Evaluation of the Dehydration Kinetics of Cassava (*Manihot Esculenta*) Slices Dried Using a Refractance Window^{TM} Dryer

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Abstract

The dehydration kinetics of cassava slices dried using a Refractance Window^{TM}, a novel contact surface drying technique, is presented in this study. The dryer was constructed by modifying a laboratory water bath. Cassava slices of 3 mm thick were dried on the Refractance Window^{TM}, and the moisture content of the slices was measured as the drying progressed. A water temperature between 75 – 80 ^oC was maintained beneath the plastic film. Drying curves were obtained from the drying data, and the thin layer model that best fit the drying data was determined. The bulk density and rehydration ratio of the dried cassava were determined. The cassava slices were observed to dry to about 5 % moisture content after 210 minutes. The regression analysis results showed that the Haghi and Ghanadzadeh thin layer model best described the drying data for 3 mm thick sized cassava slices. The Mean Bias Error (MBE), the Coefficient of Determination (R^2), the Root Mean Square Error (RMSE) and the Chi-square (χ2) values were -8.83x10^{-6}, 9984.34x10^{-4}, 4.20x10^{-4} and 4.41x10^{-4} respectively. The Rehydration Ratio increased to a steady value of 3.17 in about 180 minutes.

***Keywords**: Drying, Models, Rehydration Ratio, Regression Analysis*

1.0 INTRODUCTION

Cassava (*Manihot esculenta*) tubers are processed into flour and "garri" which are then used in the preparation of many Nigerian cuisines. Cassava peels have also been used as a source of feed for some animals. Cassava tubers and its products are excellent sources of dietary energy (Ayankunbi *et al*., 1991; Tunde-Akintunde and Afon, 2010). The roots contain about 32 % starch, 65 % moisture, 0.8 – 1 % protein on a wet weight basis and 92.5 % carbohydrate on a dry basis (Cock, 1985). Over 200 million people worldwide rely on cassava products as a major source of dietary calories. By supplying up to 1050 kilojoules/hectare (Cock, 1985), cassava tubers are the most efficient energy producers of all food crops.

The Cassava flour (elubo) and the processed cassava grains (garri) preparation processes involve peeling, slicing, washing and drying of its tuber. The dried cassava tuber is then ground into fine powder to make "elubo" or grated to make "garri". The preparation process is laborious and time-consuming (Lancaster *et al*., 1982) and the quality of the cassava flour or "garri" produced is determined mainly by the drying process. While cassava has been known to be dehydrated using the flash drying methods (Ajao and Adegun, 2009) and the rotary drying methods (Adebowale *et al*., 2008), natural sun drying is the most common method of drying cassava tubers in regions where they are grown (Mlingi, 1995). However, this process is slow as it depends on the ambient temperature and humidity in the regions. Similarly, natural sun drying can only be done properly during the dry season. When drying times exceed three days, the product is exposed to contamination as a result of fungi growth, infestation by micro-organisms or simply dirt from the atmosphere. If the drying process is fast enough, and the final product is dry enough, contamination can be prevented (Marsh, 2002). There is, therefore, a need to find faster methods of reducing the time to dry cassava tubers. In this study, the Refractance Window^{TM} drying method of dehydrating cassava slices is investigated. An understanding of the drying kinetics of cassava slices, using this novel technology will enhance the design of equipment that operates continuously, thereby, reducing the production time of dehydrated products.

2.0 MATERIALS AND METHOD

2.1 The Equipment

A schematic diagram of the equipment used is shown in **Figure 1**. The equipment is a Refractance Window^{TM} type dryer that consists of a laboratory water-bath, heated with a 2.5 kW electric temperature controlled emersion heater. The bath's cover was replaced with a 0.15 mm thick transparent plastic film, which was secured in place with metal brackets so that the lower face of the plastic film was always in contact with the water. The air-vapour mixture above the dryer was removed by the stream of air blown by a fan. The fan rotated at 1300/1800 rpm and produced a draft of air with a velocity of 1.7 ms^{-1} above the plastic film.

