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SOLAR DRYING KINETICS OF CASSAVA SLICES IN A MIXED FLOW DRYER

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Drying characteristics of cassava slices was investigated in a mixed mode natural convection solar dryer to obtain a suitable mathematical model describing the drying. The average drying chamber temperature was between $34 \pm 2^\circ\text{C}$ and $50 \pm 1.8^\circ\text{C}$, while 10 commonly used thin layer drying models were used for drying curve modelling. Coefficient of determination (R^2) and root mean square error (RMSE) were used to determine the models performances. The drying curve of cassava slices showed a reduction of moisture content with increased drying time in the solar dryer, and the variation of moisture ratio exponentially decreased with increased drying time. The Midilli and Logarithmic models showed better fit to the experimental drying data of cassava slices. As compared with other models tested, there were no significant differences ($p > 0.05$) in the R^2 values obtained for the Midilli and Logarithmic models; hence, the Logarithmic model was preferable because of the lower RMSE. The diffusion mechanism could be used to describe the drying of cassava slices that was found to be in the falling rate period. A diffusion coefficient (D_{eff}) of $1.22 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$ was obtained, which was within the established standard for food products.

Keywords: cassava; diffusion coefficient; moisture ratio; solar dryer; thin layer drying (TLD)

Cassava (*Manihot esculenta*) is a tropical root crop that is processed into different food products in West African countries like Nigeria, Ghana, Benin and Togo. Nigeria is the largest producer of the crop in the world with an annual output of over 34 million tons (Taiwo, 2006). Freshly harvested cassava tubers contain a moisture of between 60% and 65% (w.b.), resulting in a shelf-life of between 24 hours and 48 hours after harvest (Westby, 2002). Cutting the tuber into slices and drying is one method of reducing post-harvest losses of the crop.

According to Sacilik et al. (2006), open sun drying is a well-known and established preservation method that reduces moisture in agricultural produce and also prevents deterioration within a time regarded as the safe storage period. Despite its many disadvantages, in rural areas of Nigeria where the majority of this crop is produced, drying of cassava slices is mostly achieved by open sun drying. Open sun drying usually exposes the product to contamination by insect pests, dust and damage by unfavourable weather conditions. Simple solar dryers in which heated air rises by natural convection through the product has been proposed for rural areas (Basunia and Abe, 2001). The dryers are constructed from low cost, locally available material consequently eliminating dependence on electricity and fossil fuels which are scarce commodities in these rural areas. The solar dryer also reduces contamination of the product and encourages the use of renewable energy in our rural areas. Cost effectiveness and hygienic ways of preserving foods are of great importance given the prevailing insecurity in food supplies throughout the world (Sobukola et al., 2007).

An important factor in drying agricultural produce is to remove moisture as quickly as possible at a temperature that does not seriously affect the flavour, texture and colour of the product. If the temperature is too low in the beginning, microorganisms may grow before the grain is adequately dried (Vizcarra-Mendoza et al., 2003). Drying characteristics of agricultural products and materials are usually studied using thin layer models on the assumption that drying is achieved in layers inside a batch or continuous dryers. Knowledge of the thin layer drying properties would assist in modelling the drying kinetics of such material. These models fall into three categories, namely theoretical, semi-theoretical and empirical (Midilli et al., 2002; Ojediran and Raji, 2010; Sobukola and Dairo, 2007). The theoretical approaches account for only the internal resistance to moisture transfer while the semi-theoretical and empirical approaches consider only the external resistance to moisture transfer between the product and air (Lahsasni et al., 2004).

There have been many researches on experimental studies and mathematical modelling of thin layer characteristics using conventional, open sun drying and solar drying for different agricultural products such as leafy vegetables (Tunde-Akintunde et al., 2005; Sobukola and Dairo, 2007; Sobukola et al., 2007), millet (Ojediran and Raji, 2010); apple slices (Meisami-asl et al., 2010); sultana grapes (Yaldiz et al., 2001); strawberry (Akpınar and Biser, 2006) and sesame seed (Dairo and Olayanju, 2012). This study investigated the suitability of available thin layer drying of cassava slices in a solar dryer under natural air convection and also evaluates the suitability of available mathematical models to the experimental data.

