Mathematical modelling of thin layer solar drying of *Ighu*

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Abstract: A solar cabinet dryer was fabricated and used in evaluating thin layer drying of *Ighu*. Three air-plenums (40, 60, 80 mm), three loading densities (330, 530, 730 g mm^{-2}) and three moisture contents (57.8%, 67.3%, 75.6%) were applied to the process of drying to determine their effects on drying time. Fresh *Ighu* samples were prepared and dried by a natural open sun drying method. The experimental moisture ratios of the samples were fitted to nine drying models. The mathematical models were tested with the drying behaviour of *Ighu* in the solar dryer and open sun. The Page model and modified Page model were the best model based on statistical parameters of coefficient of determination, root mean square error and reduced mean square errors. They are applicable to predict moisture content of *Ighu* samples during solar and open sun drying.

Keywords: *Ighu*, solar drying, mathematical modeling, thin layer drying, moisture ratio

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1 Introduction

Cassava (*Manihot esculenta Crantz*) a tuberous starchy root crop of the family *Euphorbiaceae* is popular worldwide (Kordylas, 2002; Agodzo and Owusu, 2002). They are broadly classified into the sweet and the bitter varieties based on the level of the poisonous hydrogen cyanide (HCN) present in the tuber (Iwe, 2008; Agodzo and Owusu, 2002). The main products derived from processing the bitter varieties are *Ighu*, *garri*, *lafun*, *fufu*, *abacha*, *akpu*, *kokonte* and *agbelima* (Quaye et al., 2009) while the sweet varieties are boiled, pounded into dough and consumed with vegetable soup. Culturally, *Ighu* is the bread of the poor in those localities where it is processed. It is a popular food of the Isuochi people in Abia State, several towns in Oji River Local Government Area of Enugu State and various towns in the former Aguata Local Government Area of Anambra State (Iwe, 2008). In the preparation of *Ighu*, fresh cassava tuber is washed and steamed for 20 to 30 minutes and allowed to cool. The cooled tubers are peeled and manually shredded with a metallic shredder composed of sharp openings. The thinly sliced shreds are then soaked in water overnight during which time the water is changed once or twice, washed and dried on wooden trays or traditional baskets on elevated platforms (Enwere, 1998). However, this processing method differs with communities (Njoku and Banigo, 2006).

Maximizing the food production capabilities of small farmers in rural areas is difficult. To solve the problem, drying has become one of the main processing techniques used to preserve food products in sunny areas (Mustayen et al., 2014). However, traditional open sun drying leads to reduced quality and quantity of agricultural food products (Can, 2000) and it is labor intensive (Tiwari et al., 1997; Oosthuizen, 1995). The process is also fully dependent on excellent weather conditions (Mustayen et al., 2014). Solar drying is the best alternative that can help improve the quality of food products (Bala and Woods, 1994; Sharma et al., 1995). Solar dryers can cost effectively because relatively unskilled village artisans can construct, operate and maintain the dryers at minimum cost and locally available materials can be used

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for the construction (Mumba, 1995). The use of solar drying systems for grains, fruits, and vegetables is feasible, economical and ideal for farmers in many developing countries (Mustayen et al., 2014; El-Sebaii and Shalaby, 2012; Sharma et al., 2009). Most solar dryers are black inside, either painted or with black polythene inserts to absorb as much solar radiation as possible (Bala and Woods, 1994; Sharma et al., 1995). Arinze et al. (1992) used polythene as top cover to construct cheap solar dryers, affordable and adaptable to farmers. Several direct type solar dryers are fabricated, tested, and analyzed in many countries (El-Sebaii and Shalaby, 2012; Arinze et al., 1992). The simplest direct type solar dryer is solar cabinet dryer (Al-Juamily et al., 2007). This dryer has given encouraging results and reduced the drying time by one third compared to open sun drying (Maia et al., 2009; Al-Juamily et al., 2007).

