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Hot Air Oven Drying of Maize Husks Biomass: Effects of Bed Depth and Temperature on Drying Kinetics, Moisture Diffusivity and Energy Requirement

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ABSTRACT

The efficient conversion of maize husks biomass to bioenergy by pyrolysis, gasification and combustion requires the removal of moisture by drying. Hence, the hot air oven drying characteristics of maize husks was investigated. Beds (5 – 20 mm) of pulverized maize husks were dried at 80 – 120 ^oC in a laboratory hot air oven, to determine the effects of bed depth and temperature on the drying kinetics, effective moisture diffusivity and energy required for drying. Twelve thin layer drying models were fitted to the drying data. The drying rate of maize husks increased with increasing temperature and decreasing bed depth. The drying of maize husks took place entirely in the falling rate period. The effective moisture diffusivity increased from 8.03 x 10^{-9} to 2.83 x 10^{-8} m^2 s^{-1} as bed depth increased from 5 to 20 mm, and from 1.11 x 10^{-8} to 2.10 x 10^{-8} m^2 s^{-1} as the temperature increased from 80 to 120 ^oC, with an activation energy for drying of 18.6 kJ/mol. The specific energies required for drying the 5 - 20 mm husks beds at 80 - 120 ^oC were 17.43 – 34.95 kWh kg^{-1}. The Weibull model best described the drying of pulverized maize husks.

1. INTRODUCTION

Maize, also known as *Zea mays* or corn, is an agricultural produce that is grown globally (Eckhoff and Paulsen, 1996; Shiferaw et al., 2011; Ranum et al., 2014). It can be consumed directly as a staple food or processed industrially into diverse food and drink products for human consumption, feed for animal breeding and fuel ethanol for use in internal combustion engines of vehicles (Eckhoff and Paulsen, 1996; Shiferaw et al., 2011; Ranum et al., 2014; Eckert et al., 2018). A very large amount of agricultural residues are left behind after the harvest of maize kernel, which include cobs, husks and stalks (Nelson et al., 2004; Schwietzke et al., 2009; Gregg and Smith, 2010; Muth et al., 2013; Bentsen et al., 2014; Hiloidhari et al., 2014). These agricultural wastes are actually biological materials (biomass), that have a huge energy potential and can be converted to bioenergy via diverse processes (Nelson et al., 2004; Schwietzke et al., 2009; Scarlat et al., 2010; Gregg and Smith, 2010; Zhang et al., 2010; Görgens et al., 2013; Okello et al., 2013; Bentsen et al., 2014; Hiloidhari et al., 2014). Biomass are materials derived from microorganisms, animals and plants; they include algae, energy crops, animal wastes, food wastes, wood and wood wastes, agricultural residues/agro-waste, municipal solid wastes and industrial residues (McKendry, 2002; Goyal et al., 2008; Evans et al., 2010; Singh et al., 2014; Demirbas et al., 2017). Unlike, fossil fuels (coal, crude oil and natural gas) which are limited, fast depleting, highly polluting and non-renewable (Panwar et al., 2011; Demirbas et al., 2017), biomass is a renewable source of energy which is easily replenished and environmentally benign (Saxena et al., 2009; Ellabban et al., 2014; Singh et al., 2014). Biomass utilization as a fuel is a carbon neutral process, so it is deemed a mitigation against climate change (Kumar et al., 2009; Saxena et al., 2009; Evans et al., 2010; Roy and Dias, 2017).

Gasification, pyrolysis and direct combustion are thermochemical processes which can be utilised to convert biomass to biofuels or bioenergy (Kumar et al., 2009; Zhang et al., 2010; Görgens et al., 2013; Ellabban et al., 2014; Kumar et al., 2015; Patel et al., 2016; Roy and Dias, 2017). It is usually required to reduce the moisture content of biomass prior to these thermochemical processes in order to ensure their efficiencies (Bennion et al., 2015; Azizi et al., 2018). Also, the potential of agricultural residues e.g. maize husks as raw materials for the production of biofuels and bioenergy suggests the need for preservation and storage of these residues to avoid deterioration before use.

