

Modeling for Drying of Thin Layer of Native Cassava Starch in Tray Dryer

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Abstract

Purpose: The drying of a thin layer of native cassava starch in a tray dryer was modeled to establish an equation for predicting the drying behavior under given conditions. **Methods:** Drying tests were performed using samples of native cassava starch over a temperature range of 40-60°C. We investigated the variation in the drying time, dynamic equilibrium moisture content, drying rate period, critical moisture content, and effective diffusivity of the starch with temperature. The starch diffusion coefficient and drying activation energy were determined. A modification of the model developed by Hii et al. was devised and tested alongside fourteen other models. **Results:** For starch with an initial moisture content of 82% (db), the drying time and dynamic equilibrium moisture content decreased as the temperature increased. The constant drying rate phase preceded the falling rate phase between 40-55°C. Drying at 60°C occurred only in the falling rate phase. The critical moisture content was observed in the 40-55°C range and increased with the temperature. The effective diffusivity of the starch increased as the drying temperature increased from 40 to 60°C. The modified Hii et al. model produced randomized residual plots, the highest R², and the lowest standard error of estimates. **Conclusions:** Drying time decreased linearly with an increase in the temperature, while the decrease in the moisture content was linear between 40-55°C. The constant drying rate phase occurred without any period of induction over a temperature range of 40-55°C prior to the falling rate period, while drying at 60°C took place only in the falling rate phase. The effective diffusivity had an Arrhenius relationship with the temperature. The modified Hii et al. model proved to be optimum for predicting the drying behavior of the starch in the tray dryer.

Keywords: Activation energy, Cassava starch, Drying models, Effective diffusivity, Modified Hii et al.

Introduction

Nigeria is the world's leading producer of cassava (Phillips et al., 2004; FAO, 2008; Akinpelu et al., 2011). Presently, efforts are geared toward promoting the export of the crop and its by-products. Owing to the poor storage characteristics of the cassava tuber in its unprocessed state, it is necessary to process the product into a form that is more easily stored in order to minimize deterioration and losses while in transit. One of the forms in which cassava can easily be stored and transported without

deterioration and losses is as dried cassava starch.

Starch is the common name applied to a white, granular or powdery, odorless, and tasteless complex carbohydrate, which is abundantly found in the seeds of cereal plants and in bulbs, roots, and tubers. It occurs in commercial quantities in roots and tubers such as cassava, yam, and potato, as well as in cereal grains such as sorghum, millet, and maize. It consists of two types of molecules, namely, amylose, which constitutes about 20-30% of ordinary starch, and amylopectin, which makes up the remaining 70-80%. Starch finds applications as an important raw material in many industries. It functions as a thickening agent, water binder, emulsion stabilizer, bulking agent, flow aid, fat substitute, and gelling agent in food and is

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used in the manufacture of synthetic polymers such as plastics and adhesives. It is used as a molecular sieve and binder, and as a surface coating for papers. In pharmaceutical tablets, starch is used to bind and carry the active components. It acts as viscosity modifier in paints and is used in the textile industry as a stiffener. In the petroleum industry, it is mixed with pumping water to assist in the cooling of superheated drilling bits.