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The equation for thin layer drying of grains in terms of moisture or mass transfer is generally given by Eq. (1), as given by Brooker et al. (1992), where Eq. (2) is obtained by integration of Eq. (1):

$$\frac{\partial M}{\partial t} = k(M - M_e) \quad (1)$$

$$\frac{M - M_e}{M_o - M_e} = e^{-kt} \quad (2)$$

where:

M – represents the moisture content (% d.b.) at drying time t (h)

M_e – is the equilibrium moisture content (% d.b.)

k represents the drying rate constant (h^{-1})

M_o the initial moisture content (% d.b.) at $t = 0$

A dimensionless ratio given by the left hand side of Eq. (2) is usually referred to as moisture ratio (MR); however, according to several researchers on solar drying (Yaldiz et al, 2001; Tunde-Akintude and Afon, 2010; Sobukola and Dairo, 2007), the relative humidity of the drying air varies continuously during solar drying and the values of M_e are relatively small compared to M and M_o . Hence, thin layer drying equation is usually represented by Eq. (3):

$$MR = \frac{M}{M_o} = e^{-kt} \quad (3)$$

According to Vizcarra-Mendoza et al. (2003), diffusivity, a very important parameter usually considered during drying, is used to indicate the flow of moisture out of the material being dried. Moisture diffusivity is influenced mainly by moisture content and temperature of the material. For the drying process in the falling rate period, drying rate is limited by the diffusion of moisture from the inside to the surface layer, represented by the Fick's law of diffusion (Crank, 1975) given by Eq. (4). The analytical solution of Eq. (4) for infinite slab is given by Eq. (5) on assumption of uniform initial moisture distribution, negligible external resistance, constant diffusivity and negligible shrinkage according to Crank (1975):

$$\frac{\partial M}{\partial t} = D_{eff} \nabla^2 M \quad (4)$$

$$MR = \frac{8}{\pi^2} \left[\exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) + \frac{1}{9} \exp\left(-9 \frac{\pi^2 D_{eff} t}{4L^2}\right) + \frac{1}{25} \exp\left(-25 \frac{\pi^2 D_{eff} t}{4L^2}\right) + \dots \right] \quad (5)$$

When drying times are extended, the analytical solution is usually represented by Eq. (6), taking the first term of series solution expressed in a logarithmic form, as used by researchers including Doymaz (2012), and Dairo and Olayanju (2012). The slope obtained from a plot of Eq. (6) which is $\ln(MR)$ versus drying time was determined, and effective moisture diffusivity was obtained using Eq. (7), where k is the slope of Eq. (6):

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

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

where:

D_{eff} – effective moisture diffusivity ($\text{m}^2 \text{s}^{-1}$)

t – time (s)

n – a positive integer

L – the half-thickness of samples (m)

Material and methods

Freshly harvested cassava tubers were collected from the Teaching and Research Farm, Federal University of Agriculture, Abeokuta. The tubers were washed, hand peeled and sliced to a $3 \text{ mm} \pm 0.5 \text{ mm}$ thickness using a mechanical slicer. The initial moisture contents of the slices were determined by oven drying at 102°C for 6 hour according to ASAE standards (ASAE, 1998).

Solar dryer

A mixed mode type natural convection solar dryer developed at the Department of Agricultural Engineering, Federal University of Agriculture, Abeokuta was used for the study. The dryer consisted of a solar collector, a drying chamber and a transparent roof to allow direct solar radiation into the drying chamber (Figure 1). The solar collector of dimensions $45 \text{ cm} \times 53 \text{ cm} \times 20 \text{ cm}$ was covered with a 2.5 mm thick glass with the drying chamber ($50 \text{ cm} \times 45 \text{ cm} \times 45 \text{ cm}$) consisting

Figure 1 Isometric drawing of the solar dryer

of three layers of tray. The air vent was covered with a perforated wire netting to prevent insects from entering and infesting the samples in the dryer. The solar collector and transparent roof were both inclined at 17° using the latitude of location according to Alamu et al. (2010).

