Mathematical modeling of drying kinetics of untreated and pretreated cocoyam slices

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Abstract The effect of pretreatment and drying temperature on the drying kinetics and quality of cocoyam was investigated in this study. The best model to predict the drying kinetics was also determined. Cocoyam slices were pretreated by water blanching (WB) and soaking in sodium metabisulphite (SM) and dried in a hot air oven at temperatures of 50, 60 and 70 °C while untreated samples were sun dried. Seventeen drying models (Exponential, Generalized Exponential, Page, Logarithmic, Parabolic, Wang and Singh and Two-term) were fitted to the experimental data and selection was done based on model with highest correlation coefficient (R^2), and lowest reduced chi-square (χ^2), sum square error (SSE) and root mean square error (RMSE) respectively. The Logarithmic and Parabolic model was found to best describe the oven and sun drying of cocoyam respectively. The vitamin C and beta-carotene value of the dried cocoyam slices, which varied from 0.0038 to 0.0075 and 4.1 to 5.888 mg/100 g respectively generally decreased with an increase in drying temperature.

Keywords Cocoyam · Drying kinetics · Pretreatment · Mathematical modeling

Nomenclature

a Drying constant
b Drying constant

c Drying constant
DR Drying rate (g water/g dry matter* h)
 k, k_0, k_1 Drying constants, 1/min
Me Equilibrium moisture content (kg water/kg dry matter)
 M_i Initial moisture content (kg water/kg dry matter)
MR Dimensionless moisture ratio
 $MR_{exp,i}$ Experimental dimensionless moisture ratio
 $MR_{pred,i}$ Predicted dimensionless moisture ratio
 M_t Moisture content at any time of drying (kg water/kg dry matter)
 $M_t + dt$ Moisture content at $t + dt$ (kg water/kg dry matter)
 N Number of observations
 n Drying constant positive integer
 R^2 Correlation coefficient
 t Time (min)
 w_1 Weight loss at time t (g)
 w_d Sample dry matter weight (g)
 z Number of constants
 χ^2 Reduced chi-square

Introduction

Cocoyam (*Colocasia esculenta*), a root and tuber crop belonging to the Araceae family is a good source of nutrients (Akanbi et al. 2004). They contain dietary carbohydrates, relatively high levels of protein, and are rich in fat (with linoleic acid being the most abundant form of fatty acids). They contain other vitamins and minerals including vitamins A and C, thiamine, niacin, calcium, phosphorus and iron (Ihekoronye and Ngoddy 1985). Compared to most root and tuber crops including cassava and yam, cocoyam provides digestible starch and contains relatively high levels of protein (Lewu et al. 2009). Cocoyam can be boiled, roasted or pounded (singly

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or mixed with yam and cassava). Other products obtained from cocoyam includes cocoyam chips ('achicha'), porridge or cocoyam flour. The cost of the food products obtained from cocoyam makes its utilization a great potential for reducing malnutrition in rural areas in the country. However, one of the major limitations in its utilization potential is the high water content which makes it susceptible to deterioration. This situation gives rise to a need for preservation of the crop.

One of the oldest and most commonly practiced methods of preservation especially in the rural areas is drying. It involves heat and mass transfer resulting in irreversible product changes which are either physical or as a result of chemical or biochemical reactions. Drying can either be done traditionally by sun drying or industrially by solar, hot air and other drying methods (Tunde-Akintunde and Afolabi 2010). Traditional sun drying is commonly practiced among small and medium scale farmers and processors especially in developing countries, due to its low operational, installation and energy costs. The disadvantages of sun drying which include labour intensive and time-consuming operations, exposure to contamination and constraints to its use due to climatic problems, especially during the rainy season results in low quality dried products that are undesirable. This has made replacement of sun drying by industrial drying methods that are more efficient inevitable (Ertekin and Yaldiz 2004). These industrial dryers have more rapid drying and hygienic products, while hot-air drying has an extra advantage of providing uniformity of drying (Tiris et al. 1994).

The use of pretreatment has been reported to have a positive effect on the residual nutrient in dried food materials due to the resultant reduction in drying time (Doymaz and Pala 2002; Ade-Omowaye et al. 2003; Doymaz 2004; Piga et al. 2004). These forms of pretreatment includes chemical pretreatment, blanching and osmotic dehydration increases drying rates and gives rise to dried products of the desired quality level.

