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Research Article

Mathematical Modelling of Thin-layer Drying Kinetics of Cassava Meal in a Conductive Rotary Dryer

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Abstract: A conductive rotary dryer was developed for indirect drying of cassava meal in *gari* and cassava flour production. Drum temperature, T_d, batch quantity, Q_b and vapour extraction rate, R_v, of the dryer influenced drying kinetics of cassava meal. Drying data of cassava meal under different dryer conditions were fitted with seven thin-layer drying models and the Logarithmic model had the best goodness of fit with R^2>0.97 for each of the parameters. Model constants, a, k and c were generated as functions of each parameter and three Logarithmic models relating moisture ratio, MR as a function of each parameter were developed. Predicted and experimental values of MR correlated well at R^2>0.97 for each model. Gradients of drying curves of moisture loss, ML, against drying time, t, were linear between t = 0 and a critical time t_c when drying actually stopped. A mathematical model based on the linearity of drying rate, DR, was developed to predict MR as function of T_d, Q_b, R_v and t. The model was validated by comparing experimental and predicted values of MR at various combinations of dryer parameters. Drum temperature and batch quantity had greater effects on drying kinetics than vapour extraction rate. At T_d = 200°C the cassava meal was gelatinized and *gari* with swelling index, SI>2.0 was produced. Cassava flour with SI<2.0 was produced at T_d = 140°C.

Keywords: Cassava, flour, gari, indirect drying, model

INTRODUCTION

Gari and High Quality Cassava Flour (HQCF) are important food products derived from cassava (*Manihot esculenta* Crantz.). *Gari* is a staple food and a popular source of carbohydrate for millions of consumers around the world (Udofia *et al*., 2011). It is a fermented, toasted and gelatinized granular meal generally produced by the traditional manual method in Nigeria (Ajibola *et al*., 1998; Taiwo *et al*., 2010). HQCF on the other hand is unfermented, un-gelatinized and dried granular flour (USAID, 2010) which has various domestic and industrial applications (Dziedzoave *et al*., 2006). Both *gari* and HQCF can be produced from fresh cassava tubers in a process described by Sanni *et al*. (2015a, 2015b). The processing steps involved in their production are shown in the flow chart of Fig. 1.

Drying is a thermo-physical and physico-chemical action whose dynamic principles are governed by heat and mass transfer laws within and outside the grains of the material being dried (Sahay and Singh, 2001). According to several authors (Sherwood, 1936; Rozis, 1997; CIGR, 1999; Mujumdar, 2006), the drying ofagricultural materials occurs in two distinct stages-constant rate period and falling rate period but only a few agricultural products exhibit the constant rate drying which is characterized by low internal resistance to moisture movement in the grain (Brooker *et al*., 1974). Sahay and Singh (2001) agree that movement of moisture within the material takes place because of diffusion, cell contraction and vapour pressure gradient between the material and its drying medium. Most agricultural materials, especially starchy foods such as cassava meal are hygroscopic, so they can lose or absorb moisture depending on the ambient air condition (Serpil and Servet, 2006). When the ambient air temperature rises and the relative humidity of the air decreases, the water present in the food grain vaporizes and the material loses moisture to the environment and drying is said to take place.

Drying of cassava meal is generally achieved by roasting a batch of 4-5 kg of the material on a flat metallic frying pan placed on a gas or fire-wood stove (Sanni, 2014). The sensible heat required for activation and vaporization of the internal moisture is generated by conduction through the metallic wall of the frying pan and by direct contact between the cassava granules

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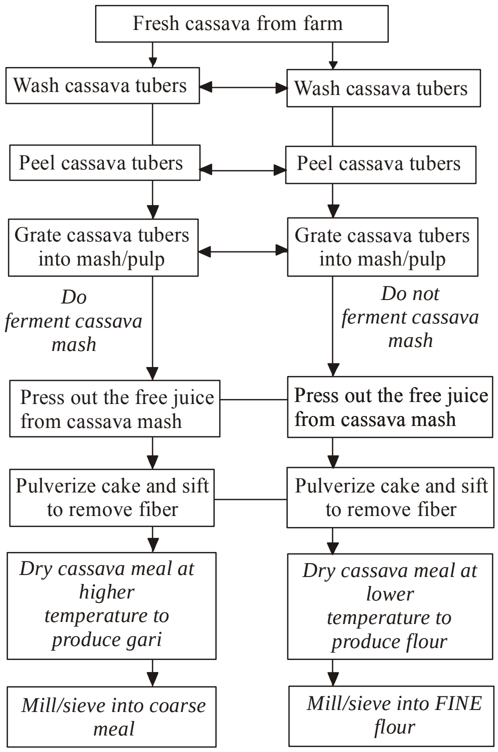