Many researches have been conducted on the mathematical modeling and experimental studies on thin layer solar drying processes of various vegetables and fruits, such as green bean (Doymaz, 2005), pistachio (Midilli and Kucuk, 2003), red pepper (Akpinar et al., 2003), mint leaves (Akpinar, 2010), tarragon (Arabhosseini et al., 2008), potato (Aghbashlo et al., 2009), chilli pepper (Tunde-Akintunde, 2011), carrot (Berruti et al., 2009) and citrus aurantium leaves (Mohamed et al., 2005). However, the drying characteristics of *Ighu* and their mathematical drying model have not been developed. Thin layer drying equations are used to estimate drying time of several products and also to generalize drying curves (Erbay and Icier, 2010). The main objectives of this study are: a) construct a solar cabinet dryer with cheap, workable and readily available materials for drying of *Ighu,* b) determine the effect of different air-plenums, loading densities and moisture contents on the drying kinetics of *Ighu*; c) evaluate the fitting of the drying experimental data to nine mathematical models.

2 Materials and methods

2.1 Sample preparation

Fresh cassava (TME 419) tubers were obtained from the National Root Crops Research Institute (NRCRI) Umudike, Abia State, Nigeria. They were washed to remove adhering dirt and mud, steamed for 20 to 30 minutes at 100°C and cooled. After cooling, they were peeled and manually shredded with a metallic shredder composed of sharp openings to form threadlike strands. The shredded product was then washed gently four times with portable water and rinsed thoroughly, drained and thinly spread on wooden trays (*mmimi*) to dry in the open sun. A convective oven (Venticell, MMM, Medcener, Germany) was used to determine the initial and final moisture content at 105°C (Ruiz, 2005).

2.2 Sample collection

Dried *Ighu* was purchased from a local market at Isiochi, Umuneche LGA Abia State. Black-*Afara* wood, Zinc, Polythene, Nails, Plywood, Saw dust, Nylon net and Black oil paint were purchased from a local market at Umuahia, Abia State.

2.3 Fabrication of solar dryer

Batch type direct mode natural convection solar dryers were fabricated using cheap, locally available materials. The dryer consists of two major components: collector section and drying chamber. Black-*Afara* wood was used for the dryer frame-work. Five star brand zinc painted black served as the collector flat plate material and for covering the sides of the drying chamber. Glass polythene was framed with wood to form the top cover of the collector and drying chamber sections. Nails of various sizes were used as fasteners. Plywood was used to cover the base and the outer parts of the dryers. Sawdust was used as back collector insulation. Nylon net was framed with wood to form the crop tray and black oil paint was used to paint the whole dryer black except the polythene that was used as the dryer top cover.

2.4 Drying experiments

Dried *Ighu* was rehydrated by soaking in water for 10, 35 and 80 minutes respectively to achieve a moisture content of 57.8%, 67.3% and 75.6% respectively before commencing the drying experiments. Thin-layer drying experiments were carried out in ambient temperature and humidity using the fabricated solar cabinet dryer. Three air-plenums (40, 60, 80 mm), three loading densities (330, 530, 730) and three moisture contents (57.8%, 67.3%, 75.6%) were tested. Analytical semi-microbalance (Model GR-200; sensitivity 0.1 mg, from A and D Co., ltd, Japan), was used to weigh the *Ighu* samples. Data was recorded manually at 120 minutes intervals. A convective oven (Venticell, MMM, Medcener, Germany) was used to determine the initial and final moisture content at 105°C (Ruiz, 2005). During the drying process, experiments continued until the mass change between two weightings was less than 0.05 g (Bagheri et al., 2013). All the experiments were conducted in triplicate. The temperature and relative humidity of the drying air were recorded every five minutes during the drying process. The diagram of *Ighu* on the solar dryer is shown in Figure 1.

Figure 1 Diagram of the drying *Ighu* on the fabricated solar dryer

2.5 Drying procedures

Drying curves were drawn for the samples taken from the three sample trays in the dryer. Ambient air temperature was monitored with an omega thermometer, model RH. 610 with digital readout and a probe for the temperature sensor, which ranges from –10°C to 60°C. The relative humidity of the ambient air every five minutes was tested using a digital probe Bioblock thermohygrometer (precision: ±3% for RH≤80% and ±4% for RH>80%). A vane anemometer, which has a graduated scale and a pointer that indicates wind speed, was mounted and used to measure atmospheric wind speed in the drying zone. Haeni solar 118 Delta instrument, a digital radiometer with sensor output in W m^{-2}, which is highly sensitive, was used to measure the total solar radiation.