Drying is however an energy-intensive operation that has great industrial significance due to its wide application especially in the food industry (Carsky 2008). Due to the global energy crisis it is desirable to have an efficient drying process in terms of energy utilization. This can be attained through good understanding and proper modeling of the drying characteristics of food crops. The drying air conditions and material dimensions are two important factors that affect the moisture removal during cocoyam drying which depends on the process variables (Kiranoudis et al. 1997; Guine and Fernandes 2006). Heat and mass transfer phenomena occur simultaneously during drying, and many models have been developed to describe the drying kinetics of food crops. These models can either be empirical or mechanistic, or a combination of both (Faustino et al. 2007; Goyal et al. 2008; Doymaz 2010a).

Since food materials are biological materials and they have varied responses to the drying process, the drying kinetics of each crop has to be determined. Therefore studies have been carried out on various crops to determine the model that best fits the experimental data which is selected as the model that best describes the individual crop drying process. The drying process for food materials have been modeled using various theoretical, semi-theoretical and empirical drying models. Among the most commonly used model for thin-layer drying is the lumped parameter type which includes the Newton (or exponential) equation and the Page equation (a modification of the Newton model) (Kajuna et al. 2001; Kingsly et al. 2007).

Increased utilisation of cocoyam due to its potential for reducing malnutrition in rural areas in the country in terms of its digestible starch and nutritive value of the products (protein, fat, vitamins and minerals content) can only thus be realized if its drying characteristics are determined. There is, therefore, the need to study the drying characteristics of cocoyam for a better understanding and proper modeling of the drying process. This study is therefore carried out (i) to determine the drying characteristics of pretreated and untreated cocoyam slices dried in the sun and in a convective hot air oven at temperatures of 50 to 70 °C, (ii) to fit the experimental data obtained to some of the generally accepted thin-layer drying models so as to select the model that best describes the drying process and (iii) to determine the effect of drying on the nutrients in cocoyam.

Materials and methods

Material selection and preparation

Cocoyam cornels of nearly the same dimension (width, length and breadth) and in very good conditions was obtained from Sabo market in Ogbomoso, Oyo state. The samples were washed; drained and other extraneous materials were removed completely. The cocoyam was peeled and sliced into uniform thickness of about 3 cm, length of 5 and 5 cm breadth. The sliced cocoyam was divided into three portions; one portion (named SM) was pretreated by soaking in a solution of 0.2% sodium metabisulphite for 5 min; the second portion (named WB) was pretreated by blanching in hot water at 100 °C for 5 min and the last portion (named UT) which was untreated and dried using sun-drying was used as the control.

Drying procedure

The pretreated cocoyam slices were spread uniformly in drying trays in a mono-layer and placed in a convective hot-air dryer. Before commencement of drying of the cocoyam slices, the dryer was operated for at least 1 h in order for the steady

state condition within the dryer to be obtained prior to the drying of the samples.

Drying of the samples were conducted at drying temperatures of 50, 60 and 70 °C and the drying was considered to have ended when three consecutive weights of the samples became constant.

Hot-air orientation was horizontal over the surface and perforated bottom of the drying material. The drying experiments were carried out in triplicates and sample weights were measured at regular time intervals during the drying process using a digital balance (PH Mettler) having an accuracy of ± 0.01 g.

Analysis

Mathematical modeling

The initial moisture content, M_i , was determined using the AOAC (1990) method and the moisture content values at time t , during the drying process were obtained using the following equation:

$$M_t = M_i - \frac{w_l}{w_d}$$

Where M_t is the moisture content at any time of drying (kg water/kg dry matter), M_i is the initial moisture content (kg water/kg dry matter), w_l is the loss in weight at time t (g) and w_d is the dry matter weight (g).

The moisture ratio was used to plot the drying curves instead of the moisture content because the initial value for all the drying experiments which is 1 is a uniform value. The moisture ratio during drying was obtained from the moisture content values using the following equation

$$M_R = \frac{M_t - M_e}{M_i - M_e} = \exp(-Kt)$$

Where M_R is the dimensionless moisture ratio, M_t is moisture content at any time of drying (kg water/kg dry matter), M_i is the initial moisture content (kg water/kg dry

matter) and M_e is the equilibrium moisture content (kg water/kg dry matter), respectively.

The drying rate is determined using the following equation:

$$DR = \frac{M_{t+dt} - M_t}{dt}$$

Where DR is the drying rate; $M_t + dt$ is the moisture content at $t + dt$ (kg water/kg dry matter); t is the time (min).

