design and evaluation. Fundamental information on drying and rewetting characteristics of seed is required for designing near ambient drying and aeration systems; they have been reportedly used in various computer-based deep-bed drying models (Pabis *et al.,* 1998). Mathematical models, which fall into three categories, namely theoretical, semi-theoretical and empirical, have been used to describe thin layer drying process of food products (Midilli *et al.,* 2002; Panchariya *et al.,* 2002). The Exponential (Newton) model, Page model, the modified Page model (I and II), the Henderson and Pabis model, the Thomson model, and the Wang and Singh model are among the most frequently used (Akpinar and Bicer, 2006). There have been several studies on thin layer drying of agricultural grains and leaves (Akpinar *et al.,* 2003; Ajibola, 1989; Sobukola and Dairo, 2007; Sobukola *et al.,* 2007; Karim and Hawlader, 2005; Doymaz, 2004 and 2005). However, there is little information available on the drying and rewetting characteristics of sesame seed. Therefore, the objective of this study was to conduct thin-layer drying and rewetting experiments on sesame seed at different air temperatures and initial moisture contents, and determine a suitable thin-layer drying equation, which fits the data and best describe the drying and rewetting behaviour.

Thin-Layer drying and rewetting equations

Mathematical models that describe drying mechanisms of grain and food can provide the required temperature and moisture information on agricultural crops during the drying process (Parti, 1993). The comprehensive review of these equations is reported in detail by Jayas *et al.,* (1991). Table 1 showed some of the available models used for thin-layer drying. The equations in Table 1 have been used widely in the literature to describe thin-layer drying and rewetting behaviour of grains and oilseeds; they were therefore fitted to the experimental data for sesame. Several researchers have successfully reported the adequate representation of these models to experimental data (Sobukola and Dairo, 2007; Kajuna *et al.,* 2001; Hii *et al.,* 2008; Misra and Brooker, 1980).

Table 1: Thin Layer drying Model Tested for drying and rewetting of Sesame Seed

Model Name	Model Equation*	Equation No
Newton	$MR = \exp^{(-kt)}$	1
Page	$MR = \exp^{(-kt^n)}$	2
Henderson and Pabis	$MR = a\exp^{(-kt)}$	3
Logarithmic	$MR = a\exp^{(-kt)} + c$	4
Midilli-Kucuk	$MR = a\exp^{(-kt^n)} + bt$	5

* Hii et al., (2008)

The drying constants in thin-layer drying equations are usually related to experimental variables and have been severally reported to be dependent on experimental variable conditions (Tabatabaee *et al.,* 2004; Verma *et al.,* 1985).

MATERIAL AND METHODS

Thin-layer drying apparatus

The thin layer drying apparatus consisted of a Gallenkhamp 200v series oven with three separated tray sections ventilated with air at the same temperature and airflow rate. The average air temperature for each tray section was determined by a digital thermometer (Model Pronto Plus, Thermo-Electric Instruments, Saddle Brook, NJ) with a resolution of ± 0.1°C. Dew point temperature was monitored at the air inlet section using a dry and wet bulb thermometer (Model Hygro-M1, General Eastern Instruments Inc., Watertown, MA) with a resolution of ± 0.1°C. The sample trays had 0.24 m × 0.24 m inside dimensions made of 0.02 m thick aluminum frames with wire mesh screen fastened at the base to hold the sesame seeds. The mass of seeds and tray was measured with an electronic balance (Model Mettler PE1600, Mettler Instruments Corporation, Zurich, Switzerland) with a resolution of ± 0.01g.

Sample preparation and drying test procedure

Sesame seed was obtained from the open market in Benue state, Nigeria. The initial moisture content was determined to be 6.9% (w.b). In the case of rewetting, the samples were conditioned to the desired moisture content by adding calculated quantities of distilled water and mixing for several hours according to the method of Tabatabaee *et al.,* (2004). All samples (dried and rewetted) were put and sealed inside a double polythene bags and kept in a refrigerator at about 5°C for 48h. Samples were brought out of the refrigerator for about 12 h before use to allow the samples to properly thaw and equilibrate with environmental conditions.