Fig. 1: Production of *gari* and HQCF from cassava (Sanni, 2014)

and the hot surface of the pan. By vigorous stirring of the cassava meal, the individual grains make contact with the hot surface and their internal moisture is vaporized by diffusion until the cassava meal is dried. This phenomenon is known as contact or indirect drying (Hall, 1980; Mujumdar, 2006) and the drying rate depends largely on the quantity of cassava meal, the pan temperature and ambient air velocity, relative humidity and temperature. The process can therefore be equated with thin-layer drying (Moreno *et al*., 2007).

The thin layer drying kinetics of various agricultural materials in different types of dryers have been studied and modelled (Zarein *et al*., 2013; Chen *et al*., 2013; Bassene *et al*., 2013; Khawas *et al*., 2014). However most literature reported findings on the use of direct or convective hot air drying of agricultural materials. Few works have been reported on thin layer drying of cassava products by convection (Nwabanne, 2009; Ademiluyi *et al*., 2010; Ajala *et al*., 2011). In this study, indirect thin-layer drying kinetics of cassava meal in a conductive rotary dryer was investigated with the objective of developing a predictive model which related the drying rate and moisture ratio with the parameters of the dryer.

MATERIALS AND METHODS

Preparation of materials: The schematic diagram of the conductive rotary dryer used for the drying experiments (Sanni *et al*., 2015b) is shown in Fig. 2. Fresh cassava tubers (TMS 30572) were harvested from the Teaching and Research farm of Obafemi Awolowo University, Ile-Ife and transported to the Processing laboratory of Department of Agricultural and Environmental Engineering where the tubers were peeled, washed and milled to produce a watery mash. The cassava mash was collected in polypropylene sacks and pressed for 3 h under a vertical screw press. The compressed cakes were pulverized and sieved to produce a fibre free granular meal from which batches were collected for the drying experiments (Taiwo *et al*., 2010). The initial moisture content of each batch was determined using the oven drying method of AOAC (2012) before the commencement of each experiment.

Experimental design: Six drying experiments were carried out using the conductive rotary dryer according to the experimental design of Table 1. For each experiment, the drum was heated up by external heating elements and the drum temperature was regulated to the desired levels by means of a sensor, contactor and temperature control meter. The drum and heaters were enclosed in a housing lagged with fibre-glass to prevent

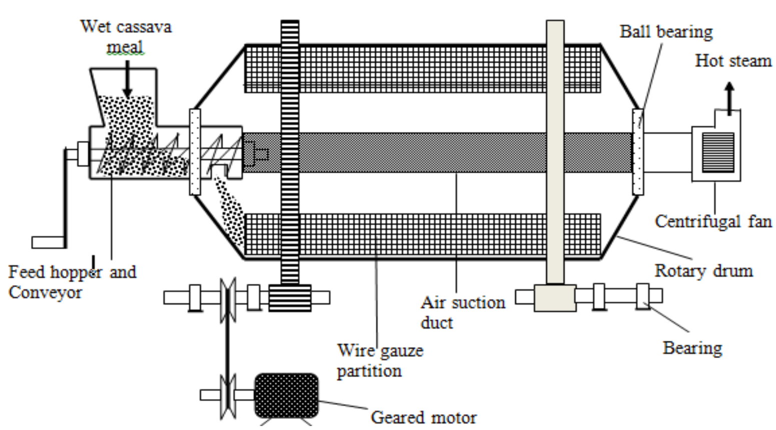


Fig. 2: Schematic diagram of the conductive rotary dryer (Sanni, 2014)