Drying is a preservation process usually employed to reduce the moisture content of agricultural products, thereby decreasing microbial and enzyme activities, and consequently enhancing product shelf-life and reducing the packing and transportation cost (Mujumdar and Law, 2010; Guine et al., 2012). The traditional method for drying agricultural produces is sun drying, but it is extremely weather dependent, takes a long time and materials are prone to contamination by insects, dust, etc. However, hot air oven drying, in a mechanical device, is more hygienic and provides better uniformity in drying (Diamante and Munro 1993). The drying of several agricultural products including fruits, vegetables and staple foods have been reported in the literature (Davishi, 2017; Doymaz, 2010; Erbay and Icier, 2010; Ojediran and Raji, 2010; Rajkumar et al., 2007) but little has been reported on the drying of agricultural residues for production of bioenergy. Drying is a process which involves simultaneous heat and mass transfer (Diamante et al. 2010), so mass and heat transfer properties of biomass such as effective moisture diffusivity, activation energy and energy consumption, essential for dryer design are usually considered. These properties are functions of temperature and the thickness or bed depth of the material undergoing drying; hence this study investigated the effects of temperature and bed depth on the drying characteristics of maize husks, an agricultural residue biomass.

Drying requires effective mathematical models for process design, optimization and control as well as energy integration. Thin layer drying models are easy to use mathematical models that have been applied in the study of the drying of foods, fruits and vegetables (Toğrul and Pehlivan, 2004; Akpinar and Bicer, 2008; Doymaz, 2010; Ojediran and Raji, 2010; Doymaz and Ismail, 2011; Tunde-Akintunde, 2011). However, the suitability of these models for the description of the thin layer drying of biomass has not been adequately investigated, so, this study also considered the thin layer mathematical modelling of the hot air oven drying of maize husks biomass.

2. MATERIALS AND METHODS

2.1. Sample Collection and Preparation

Maize husks were obtained from freshly harvested maize collected from a farmland in Ogbomoso, Nigeria. The husks were pulverized in a kitchen blender to increase the surface area of the material, prior to the drying operation.

2.2. Experimental Procedure

The pulverized maize husk samples were spread uniformly in pre-weighed aluminium pans which had been calibrated to depths of 5, 10, 15 and 20 mm. The initial mass of the pulverized maize husks in each of the pans were measured using a citizen digital weighing balance which has an accuracy of 0.001g. The pans were then placed in a Uniscope SM9053A laboratory hot air oven dryer (Surgifriend Medicals, England), which had been preheated to 80 °C. The mass of the maize husks in each pan was measured at 10 minute interval until a constant mass was observed. The dryer was operated with an air velocity of 1.5 m s^{-1}. The experiments were repeated for a bed depth of 10 mm at temperatures 100 and 120 °C. All experiments were performed in triplicates.

2.3. Determination of Drying Kinetics, Moisture Diffusivity and Energy Requirement

The moisture content of the maize husks at time t, X_t (g water. g dry matter^{-1}) was defined as:

$$X_t = \frac{m_t - m_d}{m_d} \tag{1}$$

where m_t (g) and m_d (g) are mass of sample at any time t and absolute dried mass of sample, respectively. The drying rate of the husks was computed from Equation (2):

$$D_R = \frac{X_{t+dt} - X_t}{dt} \tag{2}$$

where D_R (g water/g dry matter. min) is drying rate, X_{t+dt} (g water. g dry matter^{-1}) is moisture content at time $t+dt$ and dt (min) is time increment. The moisture content can be expressed as dimensionless moisture ratio (M_R):

$$M_R = \frac{X_t - X_e}{X_i - X_e} \tag{3}$$

where X_i and X_e (g water/g dry matter) are initial and equilibrium moisture contents, respectively. The values of X_e are small compared with X_t and X_i for a long drying time, so the moisture ratio may be simplified as (Dissa et al., 2011; Perea-Flores et al., 2012):

$$M_R = \frac{X_t}{X_i} \tag{4}$$

The diffusion of moisture from the internal part of the maize husks to the surface during the falling rate drying period, when internal mass transfer is the controlling mechanism, may be described by Fick's second law of diffusion (Doymaz, 2008; Ruiz Celma et al., 2008). The Fick's law in terms of M_R is expressed as (Vega-Galvez et al, 2010):

$$\frac{dM_R}{dt} = D_{eff} \frac{d^2 M_R}{dx^2} \tag{5}$$

where D_{eff} (m^2 s^{-1}) is the effective moisture diffusivity and x (m) is spatial dimension. The bed of maize husks in the drying pan had a slab geometry. Assuming a one-dimensional transport of moisture in an infinite slab, negligible shrinkage, uniform initial moisture distribution, negligible external resistant and constant diffusivity; the mathematical solution of Equation (5) according to Crank (1975) is:

$$M_R = \frac{8}{\pi^2}\sum_{i=0}^{\infty}\frac{1}{(2i+1)^2}\exp\left[\frac{-(2i+1)^2 D_{eff}\pi^2 t}{4L^2}\right] \tag{6}$$