Starch is normally extracted from the source material in an aqueous medium. It is usually packaged and supplied in granular or powdery form, such that drying is a fundamental unit operation in starch processing. Drying is a complex process involving heat and mass transfer between the product surface and its surrounding medium, which results in the reduction of the product moisture content over time to a safe storage level or the level required for the application of subsequent processing. The prediction of the drying kinetics of agricultural products under various conditions has been a useful tool in the design, simulation, and optimization of drying processes (Senadeera et al., 2003). Many empirical and semi-theoretical models have been proposed and applied by investigators to the estimation of the moisture ratios and drying times of several agricultural and food products. These include eggplant (Ertekin and Yaldiz, 2004), apple (Akpınar et al., 2003, Menges and Ertekin, 2006, Kaya et al., 2007 and Meisami-asl et al., 2010), apricot (Togrul and Pehlivan, 2002, Bozkir, 2006), potato (Aghbashlo et al., 2009a), carrot (Domaz, 2004, Aghbashlo et al., 2009b), coroba (Corzo et al., 2010), grape (Yaldiz et al., 2001, Zomorodian and Dadashzadeh, 2009), kiwifruit (Mohammadi et al., 2008), leek (Dadali and Ozbek, 2008), red chili pepper (Alibas, 2012), pepper, pumpkin, green bean and onion (Yaldiz and Ertekin, 2001), pumpkin (Doymaz, 2007, Perez and Schmalko, 2009), spinach leaves (Doymaz, 2009), wheat (Mohapatra and Rao, 2005), cocoa (Hii et al., 2008), pretreated sour cherry (Gazor and Roustapour, 2015), and potato starch (Dixit et al., 2012). Aviara (2010) and Aviara et al. (2010a, 2010b) reported that drying techniques and conditions significantly affect the physicochemical and functional properties of starch, and suggested that the drying techniques and conditions should be carefully chosen or modeled to avoid the adverse modification of the product characteristics that can occur when wet starch is subjected to heating. However, there appear to have been no reports on the modeling of the drying kinetics of thin layers of native cassava starch in either a natural or artificial drying system. Therefore, the present study was carried out to establish

the drying characteristics of native cassava starch in a tray dryer, model the thin layer drying kinetics of the starch, and select or propose the best thin layer drying model for the product at different drying air temperatures.

Materials and Methods

Material sample and preparation

The cassava tubers used in this study were obtained from a farm at the Amina Way, University of Ibadan, Ibadan, Nigeria. The starch was extracted from the tubers in the Industrial Chemistry Laboratory of the Chemistry Department of the University, following the wet extraction procedure (Aviara, 2010). The starch milk thus obtained was drained thoroughly and stored in a freezer at 0°C for 24 h. When needed for our experiments, the starch sample was first allowed to equilibrate in ambient conditions for 6 h. The initial moisture was determined using the AOAC (2004) method.

Description of thin-layer drying equipment

A laboratory-model tray dryer (Figure 1) was used to perform the drying tests. It consists of a drying chamber in which perforated trays are arranged vertically and placed horizontally, a plenum chamber in which the heating elements are installed, a 0.374-kW axial-flow fan that draws in drying air at 15.16 ms⁻¹, passes it through an expanded duct and perforated plate, and then over the product bed and tray floor at a rate of 0.104 ms⁻¹, and an

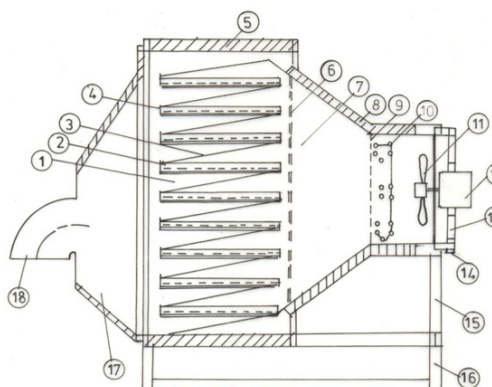


Figure 1. Laboratory-model tray dryer (1). Drying chamber (2). Tray (3). Baffle plate (4). Tray support platform (5). Insulated drying cabinet wall (6). Perforated plate (7). Inlet air duct (8). Insulated air duct wall (9). Air inlet perforated plate (10). Heating elements (11). Air supply fan (12). Fan drive motor (13). Motor mounting (14). Motor mounting support frame (15). Tool frame (16). Dryer mounting (17). Dryer door (18). Exhaust air outlet.

outlet for discharging the used air. The tool frame and lagged casing enclosing the functional units form the body of the equipment and give it a compact look. It is also fitted with a temperature-control device that uses a sensor and thermostatic system to maintain a set temperature in the drying chamber to within $\pm 2^\circ\text{C}$. When the dryer is operating, air is heated to the set temperature in the plenum chamber and is then blown into the drying chamber where it picks up moisture from the product being dried and is then discharged through the air outlet. The continual picking-up and discharge of moisture by the drying air leads to a reduction in the mass and, of course, the moisture content of the product in the drying chamber. This continues until further reduction in the product mass becomes negligible, indicating that equilibrium with the environment has been obtained. At this point, the drying process is stopped. The moisture content at which drying terminates is determined and termed the “dynamic equilibrium moisture content.”