Sesame seed samples with initial moisture contents (6.9%, 11.5%, and 18.2% w.b) weighing 10g each spread on drying trays in triplicates were placed on shelves in the oven at preset temperatures (40 , 50 and 60). The seed on each tray were uniformly spread over to form a one kernel thick layer. Prior to starting the tests, the oven unit was left running for 2h in order to stabilize the oven air conditions. The mass of the tray with grains was recorded every ten minutes for the first one hour and every 30min thereafter until the mass was within ± 0.01 g between two successive readings. The moisture content at this point was taken as the equilibrium moisture content. The time to reach equilibrium ranged from 3 to 4 h depending on the air conditions. The initial and final moisture contents of the grain were measured using the oven-drying method in which 10 g of the grains of sesame were dried at 130°C for 6h as recommended by Young *et al.,* (1982) for oil seeds with high oil contents. The change of the grain moisture content, with time, was calculated from the mass change data

Data analysis

The experimental drying and rewetting data of sesame seed were fitted to the five equations presented in Table 1 using Non-Regression Analysis of Datafit 9.1 (Datafit Oakland, 2008) and parameters for each equation were determined. The observed and predicted moisture contents were compared and statistically analyzed to determine the best-fit equation. The suitability of the equations was evaluated using the mean relative percent error (e), standard error of moisture content (SEM) and coefficient of determination (R^2). The mean relative percent error (e) was defined as:

$$e = \frac{\sum (M_m - M_p)}{N} \tag{6}$$

where:
M_m = measured moisture content (% w.b.),
M_p = predicted moisture content (% w.b.) and
N = number of observations.
The values of the parameters were back-substituted into the model to predict moisture content at time, t. The best-fit equation was then used to correlate the effects of temperature and initial moisture content over the entire range of thin-layer drying and rewetting data.

RESULTS AND DISCUSSION

The results of the statistical analysis of the models are presented in Table 2. The Page model had the lowest values of e and SEM ranging from 0.20 to 0.3%, and 0.010 to 0.023, respectively, while the R^2 value ranged from 97.8 to 98.8%. These statistical parameters were calculated for all conditions and models. The model that best described the thin layer drying and rewetting characteristics is the one that gives the highest R^2, and lowest SEM and e values (Doymaz *et al.,* 2004; Ertekin and Yaldiz, 2004). Therefore, for further analysis of data, only Page's equation was used. The Page model had been satisfactorily found to adequately describe drying characteristics of various crops (Basunia and Abe, 2005).

Drying parameters of Page's equation

The parameters of the Page's equation were estimated using the regression technique of Datafit 9.1 (Datafit Oakland, 2008). Values of these parameters (K and n) were then related to the various drying and rewetting conditions in form of Eq. 7 and Eq.8.

$$k = Exp(A - B\ln(T) + CM_0 \tag{7}$$

Where T = drying air temperature (°C).
M_0 is the initial moisture content (% w.b)
The R^2 for Eq. (7) was 0.95 with standard error of 0.08

$$n = DM_0 + ET + F \tag{8}$$

The R^2 value for Eq. (8) was 0.87 with a standard error of 0.25. Table 3 shows the estimated parameter values and standard errors obtained from the equations.

Table 2: Non Linear Regression Parameters and Regression Statistics of thin-layer drying and rewetting of sesame seed at 6.9% moisture content

Regression Statistics	Tempera-ture (oC)	Models: Page	Midilli-Kucuk	Logarith-mic	Henderson and Pabis	Newton
Coefficient of Determination (R2)	40	0.988	0.952	0.948	0.932	0.898
Standard Error of Moisture Content (SEM) X 10-2		1.411	2.145	2.538	2.584	3.562
Mean Relative Percent Error (e)		0.00371	0.00451	0.00497	0.00512	0.00752
Coefficient of Determination R2	50	0.985	0.957	0.943	0.942	0.910
Standard Error of Moisture Content (SEM) X 10-2		1.041	2.095	2.125	2.512	3.812
Mean Relative Percent Error (e)		0.00289	0.00389	0.00418	0.00499	0.00798
Coefficient of Determination R2	60	0.975	0.953	0.939	0.941	0.925
Standard Error of Moisture Content (SEM) X 10-2		2.294	2.315	2.411	2.687	4.258
Mean Relative Percent Error (e)		0.00251	0.00411	0.00417	0.00501	0.00801

Table 3: Estimated Coefficients and standard error of parameter K and n of the Page Model