2.6 Mathematical modelling of drying curves

The moisture content was expressed in percentage wet basis (%, w.b) and then converted to kilogram water per kilogram dry matter. The drying curves were fitted to nine different moisture ratio models to select a suitable model for describing the drying process of *Ighu*. The samples from open sun drying were also included, for comparison. Mathematical models applied to the drying curves are shown in Table 1.

Table 1 Mathematical models applied to the drying curves

Model Name	Equation	References
Newton	MR=exp(–kt))	(Ayensu, 1997)
Page	MR=exp(–kt^n)	(Doymaz, 2004a)
Henderson and Pabis	MR=aexp(–kt)	(Rahman et al., 1998)
Logarithmic	MR=$a$exp(–kt)+c	(Lahsasni et al., 2004b)
Two-term	MR=$a$exp(–k_0t)+cexp(–k_1t)	(Dandamrongrak et al., 2002)
Modified Page	MR=exp[–(kt)^n]	(Hayaloglu et al., 2007)
Two-term exponential	MR=$a$exp(–kt)+(1–a)cexp(–kat)	(Hayaloglu et al., 2007
Wang and Singh	MR=1+at+ct^2	(Hayaloglu et al., 2007)
Midilli et al.	MR=$a$exp(–kt)+ct	(Hayaloglu et al., 2007)

Note: a, c, k, k_0, k_1 and n are drying constants and t is the drying time measured in seconds.

Moisture ratio of the samples during drying was expressed by Equation (1):

$$MR = \frac{M_d}{M_o} - 1 \tag{1}$$

where, M_d, M_o and M_e are moisture content at any time, initial and equilibrium moisture content (Kg water/Kg dry matter), respectively. The values of M_e are usually little compared to those of M or M_o, the error that is usually involved in the simplification is negligible (Aghbashlo et al., 2008), thus moisture ratio was calculated using Equation (2) below (Shanmugam and Natarajan, 2006):

$$MR = \frac{M_d}{M_o} \tag{2}$$

The moisture content data at each drying process, obtained at different loading densities and air-plenum were converted to the moisture ratio values and fitted versus the drying time. Then the selected thin layer drying models were compared according to the statistical results of coefficient of determination (R^2), root mean square error (*RMSE*) and reduced mean square errors (*MSE*) (Hossain and Bala, 2002; Bagheri et al., 2013). The model with the highest value for R^2 was selected to describe the drying curves. As well, the lowest values of *RMSE* and *MSE* described how good the fit is (Doymaz, 2004a; Saeed et al., 2006; Kingsly and Singh, 2007). The statistical values were calculated from Equations (3), (4) and (5):

$$R^2 = 1 - \sum_{i=1}^{N} (MR_{per} - MR_{exp,i})^2 \tag{3}$$

$$MSE = \frac{\sum_{i=1}^{n}(MR_{exp,i} - MR_{pre,i})^2}{N} \quad (4)$$

$$RMSE = MSE^{1/2} \quad (5)$$

In the above equations, $MR_{pre,i}$ is the i_{th} prediction moisture ratio, $MR_{exp,i}$ is the experimental moisture ratio, N is number of observations and n is number of constants.

3 Results and discussion

3.1 Drying procedures

During the drying experiments, the daily mean values of ambient air temperature and solar radiation ranged from 25°C to 45°C, 165.3-835 W m^{-2}, respectively. The ambient air temperature and solar radiation reached the highest figures between 12:10 h and 14:10 h.