Table 1: Contact drying experiments in the conductive rotary dryer

	Dryer parameters				
Experiment	No. of flights	Drum speed (rpm)	Batch quantity, Q_b (kg)	Vapour extraction rate, R_v (m^3/s)	Drum temp., T_d (°C)
1	2	20	5	0.0075	140
2	2	20	5	0.03	200
3	2	20	8	0.03	140
4	2	20	8	0.0075	200
5	2	20	8	0.03	200
6	2	20	5	0.0075	200

Table 2: Thin layer drying models fitted with cassava meal drying data

S/No.	Name of model	Model equation	References
1	Newton (or Lewis)	$MR = \exp(-kt)$	Liu and Bakker-Arkema (1997)
2	Modified Page	$MR = \exp(-kt)^n$	White *et al*. (1981)
3	Henderson and Pabis	$MR = a \exp(-kt)$	Henderson and Pabis (1961)
4	Logarithmic	$MR = a \exp(-kt) + c$	Toğrul and Pehlivan (2002)
5	Two-term	$MR = a \exp(-k_0 t) + b \exp(-k_1 t)$	Henderson (1974)
6	Wang and Singh	$MR = 1 + at + bt^2$	Wang and Singh (1978)
7	Newly-proposed model by Ademiluyi	$MR = a \exp[-(kt)^n]$	Ademiluyi (2009) and Ademiluyi and Puyate (2013)

heat loss to the environment. The rate of vapour extraction from the drum was regulated to the desired level by controlling the speed of the centrifugal fan and hence its air flow rate. The rotation of the drum and the two wire-gauze flights inside the drum were fixed to constantly lift the cassava granules from the bottom of the heated drum and disperse them into the ambient air thereby exposing every grain to the drying medium. The cyclic cascading motion and fluidization of the cassava granules makes the drying process analogous to thin layer drying.

Experimental procedure: During each of the six drying experiments the conductive rotary dryer was left to run for 60 min and a small sample was taken from each batch at 5 min interval and used to determine the moisture content of the cassava meal using the AOAC (2012) method. The instantaneous moisture contents were used to calculate the moisture ratios which were in turn used to plot the graphs of moisture ratio against drying time (minutes) for each level of the process variables. After each drying experiment, a sample was taken from each batch and used to determine its swelling index according to the method described by Sanni *et al*. (2015a). The swelling index was used to evaluate the degree of gelatinization of the cassava meal after drying and to categorize the dried products into *gari* or HQCF.

Modelling of the thin-layer drying kinetics: For each set of experimental data, the Moisture Ratio (MR) was calculated using Eq. (1) (Radhika *et al*., 2011; Chen *et al*., 2013; Khawas *et al*., 2014):

$$MR = \frac{M_t - M_e}{M_o - M_e} \tag{1}$$

where,

MR : Dimensionless moisture ratio
M_t : Moisture content (dry basis) of cassava meal at time 0<t<60, kg/kg
M_o : Moisture content (dry basis) of cassava meal at time t = 0, kg/kg
M_e : Equilibrium moisture content (% dry basis) of cassava meal (negligible at t = 60)

Because M_e is negligible towards the end of drying, the simplified form of Eq. (2) was used to calculate MR.

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

The MR data for each experiment were plotted against drying time for batch quantity, vapour extraction rate and drum temperature. Sigma-Plot 11.0 was used to perform non-linear regression analysis to fit the 2-level curves of each process variable with seven thin layer drying models presented in Table 2. The goodness of fit of the mathematical models with experimental data was determined using the coefficient of correlation, R^2. The model with the highest R^2 was selected as that which best described the drying kinetics of cassava meal in the dryer (Khawas *et al*., 2014). The constants of the selected model were determined as functions of the three parameters and new mathematical models were developed for each process parameter. The validity of each of the models was tested by comparing predicted and experimental values of MR using coefficient of correlation R^2.

For a closer understanding of the drying kinetics of cassava meal in the conductive rotary dryer, the moisture loss, ML (kg of water) during each drying experiment was calculated using Eq. (3) (Moreno *et al*., 2007).

$$ML = (M_o - M_t)M_d \tag{3}$$

where,

M_d = Dry matter content in the batch of cassava meal (kg).