The first term in the series expansion of Equation (6) gives a good estimate of the solution for sufficiently long drying time (Di Scala and Crapiste, 2008):

$$M_R = \frac{8}{\pi^2}\exp\left[\frac{-D_{eff}\pi^2 t}{4L^2}\right] \tag{7}$$

where L (m) is half of the thickness of the slab and t (s) the time of drying. Equation (7) can be written in a linear form as:

$$In(M_R) = In\left(\frac{8}{\pi^2}\right) - \left(\frac{D_{eff}\pi^2 t}{4L^2}\right) \tag{8}$$

A plot of $In(M_R)$ versus t yields a straight line with slope (S_1) from which D_{eff} is calculated:

$$S_1 = \frac{D_{eff}\pi^2}{4L^2} \tag{9}$$

An Arrhenius relationship may be used to describe the hot air temperature dependence of the effective moisture diffusivity (Doymaz and Ismail, 2011; Tunde-Akintunde and Ogunlakin, 2011):

$$D_{eff} = D_o \exp\left({-E_a}/{RT}\right) \tag{10}$$

where D_o (m^2 s^{-1}) is the Arrhenius factor, E_a (kJ mol^{-1}) the activation energy, R the universal gas constant (8.314 J mol^{-1} K^{-1}) and T (K) the absolute temperature. A linear equation is obtained on taking the natural logarithm of both sides of Equation (10):

$$In\ D_{eff} = In\ D_o - \frac{E_a}{RT} \tag{11}$$

The activation energy E_a (kJ mol^{-1}) for the drying of the maize husks can be determined from the slope (S_2) of the straight line obtained from the plot of $In\ D_{eff}$ versus ${1}/{T}$:

$$S_2 = \frac{E_a}{R} \tag{12}$$

The total energy E_t (kWh) and specific energy E_{sp} (kWh/kg) required for drying the maize husks were computed from Equation (13) and Equation (14), respectively:

$$E_t = A\upsilon\rho_a c_a \Delta T D_t \tag{13}$$

$$E_{sp} = \frac{E_t}{W_o} \tag{14}$$

Where A (m^2) is tray area, ΔT (°C) is temperature difference, υ (m s^{-1}) is air velocity, ρ_a (kg/m^3) is air density, c_a (kJ/kg °C) is specific heat of air, D_t (s) is total drying time and W_o (kg) is initial mass of the maize husks.

2.4. Mathematical Modelling of Drying Kinetics

The Midilli-Kucuk, Page, Logarithmic, Two-term, Wang and Singh, Approximation of diffusion, Modified Henderson and Pabis, Modified Page, Henderson and Pabis, two-term exponential, Verma *et al* and Weibull thin layer drying models, presented in Table 1, were fitted to the drying data. These twelve thin layer drying models have been commonly reported to suitably describe the drying of several agricultural products (Kucuk et al., 2014).

Table 1: Thin layer drying models fitted to drying data

S/No	Model Name	Model	References
1	Midilli-Kucuk	$M_R = a\exp(-kt^n) + bt$	Midilli et al., 2002
2	Page	$M_R = \exp(-kt^n)$	Page, 1949
3	Logarithmic	$M_R = a\exp(-kt) + c$	Chandra and Singh, 1995; Yagcioglu *et al.*, 1999
4	Two-term	$M_R = a\exp(-k_0 t) + b\exp(-k_1 t)$	Henderson, 1974; Glenn, 1978
5	Wang and Singh	$M_R = 1 + at + bt^2$	Wang and Singh, 1978
6	Approximation of diffusion	$M_R = a\exp(-kt) + (1-a)\exp(-kbt)$	Kaseem, 1998
7	Modified Henderson and Pabis	$M_R = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$	Karathanos, 1999
8	Modified Page	$M_R = \exp(-(kt)^n)$	White *et al.*, 1978
9	Henderson and Pabis	$M_R = a\exp(-kt)$	Henderson and Pabis, 1961
10	Two-term exponential	$M_R = a\exp(-kt) + (1-a)\exp(-kat)$	Sharaf-Eldeen *et al.*, 1980
11	Verma et al.	$M_R = a\exp(-kt) + (1-a)\exp(-gt)$	Verma *et al.*, 1985
12	Weibull	$M_R = a - b\exp(-kt^n)$	Weibull, 1951; Yi et al., 2012