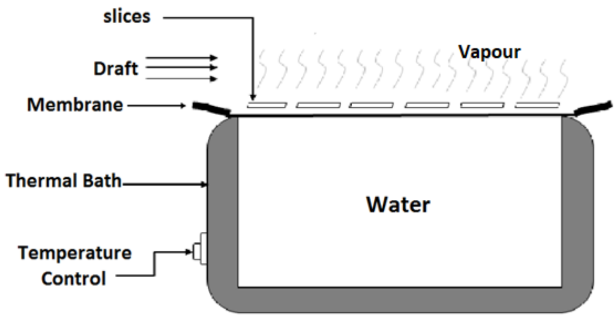

Figure 1: Set up of the Apparatus Used

2.2 Preparation of Cassava Slices

The Cassava tubers used in this study were obtained from a local farm. The tubers were washed, peeled and cut into 3 mm thick slices using a Benriner Japanese Mandolin type slicer manufactured by Benriner Co. Ltd., Iwakuni-City, Japan. The Cassava slices were soaked in water at an initial temperature of 70 ^{o}C. Soaking was performed to detoxify the tuber of the free cyanide in the fresh root. After 72 hours the cassava slices were placed on an absorbent to remove the unbound water. The slices were then dried on the plastic film of the dryer.

2.3 The Experiment

With the plastic film secured in place, the water in the bath was heated to a temperature of 75– 80 ^{o}C and this temperature range was maintained throughout the experiment. The cassava slices were then placed on the plastic film to dry. As the experiment progressed and at intervals of 15 minutes, some cassava slices were removed. The moisture content of the removed cassava slices was determined using a moisture analyzer. The drying process was stopped when the moisture content of the cassava slices was about 6 – 7 % (wet basis). The drying experiments were replicated three times for each drying period, and the average moisture content values were taken.

2.4 Measurements

The moisture content and the weights of the cassava slices, both before and after the drying operation were measured using an MB45 OHAUS Moisture Analyser. The OHAUS moisture analyser gives mass readings and percentage moisture contents readings to an accuracy of ± 0.01g and 0.01% respectively. A digital Vernier caliper was used in measuring the thickness of the cassava slices. The room humidity and temperature were determined with a Digital Hygrometer Thermometer Indoor Humidity Monitor, which had both a temperature gauge and a humidity meter. The speed of the draft of air above the transparent plastic film was measured by an anemometer - Proster Anemometer Digital LCD Wind Speed Meter Gauge.

2.4.1 The Moisture Ratio

The moisture ratio (MR) is an important property of drying materials when considering their drying kinetics. The moisture ratio was determined from the experimentally observed data as in Eq. 1.

$$MR = \frac{MC_t - MC_e}{MC_i - MC_e} \quad (1)$$

where MC_t is the moisture content of cassava after drying for a period of time t; MC_e is the equilibrium moisture content of dried cassava and MC_i is the initial moisture content of fresh cassava all in the unit of kg of water removed per kg of solids.

2.4.2 Bulk Density (ρ_b) Determination

The bulk density of the dried cassava slices was determined using the procedure described by Abdul-Fadl and Ghanem (2011). A known volume of water, V_i was measured into a graduated measuring cylinder. The cassava slice(s) of known mass, M_s, was dropped into the water in the measuring cylinder; this causes the water mark to rise to a final volume, V_f. The volume, V_s of the sample was calculated as $V_f - V_i$. The bulk density, ρ_b , was then determined using Eq. 2.

$$\rho_b = \frac{M_s}{V_s} = \frac{M_s}{V_f - V_i} \quad (2)$$

where ρ_b is the bulk density in grams per ml, M_s is the mass of sample used in grams and V_s is the volume in ml occupied by sample in the measuring cylinder.