Experimental procedure

The solar dryer was positioned in the open with the collector facing the direction of the sun and a no-load test was carried out by taking the temperature inside the collector, the drying chamber and the ambient air using a digital infrared thermometer at a 1 h interval for 9 h a day, starting from 08:00 to 18:00 h, for three days.

Single layers of 3 mm slices of cassava tubers of known initial mass were spread on the drying trays in the drying chamber of the solar dryer to determine the thin layer drying kinetics. The losses in weight of the slices were monitored at a 1 h interval by using an electronic weighing balance (Mettler, model AE 240) of ±0.01 g accuracy. All measurements were repeated three times to obtain an average value which was used in the analysis.

The moisture content at hourly basis was calculated from the initial moisture content and weight loss using Eq. (8), as used by Ojediran and Raji (2010):

$$M_t = \frac{M_{imi} - w_i}{m_i - w_i} \quad (8)$$

where:

M_t – moisture content at any time t (% w.b.)

M_{imi} – initial moisture content (% w.b.)

m_i – initial mass of sample (g)

w_i – weight loss at time t (g)

Thin layer drying models

The experimental data were fitted to ten commonly used thin layer drying models presented in Table 1 to determine their suitability in describing the thin layer behaviour of cassava slices using Datafit version 9.0.59 (Oakdale, 2008). The coefficient of determination (R^2) and root mean square error (RMSE) were used as criteria for adequacy and goodness of fit for the models. The best model for describing the thin layer characteristics

Table 1 Mathematical models applied to the solar drying of cassava slices

No	Model name	Equation
1	Midilli	$MR = a \cdot \exp(-kt^n) + bt$
2	Logarithm	$MR = a \cdot \exp(-kt) + c$
3	Modified Page	$MR = a \cdot \exp(-kt^n)$
4	Page	$MR = \exp(-kt^n)$
5	Weibull	$MR = \exp\left(-\left(\frac{t}{a}\right)^n\right)$
6	Wang & Singh	$MR = 1 + at + bt^2$
7	Henderson & Pabis	$MR = a \cdot \exp(-kt)$
8	Logit	$MR = \frac{a}{(1 + a \cdot \exp(kt))}$
9	Newton	$MR = \exp(-kt)$
10	Approach to Diffusion	$MR = a \cdot \exp(-kt) + (1 - a) \cdot \exp(-kbt)$

Source: Meisami-asl et al. (2010); Ojediran and Raji (2010)

of solar drying of cassava under natural convection was selected as the one with the highest R^2 and the least RMSE (Ertekin and Yaldiz, 2004; Dairo and Olayanju, 2012).

Results and discussion

The initial moisture content for the cassava slices was found to be 62.4% ± 1.2 (w.b.). The temperature distribution on a typical day during the no-load test is as shown in Figure 2. The temperature of the ambient air ranged from 31 °C to 36 °C, while that of the collector varied from 35 °C to 61 °C, and the drying chamber temperature was from 34 °C to 50 °C. The maximum temperature was reached at 13 h for ambient while it was between 13 h and 15 h for the collector and drying chamber. The temperature in the

drying chamber was always higher than the ambient air temperature throughout the duration of the experiment, thus confirming that the dual mode solar dryer could raise the temperature of the drying chamber for effective drying.

The drying curve shown in Figure 3a depicts the reduction of moisture content with increased drying time in the solar dryer. The moisture content was reduced with increased drying time, as expected and observed by several other researchers. The rate of water removal was highest in the first two hours of drying, as shown in the drying rate curve (Figure 3b), after which removal rate began to reduce until it appeared constant between 13:00 and 16:00. After 16:00, there was decreased drying rate. It could be observed that the drying rate curve slightly followed the average daily

Figure 2 Hourly temperature variation in the ambient air, solar collector and drying chamber on a typical day during the drying experiment

Figure 3a Drying curve of cassava slices under convectonal solar drying

Figure 3b Drying curve of cassava slices under convectonal solar drying

temperature variation observed in the study. The thin layer drying could be described as a falling rate drying, as shown in Figure 3a. Diffusion has been described by several researchers as the

most likely mechanism for moisture movement during this period, where moisture movement is from the interior to the surface of the product (Sobukola et al., 2007).