Coefficient	K	Std Error	n	Std Error
A	-18.142	0.972		
B	3.613	0.236		
C	0.080	0.010		
D			-0.0113	0.0012
E			-0.0142	0.0030
F			1.6740	0.0086

Drying Curves

Fig. 1a and b show the typical thin layer drying curves of sesame seed at all drying temperatures studied (40, 50 and 60^{o}C) and initial moisture contents of 18.2 % (w.b) and 6.9% (w.b) respectively using the Page model. The plot showed that the rate of moisture loss decreased as the elapsed time increased (Fig. 1a, b) at both moisture levels until equilibrium was reached. It was observed from the drying curves that there was a fast moisture removal phase during the first few minutes of drying, followed by a reduced moisture removal rate which indicated the falling rate phase. The drying curve showed no constant moisture removal period during drying, implying that there was no marked constant rate phase. These observations are in consonance with reports of khazaei (2008) on the natural drying of sesame seed, and other researchers such as Kashaninejad *et al.,* (2007). The result suggested that diffusion is the most likely physical mechanism governing the moisture movement in sesame seed and this appears to be in agreement with past studies on drying of various food products. At the beginning of drying, free water was available and the rate of drying was controlled by free water on the surface or outer layers of seeds. As the drying time increased, the drying rate decreased lower than the first stage of the drying period, this showed that at this stage, water was no longer free; water in seeds was held by molecular adsorption and capillary condensation. It can, therefore, be considered a diffusion-controlled process, in which the rate of moisture removal is limited by diffusion of moisture from inside to the surface of the product. Previous studies have also showed that drying biological material is a diffusion-controlled process and may be represented by the Fick's law (Tabatabaee *et al.,* 2004; Hii *et al.,* 2008; Sobukola and Dairo, 2007). In addition, the high drying rate found for sesame could be attributed to the small size of the seed. This is in consonance with the findings of Bakker-Arkema *et al.,* (1980) where it was reported that oil seeds with high oil contents exhibit high drying rate.

There was increased drying rate with increased temperature from 40 to 60^{o}C. The drying rate at 40^{o}C was generally lower, with a marked difference between it and the other

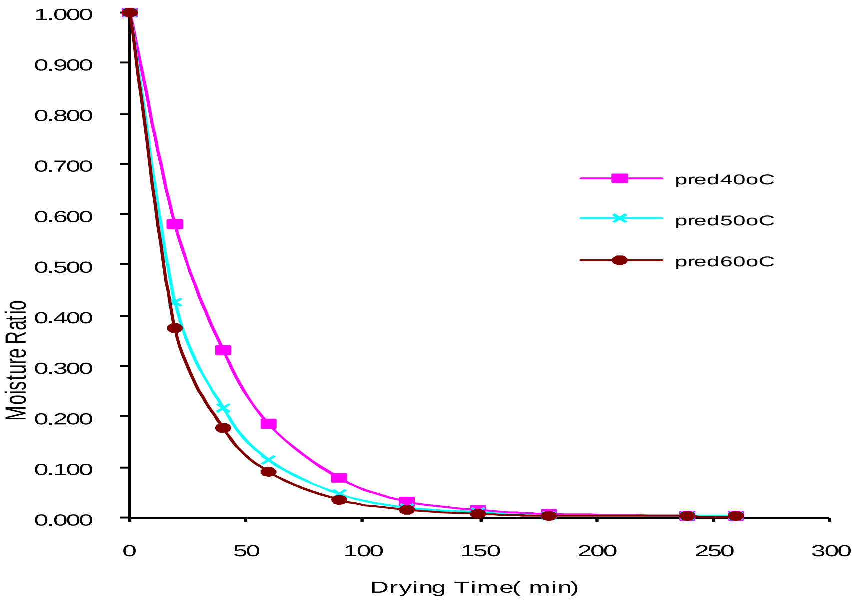

Fig 1a. Drying Curve of Sesame seed at moisture content of 18.2% (w,b) using Page model at drying Temperatures of 40, 50 and 60 ^{0}C.