The moisture loss was plotted against drying time and the gradient of the ML/t curves which is equal to the drying rate was used to study their curvy-linear configuration. It was observed that the gradient of ML/t curve for all the drying experiments was approximately constant between the beginning of drying at t = 0 and a critical time t_c after which it changed to zero, meaning there was no more moisture loss after the critical time t_c. Based on this phenomenon of linearity of drying rate, DR at $0 \leq t \leq t_c$, the multiple linear regression expression of Eq. (4) was assumed to describe the drying process within the linear range of each ML/t curve.

$$\mathrm{DR} = \mathrm{a} + \mathrm{bx} + \mathrm{cy} + \mathrm{dz} \tag{4}$$

where,

DR : ML/t, kg water/min
x, y, z : Drum temperature, vapour extraction rate, batch quantity respectively
a, b, c, d : Model constants

Multiple regression analysis was carried out using Sigma-Plot 11.0 to analyse how variations in each of the three parameters, x, y and z simultaneously affected the drying rate, DR and a mathematical model relating drying rate, DR as a function of drum temperature, vapour extraction rate and batch quantity was generated in the form of Eq. (5):

$$\mathrm{DR} = \frac{(\mathrm{M_o} - \mathrm{M_t})\mathrm{M_d}}{\mathrm{t}} = \mathrm{a} + \mathrm{bT_d} + \mathrm{cR_v} + \mathrm{dQ_b} \text{ valid at } 0 \leq \mathrm{t} \leq \mathrm{t_c} \tag{5}$$

By combining Eq. (2) and (5) and making MR subject of the formula, a general mathematical model of moisture ratio, MR as a function of the three parameters, T_d, R_v, Q_b and drying time, t was generated as shown in Eq. (6):

$$\mathrm{MR} = \frac{\mathrm{M_t}}{\mathrm{M_o}} = 1 - \frac{(\mathrm{DR})\mathrm{t}}{\mathrm{M_o M_d}} = \frac{(\mathrm{a} + \mathrm{bT_d} + \mathrm{cR_v} + \mathrm{dQ_b})t}{\mathrm{M_o M_d}} \text{ valid at } 0 \leq \mathrm{t} \leq \mathrm{t_c} \tag{6}$$

The validity of the model was tested by comparing the experimental and predicted values of MR graphically and statistically using coefficient of correlation, R^2 (Radhika *et al*., 2011).

RESULTS AND DISCUSSION

The drying curves of moisture content against drying time, of the six drying experiments are presented in Fig. 3.

The swelling indices of the dried products from the experiments in chronological order were 1.75, 2.36, 1.78, 1.94, 2.19 and 3.22, consecutively. According to Apea-Bah *et al*. (2009), the swelling capacity of dried cassava meal indicates the extent of gelatinization of its starch content and for good quality *gari*, the swelling index can vary between 2.0 and 3.5 (Ajibola *et al*., 1987; Sanni *et al*., 2008; Udofia *et al*., 2011). It follows that dried cassava samples from experiments 2, 5 and 6 were more gelatinized to *gari* while the products of experiments 1, 3 and 4 with swelling index below 2.0 were less gelatinized flour. Figure 3 further shows that the drying curves of the floury products were more linear than those of *garified* samples and it took longer drying time of 40-50 min for the cassava meal to reach safe moisture content of 10%. The drying time of the *gari* samples was 19-31 min. This can be attributed to the generally lower temperature and higher batch quantity under which experiments, 1, 3 and 4 were conducted. However all the samples were dried to the recommended 10-13% moisture content (SON, 2004) in less than 60 min. The average roasting time for *gari* in the traditional manual method is 40 min (Sanni, 2014).

The graphs of moisture ratio against drying time at the two levels of batch quantity vapour extraction rate and drum temperature are presented in Fig. 4a to 4c, respectively.