2.4.3 Rehydration Ratio (RR) Determination

The essence of dehydrating food is ultimately to be able to rehydrate and consume the product at some future time. The ability of the dried product to rehydrate is therefore an important quality as it indicates the ease of the product to be reconstituted to its original state. The rehydration ratio was determined by soaking the dried cassava in water with a water-to-cassava weight ratio greater than 6 as recommended by Baron Spices and Seasonings (2014). The experiments were repeated by increasing the soaking time. In each instance the mass of the rehydrated solid was then measured and the rehydration ratio determined using Eq. 3.

$$RR = \frac{M_r}{M_d} \quad (3)$$

where, M_r is the mass of the rehydrated solid and M_d is the mass of the dry sample.

2.4.4 Effective Moisture Diffusivity Determination

Fick's second equation of diffusion is used in determining the effective moisture diffusivity (D_{eff}); as presented in Eq. 4 (Crank, 1975).

$$MR = \frac{8}{\pi}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2} exp^{\left(-\frac{(2n-1)^2\pi^2 D_{eff}t}{4L^2}\right)} \quad (4)$$

while the slices were assumed to be of constant moisture diffusivity and of a uniform initial moisture distribution (Crank, 1975).

The moisture ratio equation can be simplified to Eq. 5 (Lopez *et al.,* 2000). Further details on how Eq. 5 is derived can be found in Jena and Das (2007), and Taheri-Garavand *et al.* (2011).

$$MR = \frac{8}{\pi^2}\exp(-\frac{\pi^2 D_{eff}t}{4L^2}) \quad (5)$$

where, MR is the moisture ratio, D_{eff} (m^2s^{-1}) is the effective moisture diffusivity, L (m) is the sample thickness and t is the drying time (s).
A plot of $-\ln(MR)$ against time gives a slope k_d, from which D_{eff} can be obtained using Eq. 6.

$$k_d = \frac{\pi^2 D_{eff}}{4L^2} \quad (6)$$

2.5 The Drying Curves

Drying curves were plotted from the data obtained from the experiments, which are the Moisture Content (wet basis) and Moisture Ratio (MR) against Drying Time.

2.5.1 Obtaining the Best Drying Model

The drying models were evaluated by performing regression analysis using the drying data and the models listed in **Table 1**. The model was selected to be the best, if the value of the Coefficient of Determination (R^2) was closest to unity and Mean Bias Error (MBE), Chi-square (χ2), Root Mean Square Error (RMSE) values are minimal (Akpinar, 2010; Tunde-Akintunde and Afon, 2010; Gikuru and EL-Mesery, 2014; John *et al.*, 2014).

The value of the Coefficient of Determination (R^2) is calculated using Eq. 7.

$$R^2 = \frac{\sum_{i-1}^{N}(MR_i - MR_{prev,i}).\sum_{i=1}^{N}(MR_i - MR_{\exp,i})}{\sqrt{\left[\sum_{i-1}^{N}(MR_i - MR_{pre,i}{}^2)\right]\left[\sum (MR_i - MR_{\exp,i}{}^2)\right]}} \quad (7)$$

The Root Mean Square Error (RMSE) is determined using Eq. 8.

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{\exp,i})^2\right]^{1/2} \quad (8)$$

Chi-square (χ2) is determined using Eq. 9.

$$\chi 2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2}{N-n} \quad (9)$$

Mean Bias Error (MBE) is determined using Eq. 10.

$$MBE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{\exp,i})\right] \quad (10)$$

where, N is the total number of observations, n is the number of model parameters, MR denotes the moisture ratio; $MR_{pre,i}$ and $MR_{\exp,i}$ is the predicted and experimental moisture ratio at *i*th observation respectively.

The thin-layer drying models to which the drying data were fitted are presented in **Table 1.** The parametric coefficients of each model were determined using the Datafit 9.1 data regression software developed by Oakdale Engineering, Oakdale, (2014) PA USA. The software uses the Levenberg-Marquardt Method for Nonlinear Least Square Problems in determining its solution (Gavin, 2013). **Table 2** presents the parametric constants, the Mean Bias Error (MBE), the Coefficient of Determination (R^2), the Root Mean Square Error (RMSE), and the Chi-square (χ2) values for each model.