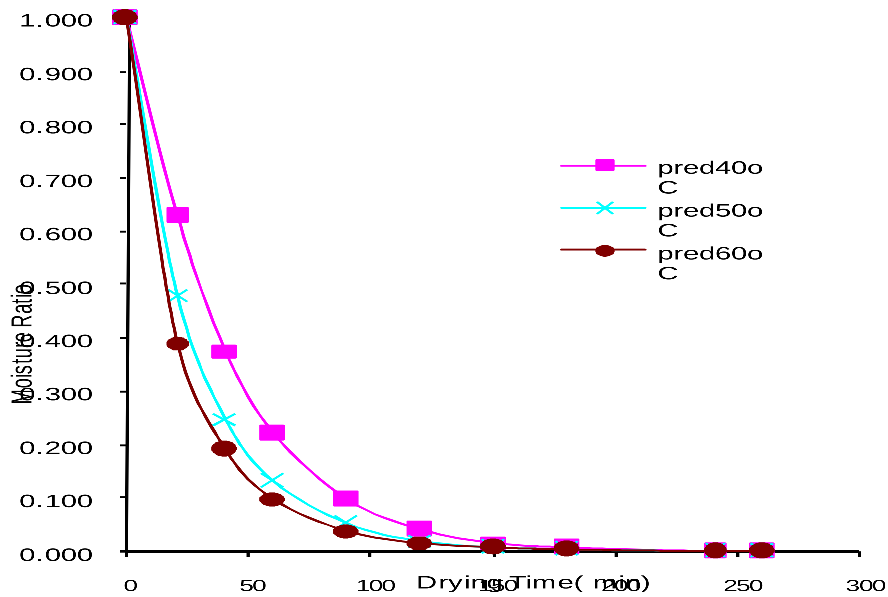

Fig 1b: Drying Curve of Sesame seed at moisture content of 6.9% (w,b) using Page model at drying Temperatures of 40, 50 and 60 ^{0}C.

temperatures. This could probably be explained that the seed required heating 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 might have been slower compared to other temperature levels, hence the wide gap in the curve of 40°C and the other two temperatures investigated. It can be observed from Fig. 1a and 1b that moisture ratio decreased exponentially with time. The difference between moisture ratios increased gradually at the commencement of drying and the time to reach equilibrium moisture content decreases with increased temperature. Thus, the effect of temperature on drying rate can be established for sesame seed in consonance with observations reported by Misra and Brooker (1980) for shelled yellow corn, melon (Ajibola, 1989); diced cassava cubes by Kajuna *et al.,* (2001); fever leaves by Sobukola and Dairo (2007), among other researchers.

Figures 2a and 2b show the drying curves of sesame seed at all moisture content levels (6.9%, 11.5% and 18.2% w.b) using Page model with drying temperatures of 40 and 60°C respectively. The typical effect of initial moisture content on the drying rate at all temperature levels studied is shown in Fig. 2a and 2b. Both figures show that the drying rate increased with increased initial moisture content of seed samples. This observation may be attributed to the availability of more water at the surface for evaporation at high moisture levels resulting to a higher drying rate at the initial stage of drying. At longer drying times less water is available leading to reduced moisture removal rate, where moisture movement is better controlled by diffusions as earlier reported. Similar observations have been made by other researchers.

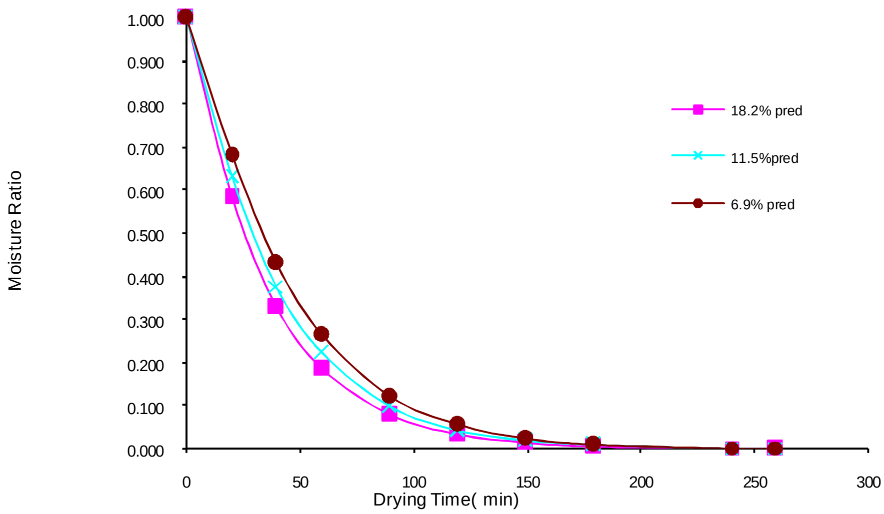

Fig 2a Thin layer drying curve of sesame seed at drying temperature of 40oC using Page model at moisture content of 6.9%, 11.5% and 18.2 % (w.b)..