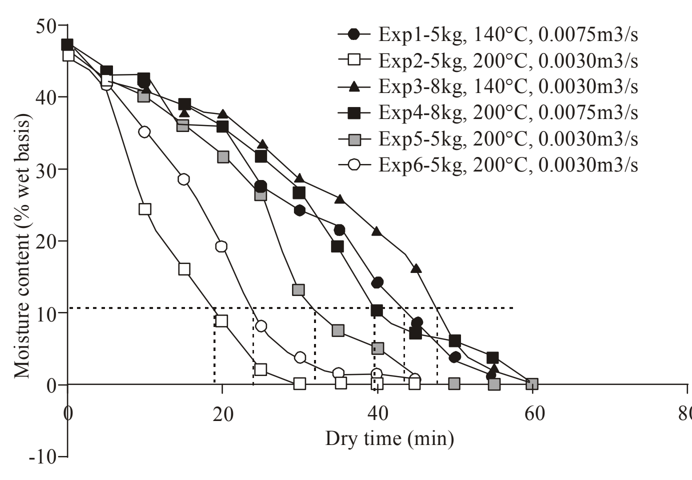


Fig. 3: Drying curves of cassava meal at different dryer conditions

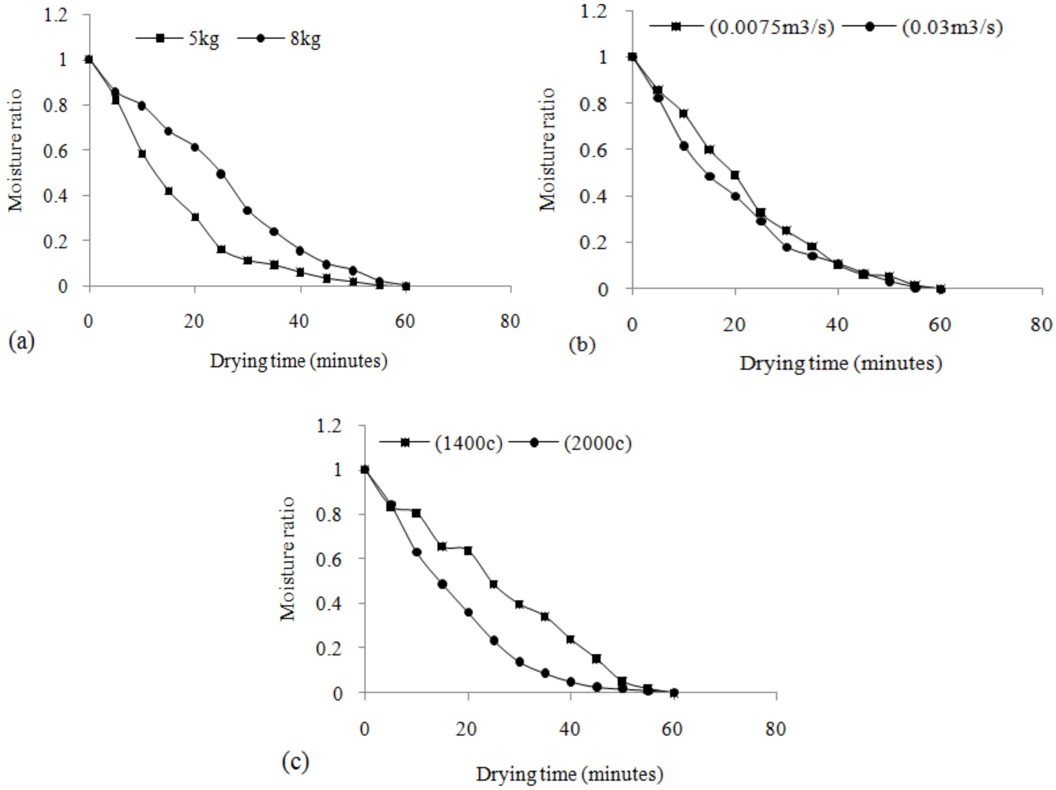


Fig. 4: Drying kinetics of cassava meal under different dryer conditions

Table 3: Result of non-linear regression analysis using SigmaPlot 11.0

Model of best fit	Dryer parameters	Model constants			R	R^2	Adj. R^2	Std. Error
Logarithmic Model:	Batch Quantity (kg)	a	k	c				
MR = *a*exp (-*k*t) +*c*	5	1.0926	0.0567	-0.0529	0.9967	0.9934	0.9921	0.0296
	8	1.8113	0.0150	-0.7899	0.9939	0.9878	0.9854	0.0424
	Vapor Extraction Rate (m^3/s)	a	k	c				
	0.0075	1.2776	0.0301	-0.2410	0.9961	0.9921	0.9905	0.0335
	0.03	1.1150	0.0422	-0.1022	0.9990	0.9979	0.9975	0.0164
	Drum Temperature (°C)	a	k	c				
	140	2.5066	0.0088	-1.5175	0.9960	0.9921	0.9905	0.0326
	200	1.1390	0.0472	-0.0979	0.9964	0.9929	0.9915	0.0315