The Statistical Package for the Social Sciences (SPSS) version 20 (SPSS Inc., Chicago, Illinois), was used for the non-linear regression analysis of the experimental drying data. The coefficient of determination (R^2), sum of square error (SSE), root mean square error (RMSE) and Chi-square (χ^2) were used as criteria to determine the model that best fit the drying moisture ratio – time data. These criteria are given as:

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N} \left(M_{R_{\exp,i}} - M_{R_{pred,i}} \right)^2}{\sum_{i=1}^{N} \left(M_{R_{\exp,i}} - \bar{M}_R \right)^2} \right] \tag{15}$$

where $\bar{M}_R = \frac{1}{N} \sum_{i=1}^{N} M_{R_{\exp,i}}$

$$SSE = \frac{1}{N} \sum_{i=1}^{N} \left(M_{R_{\exp,i}} - M_{R_{pred,i}} \right)^2 \tag{16}$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(M_{R_{pred,i}} - M_{R_{\exp,i}} \right)^2 \right]^{\frac{1}{2}} \tag{17}$$

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(M_{R_{\exp,i}} - M_{R_{pred,i}} \right)^2}{N - z} \tag{18}$$

where $M_{R_{\exp,i}}$, $M_{R_{pred,i}}$, N and z are experimental moisture ratio, predicted moisture ratio, number of observations and number of constants, respectively. The R^2 values were computed by SPSS while SSE, RMSE and χ^2 were calculated from Equations 16, 17 and 18, respectively, using Microsoft Excel. The model that best fit the data is one that has the highest value of R^2 and lowest values of SSE, RMSE and χ^2 (Erbay and Icier, 2010; Kucuk *et al.*, 2014).

3. RESULTS AND DISCUSSION

3.1. Effect of Bed Depth on Drying Kinetics

The plots of moisture ratio versus drying time for the drying of maize husks biomass of depths 5 – 20 mm at 80 ^{o}C, presented in Figure 1 reveal that the moisture ratio decreased progressively with drying time. This indicates that moisture was effectively removed from the maize husks during the drying operation. It was also observed that the drying time decreased with decreasing bed depth of maize husks, implying that the rate of moisture removal from the husks increased with decreasing bed depth and so faster drying rate can be achieved by reducing the bed depth or using thinner layer of maize husks. The path or distance through which moisture has to diffuse through the material decreases as the bed depth decreases, so moisture is expected to be removed faster through thinner material or bed depth (Falade and Solademi, 2010; Doymaz and Özdemir, 2013).

The variation in material bed depth represents a variation in the initial mass of material and initial moisture present in the maize husks bed, since drying pans of similar constant cross-sectional area were utilised in all the drying experiments. Hence, this result also implies that the drying rate increased and consequently the drying time decreased, as the initial mass and moisture present in the material decreased. An increase in drying rate and reduction in drying time with decreasing bed depth or material thickness has been reported for the drying of pumpkin (Limpaiboon, 2011), eggplant (Ertekin and Yaldiz, 2004), leek slices (Doymaz, 2008) and tomato (Doymaz and Özdemir, 2013).