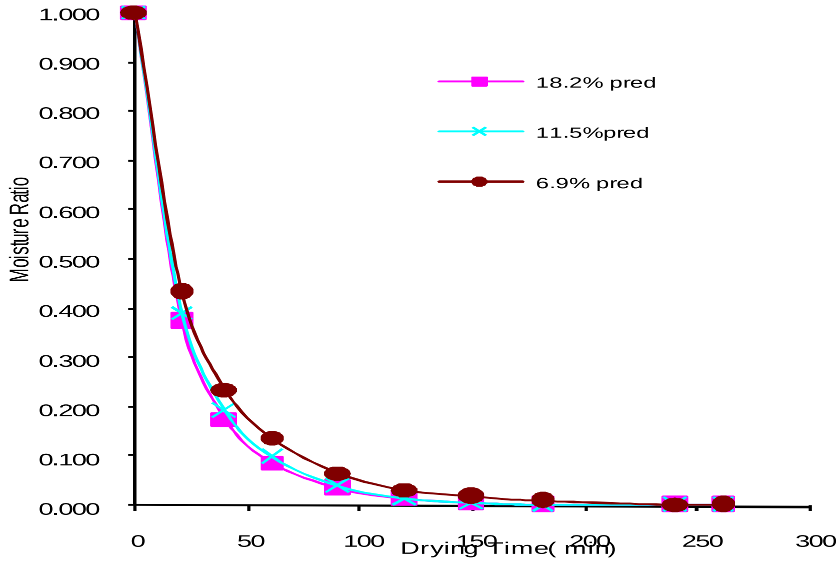

Fig 2b. Thin layer drying curve of sesame seed at drying temperature of 60ºC using Page model at moisture content of 6.9%, 11.5% and 18.2 % (w.b)..

Effective diffusivity determination

With the assumptions of moisture migration being by diffusion with negligible shrinkage and constant diffusion coefficients, the Fick's second law can be used to describe the drying behaviour of agricultural products (Crank, 1975). The analytical solution for long drying periods in logarithmic form, simplified for only the first term is given by Eq. (9) for an infinite flat shaped material.

$$\ln\frac{m_t}{m_o} = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff}\,t}{4H^2} \qquad (9)$$

Drying of many food products, such as wheat (Gaston *et al.*, 2004), chestnuts (Guine and Fernandes, 2006), hull-less seed pumpkin (Sacilik, 2007), and pistachio nuts (Kashaninejad *et al.*, 2007) has been successfully predicted using Fick second law. The diffusivity is the slope of Eq. (9), obtained by plotting experimental data in terms of Ln (MR) versus drying time. The effective diffusivity was found to be 2.32 x 10^{-11} m^2s^{-1}. The value was however lower than the value obtained for forced convectional drying (3.11 X 10^{-11} m^2s^{-1}) and higher than 1.1 X 10^{-11} m^2s^{-1} for natural convective drying of sesame seed obtained by Khazaei and Daneshmandi (2007). The differences might be due to the sphere shape configuration used, this study assumed infinite flat shaped configuration of Fick's Law. However the diffusivity value obtained was within the general range of between 10^{-9} and 10^{-11} for food and agricultural crops (Madamba *et al.*, 1996; Doulia *et al.*, 2000).

CONCLUSION

The effects of temperature and initial moisture content were investigated on drying and rewetting characteristics of sesame. The drying rate increased with increased temperature and moisture content. Five thin layer drying equations were used to assess the goodness-of-fit to the experimental data. Page's equation was found to give the best fit with the best R^2 values and lowest SEM and mean relative percent error (e) values. The parameters k and n in the Page equation were regressed as a function of the air temperature and moisture content with R^2 value of 0.95 and 0.87 respectively. The effective diffusivity obtained from Fick's model was 2.32 x 10^{-11} m^2s^{-1} assuming an infinite flat seed.

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