Table 4: Logarithmic model constants as function of dryer parameters

Logarithmic Model Constants	Batch Quantity (Q_b)	Vapour Extraction Rate (R_v)	Drum Temperature (T_d)
a	$a = -0.1052+0.2396Q_b$	$a = 1.3318-7.2267R_v$	$a = 5.6977 - 0.0228T_d$
k	$k = 0.1262-0.0139Q_b$	$k = 0.0261+0.5378R_v$	$k = -0.0808+0.0006T_d$
c	$c = 1.1754-0.2457Q_b$	$c = -0.2873+6.1689R_v$	$c = -4.8299+0.0237T_d$

Table 5: Logarithmic models of thin-layer drying of cassava meal

Process parameter	Mathematical Model
Batch Quantity (Q_b)	$MR= (-0.1052+0.2396Q_b) \exp\{(-0.1262 + 0.0139Q_b)t\}+1.1754-0.2457Q_b$
Vapour Extraction Rate (R_v)	$MR= (1.3318-7.2267R_v) \exp\{(-0.0261-0.5378R_v)t\}-0.2873+6.1689R_v$
Drum Temperature (T_d)	$MR= (5.6977-0.0228T_d) \exp\{(0.0808 - 0.0006T_d)t\}- 4.8299+0.0237T_d$

Figure 4b shows that vapour extraction rate of the conductive rotary dryer had the least effect on the drying kinetics of cassava meal but batch quantity and drum temperature had more significant effects on the drying kinetics. This result agrees with the finding of Ademiluyi and Puyate (2013).

After using SigmaPlot 11.0 to fit the experimental drying data with the seven thin layer drying models of Table 2, the Logarithmic model had the highest R^2 and smallest standard error. The result of the non-linear regression analysis for the Logarithmic model and its constants are presented in Table 3.

The Logarithmic model constants were regressed with the two levels of each dryer parameter and each constant was generated as a function of the dryer parameters. All the linear equations were regressed at R^2 of 1.0 using Sigma Plot 11.0 as presented in Table 4.