Table 1 Thin Layer Drying Models

No.	Model Name	Model	Source
1	Newton	MR = exp (-k.t)	Ayensu (1997).
2	Page	MR = exp (−k.t^n)	Page (1949)
3	Modified Page	MR = exp (−$(k.t)^n$)	Ozdemir and Devres (1999)
4	Henderson and Pabis	MR = a.exp (-k.t)	Henderson and Pabis (1961)
5	Modified Henderson and Pabis	MR = a.exp (-k.t)+b.exp (-g.t)+c.exp (-h.t)	Karathanos (1999)
6	Logarithmic	MR = a.exp (-k.t) + c	Togrul and Pehlivan (2003)
7	Two term	MR = a.exp (−k_0.t) + b exp (−k_1.t)	Madamba (1996)
8	Two term exponential	MR = a.exp (-k.t) + (1-a) exp (-k.a.t)	Sharaf-Elden *et al.* (1980)
9	Wang and Singh	MR = 1+ a.t + b.t^2	Wang and Singh (1978)
10	Diffusion Approach	MR = a.exp (-k.t) + (1-a).exp (-k.b.t)	Demir *et al.* (2007)
11	Verma *et al.*	MR = a.exp (-k.t) + (1-a).exp (-g.t)	Verma *et al.* (1985)
12	Aghbashlo *et al.*	MR = exp (-k_1.t/1+k_2.t)	Aghbashlo *et al.* (2009)
13	Midilli *et al.*	MR = a.exp (−k.t^n) + b.t	Midilli *et al.* (2002)
14	Haghi and Ghanadzadeh	MR = a.exp (-b.t^c) + d.t^2 + e.t + f	Haghi and Ghanadzadeh (2005).
15	Simplified Fick's diffusion (SFFD) equation	MR = a.exp[-ct/L^2]	Diamente and Munro (1991)
16	Modified Page equation -II	MR = exp[-k$(t/L^2)^n$]	Diamente and Munro (1993)
17	Weibull	MR = exp(-$(t/a)^b$)	Corzo *et al.* (2008)

3.0 RESULTS AND DISCUSSION

The initial moisture content of the cassava slices was found to be 65 % determined on a wet basis. The humidity of the air during experimentation varied between 48 and 59 %, while the ambient air temperature varied between 26 and 29 ^{o}C. The Moisture content plotted against drying time showed that the moisture content of the cassava slices decreased with increase in drying time to 5 % moisture content for a drying time of 210 minutes **(Figure 2)**. The experimental data of the drying process were fitted into thin layer mathematical drying models frequently used in food drying (see **Table 1**). The drying model that best fitted the experimental data was the Haghi and Ghanadzadeh thin layer drying model because the Coefficient of Determination (R^2) was closest to unity and Mean Bias Error (MBE), Chi-square (χ2), Root Mean Square Error (RMSE) values are minimum (see **Table 2**).

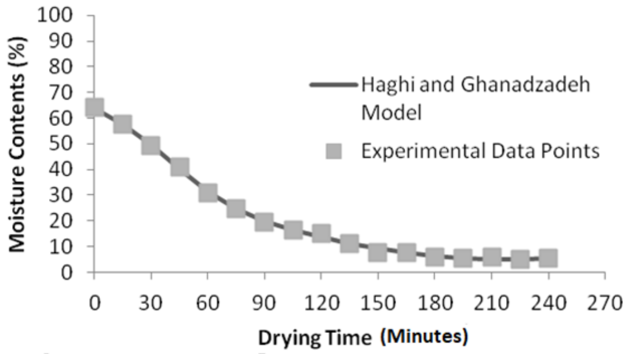

Figure 2: Drying rate: Moisture content *vs.* Drying time

The drying rate plotted against drying time (**Figure 3),** shows an initial rapid increase in the drying rate from about 0.4 kg/kg/min to a peak value of 0.6 kg/kg/min in about 60 minutes. The drying rate then decreased rapidly afterwards.