A plot of the observed dimensionless ratio (MR) against drying time is shown in Figure 4. The variation of MR was observed to exponentially decrease with increased drying time of cassava slices under natural convective solar drying, similar to observation made by other researchers (Ojediran and Raji, 2010; Ajibola 1989).

Model evaluation

The values for the coefficient of determination (R^2) and RMSE for the evaluated models are presented in Table 2 in four groups – A, B, C and D having four, three, two and one parameters, respectively. The coefficient of determination (R^2) ranged from 0.9872 to 0.9899, while the RMSE values obtained ranged from 0.0144 to 0.0180 for the four groups of models. The coefficient of determination (R^2) for Midilli (group A) was not different from the Logarithm and Modified Page model in group B. The two group B models could be better than the four parameter Midilli model in terms of RMSE and the number of parameters.

The group C models also had R^2 values close to one another with the Logit and Henderson & Pabis models having the least R^2 and highest RMSE values. The Newton model, the only one parameter model tested had the least R^2 value with a moderate RMSE.

A t -test for the identified models revealed no significant differences ($p > 0.05$) between the models tested; consequently, any one of the tested

Table 2 TLD models, model constants with the coefficient of determination (R^2) and standard error of estimates for solar drying of cassava slices

Group	Model	Model parameters					R^2	RMSE
		a	b	c	k	n		
A	Midilli	1.001	-0.083		-0.015	1.344	0.9909	0.0164
B	Logarithm	0.699		0.302	0.101		0.9909	0.0153
	Modified Page	1.004			0.076	0.896	0.9908	0.0153
	Approach to Diffusion	-1132.805	1.000		0.063		0.9872	0.0180
	Page				0.074	0.910	0.9907	0.0144
C	Weibull	17.568	0.910				0.9907	0.0144
	Wang & Singh	-0.067	0.002				0.9906	0.0145
	Henderson & Pabis	0.990			0.061		0.9884	0.0161
	Logit	105.079			0.061		0.9884	0.0161
D	Newton				0.062		0.9872	0.0159

Figure 4 Plot of observed moisture ratio (MR) against drying time of cassava slices

Figure 5 Plot of observed and predicted moisture ratio (MR) against drying time of cassava slices using Logarithmic model

Figure 6 Plot of $\ln(MR)$ against drying time for solar drying of cassava

models could be used, except the Henderson & Pabis, Logit and Newton models. However, considering the best two models, Logarithmic would be preferred in terms of the number of parameters and lower RMSE values over the Midilli model; consequently, the Logarithmic model was taken as the best fit for solar drying of cassava slices under natural convection. A plot of moisture ratio (MR) against time using the Logarithm model is shown in Figure 5.

Effective diffusivity

The diffusivity was obtained by evaluating Eq. (7) where the slope of Eq. (6) was obtained by plotting experimental data in terms of natural logarithm of moisture ratio against drying time, as shown in Figure 6. Effective diffusivity (D_{eff}) was obtained as $1.22 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$, which was within the range of 10^{-12} and 10^{-8} reported for food materials by Madamba et al. (1996).

Conclusion

The drying of cassava slices in a natural convection mixed solar drying system was investigated. A mixed mode solar dryer was used for the experiment with average drying chamber temperature ranging from 34°C to 50°C . The drying curve showed a reduction of moisture content with increased drying time of cassava slices in the solar dryer. The drying rate curve slightly followed the average daily temperature variation observed in the study. The variation of MR was observed to decrease exponentially with increased drying time. The experimental data was fitted to 10 different drying models using the coefficient of determination (R^2) and RMSE as fitness criteria. The Midilli and Logarithmic models showed better fit to the experimental drying data as compared to other models tested; however, the Logarithmic model would be preferable because of the lower RMSE since there were no significant differences ($p > 0.05$) in the R^2 values obtained for the two models. The diffusion mechanism could be used to describe the drying of cassava slices which was found to be in the falling rate period. The obtained effective diffusion coefficient (D_{eff}) of $1.22 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$ was within the established standard for food

products. These results would be useful in the design of equipment, processes and research study involving solar drying of cassava slices under natural convection.

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