The model the best describes the drying characteristics of cocoyam slices was determined by fitting the moisture ratio drying curves into seven semi theoretical thin layer-drying models.

The models that were considered which were Exponential, Generalized Exponential, Page, Logarithmic, Parabolic, Wang and Singh and Two-term models are as indicated in Table 1. The linear forms of these models were used to fit the experimental data. The models were evaluated using the nonlinear regression procedure of SPSS (Statistical Package for social scientists) 11.5.1 software package. The statistical parameters used to determine the equation that best describes the variation in the moisture ratio values of dried cocoyam was the correlation coefficient (R^2), reduced mean square of the deviation or the reduced chi-square (χ^2), sum square error (SSE) and root mean square error (RMSE). The correlation coefficient was used primarily while the other parameters were also used in order to determine the quality of the fit. The model that had the highest value of R^2 and the lowest values of reduced chi-square, SSE and RMSE indicates that the model had the best goodness of fit (Goyal et al. 2006).

The above statistical parameters were determined as follows:

$$X^2 = \frac{\sum_{i=1}^N (MR_{(exp,i)} - MR_{(pred,i)})^2}{N - z}$$

$$SSE = \frac{1}{N} \sum_{i=1}^N (MR_{(exp,i)} - MR_{(pred,i)})^2$$

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

Table 1 Thin layer mathematical models used to describe cocoyam drying

Model name	Model	References
Exponential model	$MR = \exp(-kt)$	Tiris et al. (1994) and El-Beltagy et al. (2007)
Generalized exponential model	$MR = A \exp(-kt)$	Henderson and Pabis (1961) and Shittu and Raji (2011)
Logarithmic model	$MR = a \exp(-kt) + c$	Wang et al. (2007)
Page's model	$MR = \exp(-kt^n)$	Doymaz (2007) and Singh et al. (2008)
Parabolic model	$MR = a + bt + ct^2$	Sharma and Prasad (2004); Doymaz (2010a, b)
Wang and Singh	$MR = 1 + at + bt^2$	Mohapatra and Rao 2005; Arumuganathan et al. 2009
Two-term	$MR = a \exp(k_0 t) + b \exp(-k_1 t)$	Henderson (1974) and Chayjan et al. (2011)

Where $MR_{exp,i}$ is the experimental dimensionless moisture ratios; $MR_{pre,i}$ is the predicted dimensionless moisture ratios; N is the number of observations; z is the number of constants.

Nutritional composition

The Beta-carotene and vitamin C content were determined using the spectrophotometer and Iodine determination methods of the AOAC (1990).

Results and discussions

Drying characteristics

The drying curves obtained from plotting the graphs of experimental moisture content against drying time for the drying temperatures (50 to 70 °C) are as shown in Fig. 1. The graphs follow the characteristic curve reported for food materials (Pal et al. 2008; Rayaguru and Routray 2012). At the initial stage

moisture evaporation proceeds rapidly in an exponential manner and then slowly decreased with increase in drying time until the latter stages of drying when moisture evaporation became non-existent. The moisture content was observed to reduce as the time of drying increased which is probably due to the reduction in available water for evaporation as drying progresses. The drying time generally for oven drying process was less than that of sun drying. Oven dried water blanched (WB) samples had a drying process time of between 6 and 12 h and that of samples soaked in sodium metabisulphite (SM) varied from 5 to 10 h while sun-drying took a total of 18 h for drying to be completed. This longer drying time for sun drying will invariably give rise to products of lower quality thus collaborating the need for the use of alternative drying methods to achieve reduction in drying time.

The variation of the moisture ratio with respect to drying time is shown in Fig. 2. The drying time taken to reach a moisture ratio of approximately 0.1 g water/g dm reduced from 720, 540, 270 min for water blanched cocoyam slices (WB) and 450, 330, 210 min for cocoyam slices soaked in

Fig. 1 Drying curves for cocoyam slices sun dried or oven dried at 50, 60 and 70 °C **a** soaked in sodium metabisulphite (SM) and oven dried **b** water blanched (WB) and oven dried **c** untreated and sun dried