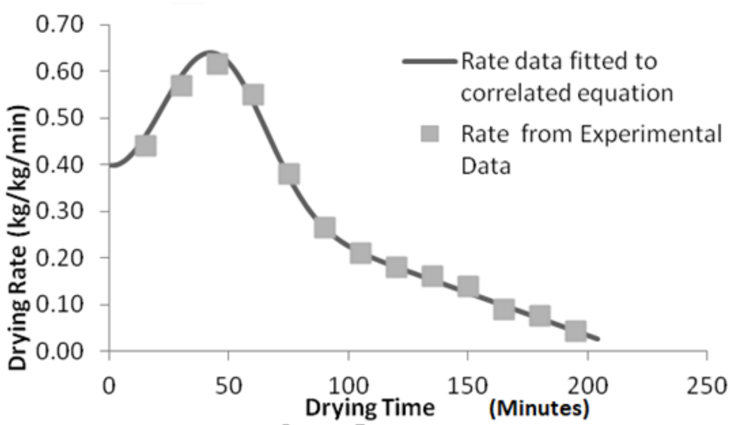

Figure 3: Drying Rate curve: Drying rate *vs.* Drying time

The rehydration ratio of the cassava slices taken at different time intervals is shown in **Figure 4**. The rehydration ratio for 3 mm thick cassava slices increases to 3.10 in the first 60 minutes and thereafter increases to a steady value of 3.17 after 180 minutes.

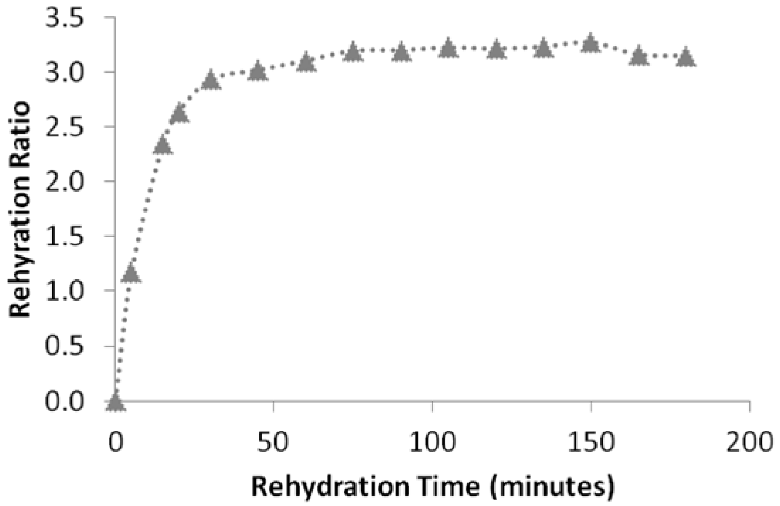

Figure 4: Rehydration Ratio *vs.* Rehydration Time

A plot of *–ln(MR)* against drying time is shown in **Figure 5.** The line and the linear relationship that best fits the data are also shown in the Figure. From the slope, k_d, of the line, the effective moisture diffusivity, D_{eff}, is obtained, according to Eq.6. For 3 mm thick cassava slices, a value of 4.95072 x 10^{-7} m^2/s is obtained as the effective moisture diffusivity.

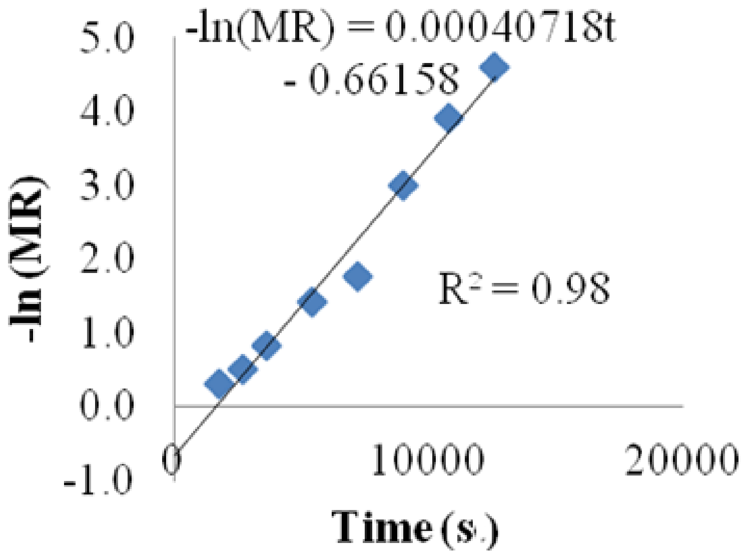

Figure 5: $-\ln(MR)$ ***vs.* time plot - Estimation of Moisture Diffusivity Coefficient**