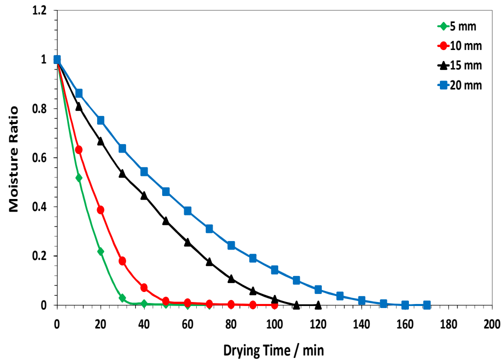

Figure 1: Plot of moisture ratio versus drying time for hot air oven drying of pulverized maize husks of depths 5 – 20 mm at 80 °C

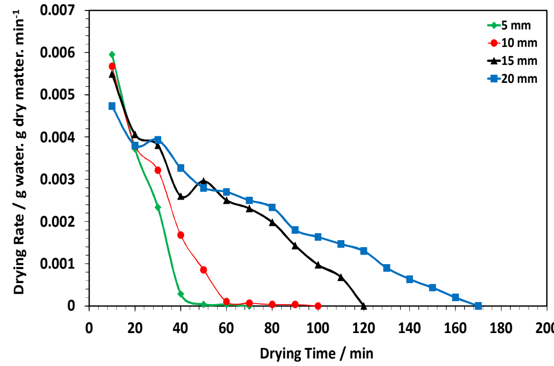

Figure 2: Plot of drying rate versus drying time for hot air oven drying of pulverized maize husks of depths 5 – 20 mm at 80 °C

The drying rate of maize husks of 5 -20 mm depth dried in hot air oven at 80 °C, decreased with increasing drying time as shown in Figure 2. The drying operation took place entirely in the falling rate period, no constant rate period was observed. This implies that hot air oven drying of maize husks was controlled by the diffusion of moisture from the inner part of the maize husk bed to the outer surface (Doymaz, 2008; Ruiz Celma et al., 2008). A falling rate drying period has been reported by several authors for the hot air oven drying of many agricultural products (Chen et al., 2012; Doymaz and Özdemir, 2013; Olanipekun et al, 2015; Tunde-Akintunde and Ogunlakin 2011; Tunde-Akintunde, 2014).

3.2. Effect of Temperature on Drying Kinetics

The drying time required for drying the maize husks decreased as the drying temperature increased as depicted in Figure 3. This is because the drying rate increased with increasing temperature. This indicates that the maize husks biomass can be dried at a faster drying rate and consequently shorter drying times at higher temperatures. Increase in drying rate of agricultural products with increasing temperature has been previously reported (Falade and Solademi, 2010; Doymaz and Özdemir, 2013; Zhu and Shen, 2014). Similar to the observation for maize husks dried at 80 °C, the drying rate of the pulverized maize husks that were oven dried at 100 and 120 °C deceased with drying time, as shown in Figure 4.

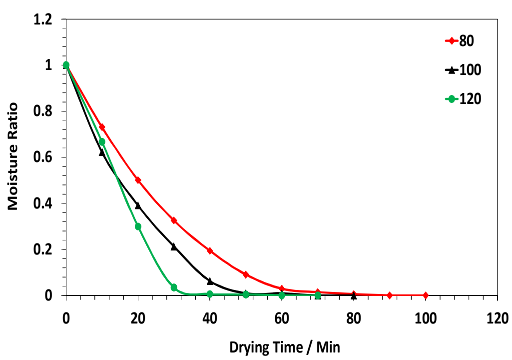

Figure 3: Plot of moisture ratio versus drying time for hot air oven drying of pulverized maize husks of 10 mm depth at 80, 100 and 120 °C

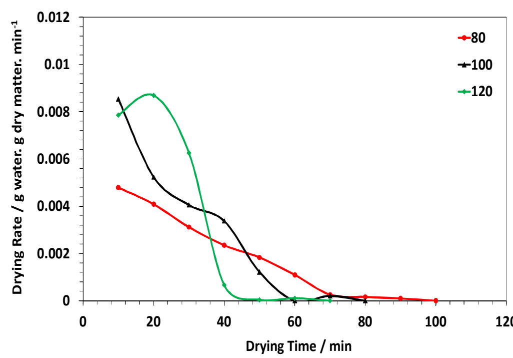

Figure 4: Plot of drying rate versus drying time for hot air oven drying of pulverized maize husks of 10 mm depth at 80, 100 and 120 °C

There was no constant drying period, the drying took place completely in the falling rate period indicating that the drying operation at all temperatures investigated was limited by diffusion of moisture from the inner part of the maize husks bed to its surface (Doymaz, 2008; Ruiz Celma et al., 2008).