3.2 Drying characteristics of *Ighu*

Rehydrated *Ighu* samples were dried from the initial moisture content of 57.8%, 67.3%, and 75.6% to an average final moisture content of 11.4% using natural convection solar dryers of air-plenum 40, 60 and 80 mm and loading density of 330, 530 and 730 g mm^{-2} in a thin-layer. Moisture ratio decreased with increase in drying time (Bagheri et al., 2013). The moisture content rapidly dropped at the initial stage and then it gradually decreased till it reached an equilibrium point. The effect of initial moisture content on drying time showed that increase in moisture content resulted in increase in drying time. *Ighu* samples with the loading density of 730, 530 and 330 g mm^{-2} that were dried in the dryers took the average of 1,000, 653 and 507 min respectively to reach the safe final moisture content of 11.4% and the same sample of 730 g mm^{-2} loading density required an average of 1,320 min in an open sun to reach the same moisture value. Therefore, from the obtained result it could be concluded that drying rate decreased continuously with increased loading density. All the drying processes occurred in the falling rate period. This indicates that diffusion is most likely the dominant physical mechanism governing moisture movement within the *Ighu* samples. Similar results have been reported by various researchers in potato slices (Akpinar et al., 2003), ripe banana (Nguyen and Price, 2007), pomegranate arils (Motevali et al., 2010), Mulberry (Doymaz, 2004a), eggplant (Erketin and Yaldiz, 2004), peach slices (Kingsly et al., 2007) and cassava chips (Tunde-Akintunde and Afon, 2010).

The moisture ratio profile of *Ighu* with respect to drying time is shown in Figures 2 to 10. From the Figures, it was observed that moisture ratio decreased with increase in drying time. The moisture content rapidly dropped at the initial stage and then it gradually decreased till it reached an equilibrium point. The effect of initial moisture content on drying time showed that increase in moisture content resulted in increase in drying time.

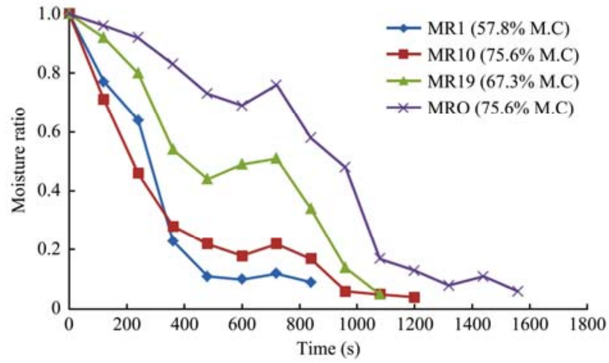

Figure 1 Moisture ratio of *Ighu* at 730 g mm^{-2} loading density and 80 mm Air-Plenum

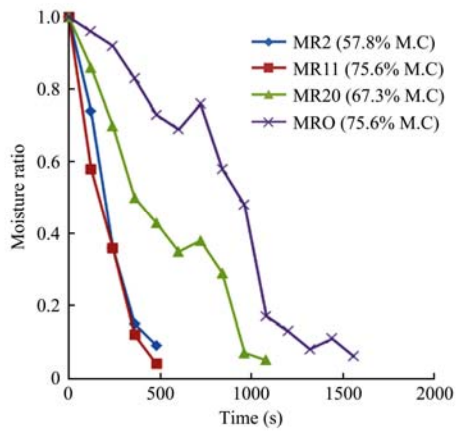

Figure 2 Moisture ratio of *Ighu* at 730 g mm^{-2} loading density and 60 mm Air-Plenum

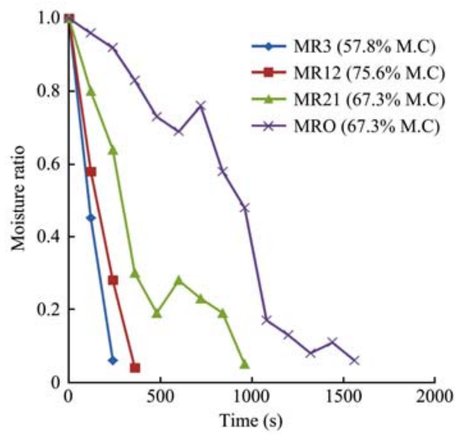

Figure 3 Moisture ratio of *Ighu* at 730 g mm^{-2} loading density and 40 mm Air-Plenum

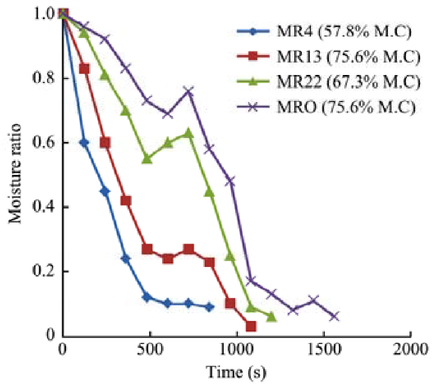

Figure 4 Moisture ratio of *Ighu* at 530 g mm^{-2} loading density and 80 mm Air-Plenum