4.0 CONCLUSION

The Refractance Window™ drying method was used to dry cassava slices with an initial moisture content of 65 % on a wet basis to less than 10 %. The drying model that best describes the dehydration kinetics is the Haghi and Ghanadzadeh thin layer model. Regression analysis indicated that the experimental data fit the model with a coefficient of determination, (R^2), of 0.9984. The cassava slices dried to a moisture content of less than 5 % on a wet basis was within 120 minutes. This time is significantly less than the 3 to 5 days required by the traditional sun drying methods. Analysis of the experimental data also indicated that the drying rate increased to a peak value of 0.6 kg/kg/min in about 60 minutes and thereafter decreased. The rehydration ratio increased to a steady value of 3.17 in about 180 minutes and for the 3 mm thick cassava slices, an effective moisture diffusivity value was estimated to be 4.95072 x 10^{-7} m^2s^{-1}.

Table 2: Constant and Coefficient Obtained by Fitting Data to the Various Thin Layer Models

No.	Model Name	Polymath Constants		R^2	MBE	χ2	RMSE
1	Newton	k = 0.01419		0.9761085	0.007008	0.002992	0.0164088
2	Page	k = 0.00274	n = 1.37990	0.9976221	0.000845264	0.000334973	0.0051767
3	Modified Page	k = 0.01391	n = 1.379611	0.9976221	0.000849	0.000334972	0.0051767
4	Henderson and Pabis	a = 1.05820	k = 0.01497	0.9800387	0.013378	0.002811942	0.0149985
5	Modified Henderson and Pabis	a = 0.35697 g = 0.01497 b = 0.35697	c = 0.34425 h = 0.01496 k = 0.01496	0.9800387	0.01337745	0.005623884	0.0149985
6	Logarithmic / Yagcioglu *et al.*	a = 1.13115 c = -0.09563	k = 0.01207	0.9899756	-1.10131E-06	0.00161388	0.0106288
7	Two term	a = 0.89604 b = 0.16216	k = 0.01497	0.9800387	0.013372	0.003749256	0.0149985
8	Two term exponential	a = 1.964319	k = 0.0220851	0.9974359	0.002954	0.0003612	0.0053755
9	Wang and Singh	a = -0.01020	b = 2.566E-05	0.9933824	0.000386	0.000932225	0.0086358
10	Diffusion Approach	a = -3.24477 b = 0.78729	k = 0.03243	0.9975813	0.002052	0.000389399	0.0052209
11	Verma *et al.*	a = -0.06132 k = 0.74118	g = 0.01490	0.9833247	0.009363	0.00268462	0.0137085
12	Aghbashlo *et al.*	k1 = 0.01021	k = -0.00318	0.9958626	-0.00305	0.00058284	0.0068284
13	Midilli *et al.*	k = 0.00295 n = 1.3612	a = 1.00188 b = -2.74E-05	0.997683	-4.96205E-05	0.0004352	0.00511
14	Haghi and Ghanadzadeh	a = 0.26440 c = 2.70342 e = -0.00674	b = 2.23E-05 d = 1.55E-05 f = 0.73030	0.998434	-8.82891E-06	0.000441201	0.004201
15	Simplified Fick's diffusion (SFFD) eqn.	a = 1.058199	c = 0.13469	0.9800387	0.013378	0.002811942	0.0149985
16	Modified Page Equation -II	k = 0.05690	n = 1.37967	0.9976221	0.000848	0.000334972	0.0051767
17	Weibull	a = 71.8679	b = 1.37961	0.9976221	0.000849	0.000334972	0.0051767

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