3.3. Effective Moisture Diffusivity

The effective moisture diffusivity for the hot air oven drying of maize husks of depths 5, 10, 15 and 20 mm at 80 °C were 8.03 x 10^{-9}, 1.11 x 10^{-8}, 2.36 x 10^{-8} and 2.83 x 10^{-8} $m^2 s^{-1}$, respectively, as shown on Table 2. The moisture diffusivity increased with increasing bed depth. This may be due to the increase in moisture activity associated with the increase in initial moisture of maize husks with increasing bed depth at constant cross sectional area (Sadin et al., 2013). An increase in effective moisture diffusivity with increasing thickness of material has been reported in the literature (Göğüş and Maskan, 2006; Falade and Solademi, 2010; Sadin et al., 2013). The effective moisture diffusivity also increased from 1.11 x 10^{-8} to 2.10 x 10^{-8} $m^2 s^{-1}$ as the temperature increased from 80 to 120 °C due to increased activity of water molecules as a result of the rise in thermal energy at elevated temperatures (Xiao et al., 2010). An increase in effective moisture diffusivity with increasing temperature has also been reported in the literature (Göğüş and Maskan, 2006; Falade and Solademi, 2010; Doymaz and Özdemir, 2013; Sadin et al., 2013). The effective moisture diffusivity of 8.03 x 10^{-9} – 2.83 x 10^{-8} $m^2 s^{-1}$ measured for the hot air oven drying of pulverized maize husks, in this study, are within the range of 10^{-12} – 10^{-6} $m^2 s^{-1}$ previously reported for the drying of agricultural products (Erbay and Icier, 2010).

Table 2: Effective moisture diffusivity for hot air oven drying of maize husks at 80 °C

Depth (mm)	D_{eff} ($m^2 s^{-1}$)
5	8.03 x 10^{-9}
10	1.11 x 10^{-8}
15	2.36 x 10^{-8}
20	2.83 x 10^{-8}

Table 3: Effective moisture diffusivity for hot air oven drying of maize husks of 10 mm depth

Temperature (°C)	D_{eff} ($m^2 s^{-1}$)
80	1.11 x 10^{-8}
100	1.48 x 10^{-8}
120	2.10 x 10^{-8}

An Arrhenius type equation for drying suitably described the temperature dependence of the effective moisture diffusivity for the drying of maize husks and an activation energy of 18.6 kJ mol^{-1} was required for drying the maize husks. This activation energy is the energy barrier that must be overcome for moisture to diffuse from the inner part of the maize husks bed to its surface (Tunde-Akintunde, 2014). The activation energy measured for maize husks in this study is within the range 18 - 49.5 kJ mol^{-1} reported for the drying of most agricultural products (Erbay and Icier, 2010).

3.4. Drying Energy Requirement

Total energies of 0.55 – 1.47 kWh and specific energies of 17.43 – 34.95 kWh kg^{-1} were required for hot air oven drying of 5 – 20 mm deep maize husks bed at 80 °C while total energies of 0.83 -0.90 and corresponding specific energies of 22.62 – 24.59 kWh kg^{-1} were consumed during the drying of maize husks of 10 mm depth at 80 – 120 °C as shown in Table 4 and Table 5, respectively. The energy required for drying maize husks increased with increasing bed depth due to the increase in initial mass and moisture present in the husks bed associated with increasing bed depth. Likewise, the energy consumed during the drying of maize husks increased with increasing temperature due to larger thermal energy required for heating at higher temperatures.

Table 4: Energy requirement for hot air oven drying of maize husks at 80 ^oC

Depth (mm)	Total energy (kWh)	Specific energy (kWh kg^{-1})
5	0.55	17.43
10	0.83	22.62
15	1.01	25.56
20	1.47	34.95

Table 5: Energy requirement for hot air oven drying of maize husks of 10 mm depth

Temperature (^oC)	Total energy (kWh)	Specific energy (kWh kg^{-1})
80	0.83	22.62
100	0.86	23.57
120	0.90	24.59