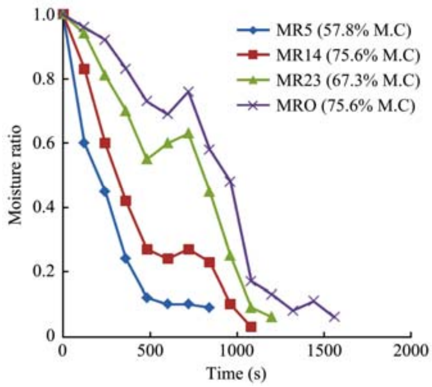

Figure 5 Graph of moisture ratio of *Ighu* at 530 g mm^{-2} loading density and 60 mm Air-Plenum

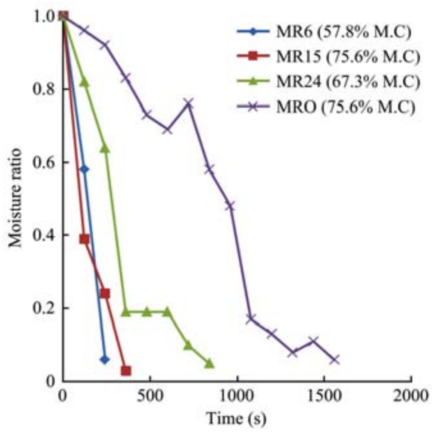

Figure 6 Moisture ratio of *Ighu* at 530 g mm^{-2} loading density and 40 mm Air-Plenum

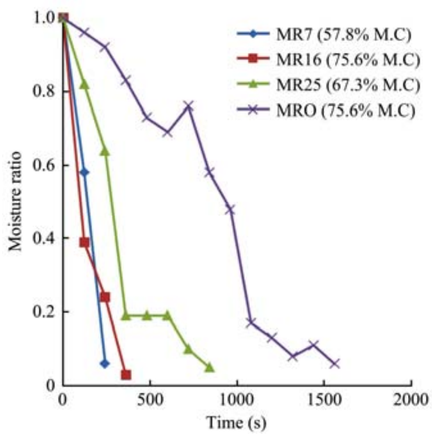

Figure 7 Moisture ratio of *Ighu* at 330 g mm^{-2} loading density and 80 mm Air-Plenum

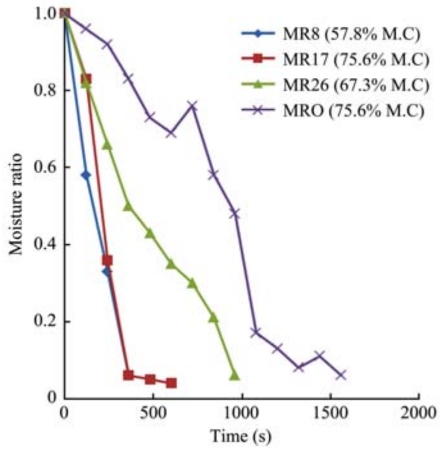

Figure 8 Moisture ratio of *Ighu* at 330 g mm^{-2} loading density and 60 mm Air-Plenum

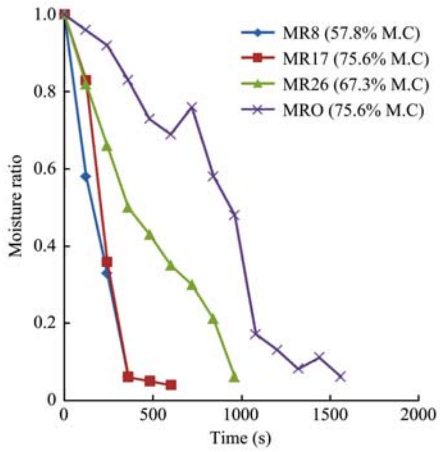

Figure 9 Moisture ratio of *Ighu* at 330 g mm^{-2} loading density and 40 mm Air-Plenum