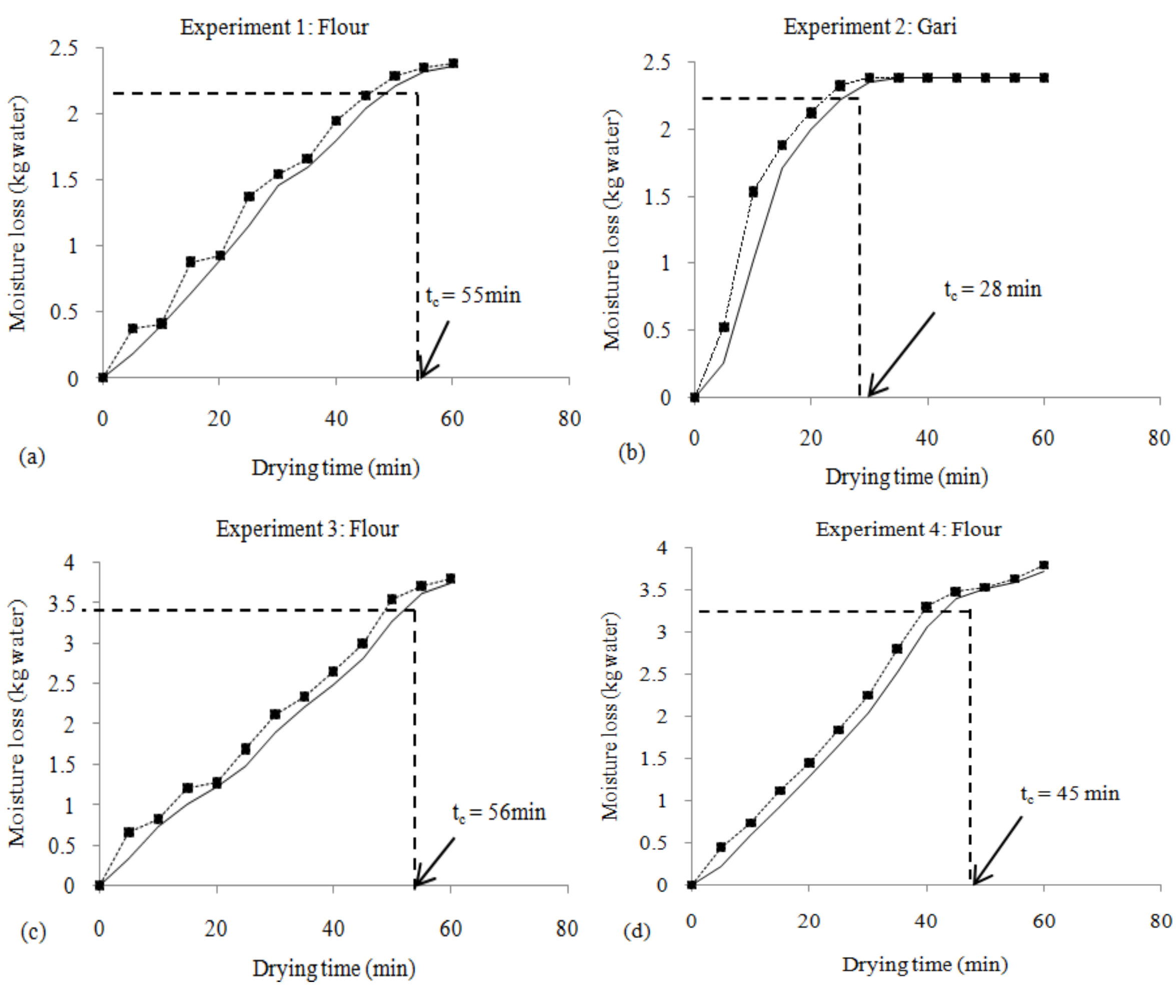
For each dryer parameter a mathematical equation was generated by inserting the expressions for its model constants into the original Logarithmic model as presented in Table 5.

The three models were valid within the range of the parameter levels and the $R^2$of the experimental and predicted drying curves of moisture ratio against drying time were all higher than 0.97 as shown in Table 6.

The graphs of moisture loss against drying time for the six drying experiments are presented in Fig. 5a to 5f. The gradients of all the graphs were approximately constant at $0 \leq t \leq t_c$ and the critical time t_c coincided with the point where drying had stopped due to the absence of moisture in the cassava meal. As earlier observed, the critical time t_c at which actual drying ended in experiments 1, 3 and 4 (swelling index <2.0), were 55, 56 and 45 min, respectively and the t_c in experiments 2, 5 and 6 (swelling index>2.0) were 28, 40 and 32 min, respectively. This confirms that longer drying time at lower drum temperature was required for HQCF production. On the other hand *gari* required a higher

Table 6: Validation parameter dependent models

Process parameter	Predictive Mathematical models	Validity R^2
Batch quantity (q_b)		
At q_b = 5 kg	Mr = 1.0928 exp (-0.0567t) – 0.0531	0.9934
At q_b = 8 kg	Mr = 1.8116 exp (-0.015t) – 0.7902	0.9878
Vapour extraction rate (r_v)		
At r_v= 0.0075 m^3/s	Mr = 1.2776 exp (-0.0301t) – 0.2410	0.9921
At r_v= 0.03 m^3/s	Mr = 1.1150 exp (-0.0422t) – 0.1022	0.9979
Drum temperature (t_d)		
At t_d = 140°c	Mr = 2.5057 exp (-0.0032t) – 1.5119	0.9899
At t_d = 200°c	Mr = 1.1377 exp (-0.0392t) – 0.0899	0.9894