3.5. Thin Layer Models

The statistical parameters of R^2, SSE, RMSE and χ^2, obtained for the twelve thin layer models, after non-linear regression analysis are presented on Tables 6 – 11. The Weibull thin layer model was considered to best describe the hot air oven drying of pulverized maize husks. This model had the highest R^2 and lowest SSE, RMSE and χ^2 compared to those of the other eleven models, for the 10 – 20 mm samples oven dried at 80 ^oC and 10 mm sample dried at 100 - 120 ^oC, as shown on Tables 7 – 9 and Tables 10 - 11, respectively. The highest value of R^2 of 0.998 was obtained for the Weibull, Midilli-Kucuk, Page and Modified Page models, compared to the other eight models, for the drying of 5 mm deep bed of maize husks at 80 ^oC as shown on Table 6. However, the SSE (0.000188354) and RMSE (0.013724213) for the Weibull model were the lowest of the twelve models but the χ^2 (0.000376708) of the Weibull model was slightly higher than that (0.000265203) of the Modified Page model. Also, the highest value of R^2 of 0.998 was obtained for the Midilli-Kucuk, Page and Modified Page and Weibull models, compared to the other eight models, for the drying of 10 mm deep bed of maize husks at 120 ^oC as shown on Table 11. However, the SSE (0.000191657), RMSE (0.013844023) and χ^2 (0.000261350) for the Weibull model were slightly larger than the SSE (0.000151506), RMSE (0.012308784) and χ^2 (0.000174815) for the Modified Page model. Generally, comparing all the data on Tables 6 – 11; the Weibull model was adjudged the model that best describe the hot air oven drying of pulverized maize husks. The Weibull model has been reported to best fit the drying data of apple slices (Aghbashlo et al., 2010) and garlic (Rasouli et al., 2011).

Table 6: Statistical parameters for hot air oven drying of 5 mm deep maize husks at 80 ^oC

Model	R^2	SSE	RMSE	χ^2
Midilli-Kucuk	0.998	0.000194706	0.013953725	0.000389413
Page	0.998	0.000202982	0.014247166	0.000270642
Logarithmic	0.992	0.000870109	0.029497604	0.001392174
Two-term	0.989	0.001224546	0.034993516	0.002449092
Wang and Singh	0.958	1.147757186	1.071334302	1.530342915
Approximation of	0.989	0.00126838	0.035614317	0.002029407
Modified Henderson	0.989	0.001224987	0.034999817	0.004899949
Modified Page	0.998	0.000198903	0.014103281	0.000265203
Henderson and Pabis	0.989	0.001224546	0.034993516	0.001632728
Two-term exponential	0.989	0.001268380	0.035614317	0.001691173
Verma et al	0.997	0.000349095	0.018684088	0.000558552
Weibull	0.998	0.000188354	0.013724213	0.000376708

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Table 7: Statistical parameters for hot air oven drying of 10 mm deep maize husks at 80 °C

Model	R^2	SSE	RMSE	χ^2
Midilli-Kucuk	0.997	0.000387884	0.01969477	0.000609532
Page	0.996	0.000387607	0.019687746	0.000473742
Logarithmic	0.991	0.000967701	0.031107887	0.001330588
Two-term	0.981	0.002069536	0.045492153	0.003252128
Wang and Singh	0.996	0.617459424	0.785785864	0.754672629
Approximation of diffusion	0.979	0.002351592	0.048493214	0.003233439
Modified Henderson and Pabis	0.981	0.002069536	0.045492153	0.004552979
Modified Page	0.240	0.083858518	0.289583352	0.102493744
Henderson and Pabis	0.981	0.002068769	0.045483727	0.002528496
Two-term exponential	0.979	0.002351592	0.048493214	0.002874168
Verma et al	0.991	0.000987424	0.031423299	0.001357708
Weibull	0.998	0.000337173	0.018362275	0.000529844

Table 8: Statistical parameters for hot air oven drying of 15 mm deep maize husks at 80 °C

Model	R^2	SSE	RMSE	χ^2
Midilli-Kucuk	0.995	0.000517331	0.022744914	0.000705451
Page	0.994	0.000474284	0.021778058	0.000547251
Logarithmic	0.992	0.000619344	0.024886616	0.00077418
Two-term	0.979	0.00158411	0.039800875	0.00216015
Wang and Singh	0.998	0.325261315	0.570316855	0.375301518
Approximation of diffusion	0.977	0.001749817	0.041830814	0.002187271
Modified Henderson and Pabis	0.979	0.001584110	0.039800875	0.002640183
Modified Page	0.994	0.000476832	0.021836491	0.000550191
Henderson and Pabis	0.979	0.00158411	0.039800875	0.001827819
Two-term exponential	0.977	0.001749817	0.041830814	0.002019020
Verma et al	0.987	0.000996037	0.031560056	0.001245046
Weibull	0.996	0.000327047	0.018084453	0.000445974