Average statistical result of the nine selected thin layer drying models resulting from fitting of the nine drying models to the experimental data from solar cabinet and open sun drying, are presented in Tables 2 and 3 respectively. The Page model and modified Page model represented the experimental values of moisture ratio satisfactorily having the lowest values of RMSE, MSE and the highest value of R^2. Thus, the Page model and Modified Page model represented the experimental values of moisture ratio satisfactorily and can be assumed to represent the drying behaviour of *Ighu*. Tuncay et al. (2005) also worked on the mathematical modeling of bay leaves and obtained Page model and Modified Page model as the best for describing the drying characteristics of the samples. However, Bagheri et al. (2013) reported that the Page model represented the experimental values of moisture ratio satisfactorily for mathematical modeling of thin layer solar drying of tomato slice. Page model predictions were more accurate for Mathematical modelling of thin layer solar drying of whole *okra* (*Abelmoschus esculentus* (L.) *Moench*) pods (Ismail and Ibn Idriss, 2013). On the other hand, Koua et al. (2009) reported that the Henderson and Pabis drying model were the most suitable for describing the solar drying curves of plantain banana, mango and cassava. Yaldiz et al. (2001) reported that a two-term drying model satisfactorily described the solar drying curve of Sultana grapes.

The values of R^2, *RMSE* and *MSE* were better compared with the findings of several previous works in fitting the model to the experimental data. Akpinar (2006) reported R^2 of 0.99869 and *MSE*, 2.31×10^{-3} in drying of apples. In the drying of green table olives, R^2 values ranging from 0.9890-0.9987 were reported (Demir et al., 2007). For Figures, R^2, *MSE* and *RMSE* values of 0.9912, 7.06×10^{3} and 0.074918 were reported (Doymaz, 2005b).

Table 2 Average statistical result of the nine selected thin layer drying models

Model	R^2	*RMSE*	*MSE*	*a*	*c*	*K*	k_0	k_1	*n*
Newton	0.9546	0.0711	0.0067			0.0040			
Page	0.9740	0.0511	0.0037			0.0023			1.3337
Henderson & Pabis	0.9566	0.0842	0.0086	1.0227		0.0041			
Logarithmic	0.9679	0.0710	0.0074	-24.0083	25.1139	0.0023			
Two-term	0.9726	0.0704	0.0066	1.5804	-0.8180		7.41E-05	1.0742	
Modified page	0.97404	0.0511	0.0037			0.0037			1.3337
Two-term exponential	0.9655	0.0624	0.0061	1.3672		0.0055			
Wang and Sing	0.9693	0.0557	0.0048	-0.0029	2.154-06				
Midilli *et al*	0.9735	0.0609	0.0052	1.0114	-0.0004	0.0030			

Note: *a*, *c*, *k*, k_0, k_1 and *n* are drying constants.

Table 3 Statistical result of the nine selected thin layer drying models for natural sun drying

Model	R^2	*MSE*	*a*	*c*	*K*	k_0	k_1	*n*
Newton	0.9173	0.0099			0.0016			
Page	0.9640	0.0044			0.0012			1.4869
Henderson & Pabis	0.9283	0.0093	1.0619		0.0017			
Logarithmic	0.9590	0.0055	63.6634	-55.3175	0.0014			
Two-term	0.9547	0.0069	53.0328	-52.0		0.0022	-0.0062	
Modified page	0.9640	0.0044			0.0017			1.4869
Two-term exponential	0.9503	0.0062	1.4012		0.0021			
Wang and Sing	0.9523	0.0057	-0.0012	6.2E-007				
Midilli *et al*	0.9593	0.0055	1.0346	-0.0002	0.0013			

Note: *a*, *c*, *k*, k_0, k_1 and *n* are drying constants.

4 Conclusion

In order to explain the drying behavior of *Ighu*, nine different thin layer drying model were fitted to experimental data and compared according to their R^2, *RMSE* and *MSE*. Page model and modified Page model were found as the best model which could be used to predict the moisture content of *Ighu* during solar and open sun drying processes. Since constant rate period was not noticed during the drying processes which could be as a result of time lag for data collection, it is recommended that the same variables be tested again based on reduced time intervals and the effect of microbes on the samples should be determined.

Disclosure Statement

The authors declare no actual or potential conflict of interest including any financial, personal, or other relationships with other people or organizations.

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