Fig. 2 Graphs of moisture ratio against drying time for cocoyam slices sun dried or oven dried at 50, 60 and 70 °C **a** soaked in sodium metabisulphite (SM) and oven dried **b** water blanched (WB) and oven dried **c** untreated and sun dried

sodium metabisulphite solution (SM) at drying temperature of 50, 60 and 70 °C respectively. This indicates that the drying time reduced as drying temperature increased from 50 to 70 °C. This implies that the time taken to reach the same moisture content at a drying temperature of 50 °C was approximately thrice (for WB) and twice (for SM) the time taken at a drying temperature of 70 °C. The reduction of total drying time with increasing temperature may be due to increase in vapour pressure within the product with increase in temperature, which resulted in faster migration of moisture to the product surface (Vega-Gálvez et al. 2011). This reduction in drying time with increase in drying temperature is similar to the results reported for other food materials including kurut, spinach leaves, corn and stone apple slices (Karabulut et al. 2007; Doymaz 2009; Chayjan et al. 2011; Rayaguru and Routray 2012).

The use of soaking in metabisulphite solution (SM) as a pretreatment compared with water blanching (WB) resulted in a reduction of drying time and subsequently in faster migration of moisture to the product surface. Moisture contents of approximately 0.1 g water/g dm were reached within 210 to 450 min for SM samples while those for WB samples varied

from 300 to 720 min. SM samples also had lower final moisture contents (0.02 to 0.086 g water/g dm) than WB samples (0.033 to 0.173 g water/g dm). The drying of cocoyam was observed to take place in the falling rate drying period throughout the drying process (Fig. 3). This is due to the fact that moisture migration is based on its diffusion rate from the internal regions and moisture evaporation from the product surface. Higher drying rates were observed at higher drying air temperature which resulted in faster moisture evaporation and subsequently faster moisture content reduction thus reducing the total drying time. This is in agreement with the results obtained for other food products (Tunde-Akintunde et al. 2005; Kingsly et al. 2007; Lee and Kim 2009; Doymaz 2010a; Rayaguru and Routray 2012). The presence of the falling rate period only within the cocoyam drying process gave rise to the use of the models indicated in Table 1.

Mathematical modeling

The experimental data was fitted with seven thin layer models to find out their suitability to describe the drying behavior for cocoyam slices. Non-linear regression of the data using SPSS

Fig. 3 Drying rate curves for cocoyam slices sun dried or oven dried at 50, 60 and 70 °C **a** soaked in sodium metabisulphite (SM) and oven dried **b** water blanching (WB) and dried **c** untreated and sun dried

was employed for statistical modeling of drying curves. The statistical analysis (i.e. correlation coefficients, R^2 , chi-square, χ^2 , and SSE values) of these models for all the drying condition (i.e. drying temperature, microwave power and pretreatments) are presented in Tables 2, 3, and 4. The R^2 values varied from 0.855 to 0.997 while that of χ^2 varied from 0.000233 to 0.01808 and SSE values from 0.00194 to 0.01658.

The model that had the highest R^2 values and the lowest values of χ^2 and SSE was used as a basis for the selecting the model that best describes the thin-layer drying characteristics of cocoyam slices. The results shown in Table 1 indicates that for the oven drying, Logarithmic model had satisfied the requirements of high R^2 and low χ^2 and SSE while Parabolic model satisfied it for sun drying. The use of Logarithmic model for the prediction of thin layer oven drying of various food products have been reported for banana and stone apple slices (Doymaz 2010b; Rayaguru and Routray 2012). The use of Parabolic for sun drying of cocoyam is in agreement with those reported for red apples, garlic cloves, tiger nut seeds and seedless grapes by other authors (Sharma and Prasad 2004;

Doymaz 2010a; Tunde-Akintunde and Oke 2012; Doymaz and Altine 2012).

The accuracy of the model selected for the prediction of thin layer drying process for cocoyam was evaluated by comparing the predicted moisture ratio (obtained from the selected models) with experimental moisture ratio. The plots of the performance of the model for all the drying experiments are shown in Fig. 4.

Quality parameters

The ascorbic acid and β -carotene values for cocoyam slices dried in a hot-air oven under the different drying temperatures and pretreatments are shown in Fig. 5. The ascorbic acid and β -carotene content varied from 0.0038 to 0.0075 and 4.1 to 5.888 mg/100 g respectively. Vitamin C content (in terms of ascorbic acid content) for cocoyam slices soaked in SM were higher than that of water blanching slices while the opposite was the case for β -carotene values in which water blanching slices had higher values than that of slices soaked in SM. An

Table 2 Statistical parameters for moisture ratio models for water blanched cocoyam slices