Table 9: Statistical parameters for hot air oven drying of 20 mm deep maize husks at 80 °C

Model	R^2	SSE	RMSE	χ^2
Midilli-Kucuk	0.994	0.000988900	0.031446773	0.001348499
Page	0.992	0.000891146	0.029852076	0.001028246
Logarithmic	0.990	0.000928756	0.030475506	0.001160946
Two-term	0.972	0.002626104	0.051245525	0.003581051
Wang and Singh	0.996	0.000772416	0.027792381	0.000891250
Approximation of diffusion	0.968	0.003022789	0.054979894	0.003778486
Modified Henderson and Pabis	0.991	0.034331593	0.185287866	0.057219322
Modified Page	0.992	0.000793406	0.028167455	0.000915468
Henderson and Pabis	0.972	0.002626104	0.051245525	0.003030120
Two-term exponential	0.968	0.003022789	0.054979894	0.003487833
Verma et al	0.990	0.001114589	0.033385454	0.001393236
Weibull	0.994	0.000608785	0.024673561	0.000830161

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Table 10: Statistical parameters for hot air oven drying of 10 mm deep maize husks at 100 °C

Model	R^2	SSE	RMSE	χ^2
Midilli-Kucuk	0.996	0.000334252	0.01828256	0.000455798
Page	0.996	0.000291087	0.017061267	0.000335869
Logarithmic	0.994	0.000383816	0.019591218	0.000479770
Two-term	0.988	0.000770042	0.027749623	0.001050057
Wang and Singh	0.987	0.446976455	0.668562978	0.515742064
Approximation of diffusion	0.988	0.000810669	0.028472246	0.001013336
Modified Henderson and Pabis	0.988	3.3056E+45	5.7494E+22	5.5094E+45
Modified Page	0.996	0.000291088	0.017061314	0.000335871
Henderson and Pabis	0.988	0.000769495	0.027739777	0.000887879
Two-term exponential	0.988	0.000810669	0.028472246	0.000935387
Verma et al	0.995	0.000335641	0.018320521	0.000419552
Weibull	0.997	0.000225992	0.015033037	0.000308171

Table 11: Statistical parameters for hot air oven drying of 10 mm deep maize husks at 120 °C

Model	R^2	SSE	RMSE	χ^2
Midilli-Kucuk	0.998	0.00017551	0.013059531	0.000232570
Page	0.998	0.000226007	0.015033536	0.000260778
Logarithmic	0.972	0.002097525	0.04579874	0.002621906
Two-term	0.967	0.002477154	0.049771012	0.003377937
Wang and Singh	0.935	0.871198136	0.933379953	1.005228618
Approximation of diffusion	0.965	0.002651076	0.514885990	0.003313845
Modified Henderson and Pabis	0.967	0.002477154	0.049771012	0.004128589
Modified Page	0.998	0.000151506	0.012308784	0.000174815
Henderson and Pabis	0.967	0.002477154	0.049771012	0.002858254
Two-term exponential	0.965	0.002651076	0.051488599	0.003058934
Verma et al	0.996	0.000307075	0.01752355	0.000383843
Weibull	0.998	0.000191657	0.013844023	0.000261350

4. CONCLUSION

Beds of pulverized maize husks biomass obtained from freshly harvested maize were successfully dried in a laboratory hot air oven dryer. The drying rate of maize husks increased, and consequently the drying time decreased, with increasing temperature and decreasing bed depth. The hot air oven drying of maize husks took place entirely in the falling rate period and was controlled by moisture diffusion. The effective moisture diffusivity increased from 8.03×10^{-9} to 2.83×10^{-8} $m^2 s^{-1}$ as bed depth increased from 5 to 20 mm at 80 °C, and from 1.11×10^{-8} to 2.10×10^{-8} $m^2 s^{-1}$ as the temperature increased from 80 to 120 °C for a bed depth of 10 mm, with an activation energy for drying of 18.6 kJ/mol. The total and specific energies required for drying were 0.55 – 1.47 kWh and 17.43 – 34.95 kWh kg^{-1}, respectively. The Weibull model best described the hot air oven drying of pulverized maize husks.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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