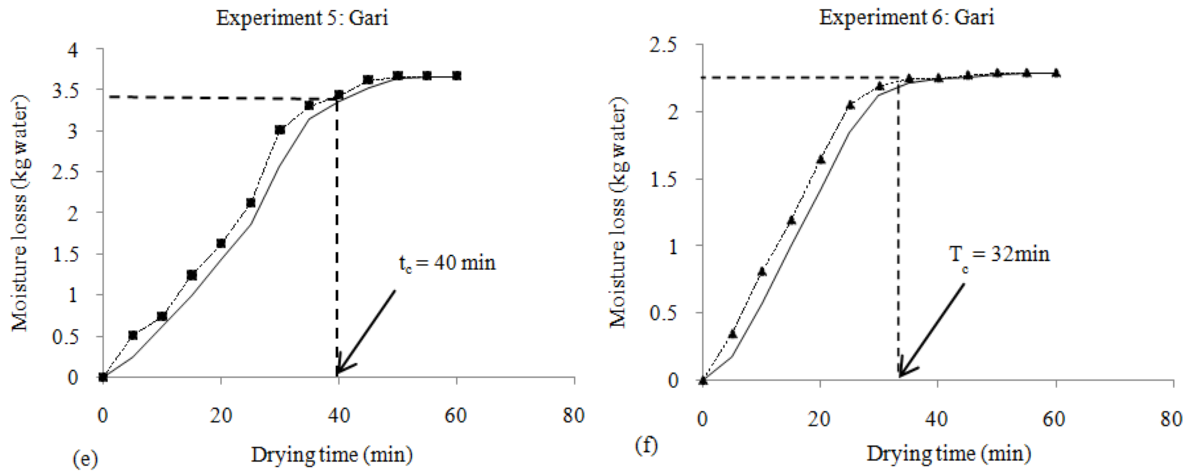


Fig. 5: Linearity of drying curves of moisture loss against time

drum temperature for gelatinization and its drying time was much shorter. This result agrees with the finding of Ademiluyi and Puyate (2013).

After the multiple linear regression of experimental data with Eq. (4), an overall linear drying model which described the drying rate of cassava meal, DR, as a function of the three dryer parameters was generated as presented in Eq. (7):

$$\mathrm{DR} = 0.00569 + (0.000325)\mathrm{T_d} + (0.998)\mathrm{R_v} - (0.0018)\mathrm{Q_b} \tag{7}$$

Even though the R^2 for the multiple linear regressions was 0.869, the analysis passed the normality (Shapiro-Wilk) and constant variance tests at p-values of 0.420 and 0.060, respectively. By substituting Eq. (7) in (6), a general mathematical model relating the moisture ratio, MR with the three dryer parameters was generated in the form of Eq. (8):

$$MR = 1 - \frac{(0.00569+0.000325T_d+0.998R_v-0.0018Q_b)t}{M_iM_d} \tag{8}$$

The model was validated by comparing the predicted values of MR from the model with experimental values at the different combinations of dryer parameters. The coefficients of determination, R^2 for the six correlations were 0.9853, 0.9445, 0.9882, 0.9938, 0.9820 and 0.9989, respectively. The model was therefore valid for predicting the drying kinetics of cassava meal under different combinations of drum temperature, vapour extraction rate and quantity of cassava meal, of the conductive rotary dryer. A major observation however was that the drying kinetics of cassava meal which produced HQCF obeyed the linearity assumption more than the drying kinetics of *gari* in the use of the conductive rotary dryer.

CONCLUSION

The major difference between this study and others is that the activation energy required for vaporization was strictly by heat conduction and not by convection. While most other works investigated only the effect of hot air temperature on drying kinetics, this work studied the effects of drum temperature, vapour extraction rate and quantity of cassava meal on drying kinetics. It can be concluded that the drying kinetics of cassava meal in the newly developed conductive rotary dryer can be validly described by the Logarithmic thin layer drying model. However this study went a step further in showing that depending on the levels of the dryer parameters a linear function of the drying rate can be assumed. A general model based on this assumption was developed which accurately predicted the drying kinetics of cassava meal in the conductive rotary dryer. Another outcome of this study is that both *gari* and High Quality Cassava Flour (HQCF) which are different but highly demanded food products, can be produced using the same dryer.

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