Air temperature (°C)	Model name	Coefficient of determination (R^2)	Reduced chi-square (χ^2)	Sum square error (SSE)
50	Exponential	0.989	0.000685	0.000647
	Generalized exponential	0.991	0.000621	0.000552
	Logarithmic	0.997	0.000233	0.000194
	Page	0.994	0.000385	0.000342
	Parabolic	0.99	0.00071	0.000591
	Wang and Singh	0.986	0.000959	0.000852
	Two term	0.997	0.000209	0.000162
60	Exponential	0.991	0.000641	0.000598
	Generalized exponential	0.991	0.000641	0.000556
	Logarithmic	0.997	0.00026	0.000208
	Page	0.991	0.00069	0.000598
	Parabolic	0.997	0.000273	0.000218
	Wang and Singh	0.997	0.000254	0.00022
	Two term	0.991	0.000758	0.000556
70	Exponential	0.855	0.018082	0.016575
	Generalized exponential	0.91	0.012334	0.010278
	Logarithmic	0.957	0.006609	0.004957
	Page	0.976	0.003232	0.002694
	Parabolic	0.961	0.005986	0.004489
	Wang and Singh	0.945	0.007549	0.006291
	Two term	0.957	0.007315	0.004877

Table 3 Statistical parameters for moisture ratio models for cocoyam slices soaked in sodium metabisulphite

Air temperature (°C)	Model name	Coefficient of determination (R^2)	Reduced chi-square (χ^2)	Sum square error (SSE)
50	Exponential	0.92	0.00996	0.0093
	Generalized exponential	0.967	0.00446	0.00387
	Logarithmic	0.984	0.00235	0.00188
	Page	0.996	0.000504	0.000437
	Parabolic	0.99	0.00146	0.00116
	Wang and Singh	0.972	0.00375	0.00325
	Two term	0.985	0.00239	0.00175
60	Exponential	0.995	0.000365	0.000337
	Generalized exponential	0.995	0.000346	0.000293
	Logarithmic	0.996	0.000335	0.000258
	Page	0.995	0.000374	0.000316
	Parabolic	0.991	0.000731	0.000563
	Wang and Singh	0.987	0.000974	0.000824
	Two term	0.995	0.000423	0.000293
70	Exponential	0.939	0.00588	0.00535
	Generalized exponential	0.964	0.00386	0.00316
	Logarithmic	0.979	0.00248	0.00181
	Page	0.986	0.00147	0.00121
	Parabolic	0.993	0.000889	0.000646
	Wang and Singh	0.989	0.00112	0.000916
	Two term	0.982	0.00250	0.00159

Table 4 Statistical parameters for moisture ratio models for sun dried untreated cocoyam slices

Model name	Coefficient of determination (R^2)	Reduced chi-square (χ^2)	Sum square error (SSE)
Exponential	0.99	0.000812	0.000721
Generalized exponential	0.99	0.000927	0.000721
Logarithmic	0.992	0.000932	0.000622
Page	0.99	0.000921	0.000716
Parabolic	0.993	0.000814	0.000543
Wang and Singh	0.993	0.00071	0.000552
Two term	0.993	0.000948	0.000527

increase in drying temperature generally decreased the residual content of the two nutrients.

This reduction in vitamin C with increase in drying temperature maybe due to the irreversible oxidative processes that occur during drying and the fact that vitamin C is a heat sensitive vitamin (Vega-Galvez et al. 2008; Thankitsunthorn et al. 2009). The reduction of vitamin C content of water blanched samples may be due to the fact that the high

Fig. 5 Nutritional quality of cocoyam slices oven dried at 50, 60 and 70 °C (soaked in sodium metabisulphite—SM, water blanched—WB)**Fig. 4** Comparison between experimental and predicted moisture ratios using **a** Logarithmic model for samples soaked in sodium metabisulphite (SM) **b** Logarithmic model for water blanched samples (WB) **c** Parabolic model for sun-dried samples

Conclusion

The drying time decreased with increase in drying temperature and SM pretreated samples had a lower drying time when compared to WB samples. The drying was observed to take place entirely in the falling-rate drying period and hence moisture migration to the surface is based on diffusion. The model that best describes the thin-layer drying characteristics of cocoyam slices was Logarithmic and Parabolic for oven and sun drying respectively. Predicted data obtained from the equations had good comparison to experimental data. Increase in drying temperature resulted in a decrease in the residual vitamin C and beta-carotene content for dried cocoyam. SM pretreated samples had higher vitamin C content and lower beta-carotene values than WB samples.

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