Drying procedure

The procedure described by Syrarief et al. (1984) and Ajibola (1989) and subsequently modified by Aviara (2010) was used to conduct the drying tests. Ambient air at a dry bulb temperature of $27\text{--}38^\circ\text{C}$ and $50\text{--}78\%$ relative humidity was heated to drying temperatures of $40, 45, 50, 55$ and 60°C . The selected temperature range was based on the contents of reports in the literature (Shimelis et al., 2006) and the need to prevent gelatinization. To perform a drying run at each temperature, the fan was turned on and the dryer was run empty for 2 h so that it would stabilize at the specified air temperature and humidity before the test began. About 25 g of starch with a known initial moisture content was weighed in triplicate and spread in a thin layer in drying dishes. The dishes and their contents were placed on the drying trays and then placed in the drying chamber with the fan running. Any change in the sample weight was monitored by regular weighing using an electronic balance. The weighing of samples was carried out as follows, every 10 min for the first 1 h; every 30 min for the next 3 h; every 1 h for the next 3 h and every 2 h for the next 6 h (Aviara et al., 2010a). This weighing was continued until three consecutive readings produced identical values. The test was then terminated, the time taken was recorded and equilibrium with the drying environment was assumed to have been reached. At this point, the samples were oven-dried at 105°C for 4 h to obtain the dry matter weight. The percentage dry basis moisture contents of the samples were then determined

and the average value was taken as the dynamic equilibrium moisture content (EMC), % (db) of the starch at the specific drying temperature. The time (min) taken from the start of drying to the dynamic EMC being reached became the drying time.

Data Analysis

Drying time, equilibrium moisture content, and drying rate phases

The drying time and dynamic equilibrium moisture content were regressed against temperature to establish the relationships existing between them. The moisture content at a given time and the drying temperature were obtained using the equation derived by Kajuna et al. (2001), stated as follows:

$$M_t = \frac{M_i m_i - W_t}{m_i - W_t} \quad (1)$$

where M_t is the moisture content (%) at a given time t , M_i is the initial moisture content of the starch, (%), m_i is the initial mass of the wet starch, (g) and W_t is the mass loss (g) at time t .

The M_t (%) obtained with t (min) at different drying temperatures was used to calculate the starch drying rate. The drying rate at a given time was computed using the following expression:

$$dR = \frac{dM}{dt} = \left(\frac{M_i - M_t}{t - t_i} \right) \quad (2)$$

where dR is the drying rate (g/g h), dM is the change in the moisture content (g/g), dt is the change in the time h and t_i is the initial time, taken as 0. The drying rate was plotted against the moisture content and the curve was used to obtain the critical moisture content and drying rate phases at different temperatures.

Effective diffusivity, diffusion coefficient, and drying activation energy

The effective diffusivity (D_e) of the starch was estimated by applying the diffusion model for spherically shaped bodies, as derived by Senadeera et al. (2003):

$$MR = \frac{6}{\pi^2} \sum \frac{1}{n^2} \exp \left[\frac{-n^2 \pi^2 D_e t_d}{r^2} \right] \quad (3)$$

where D_e is the effective diffusivity (m^2/s), t_d is the drying time (s), r is the radius (m) and n is a positive integer. When r is small and t is large, the first term of the expansion in Eq. (3) is considered (Aviara, 2010), and then stated as follows:

$$MR = \frac{6}{\pi^2} \exp \left[\frac{-\pi^2 D_e t_d}{r^2} \right] \quad (4)$$

A logarithmic transformation of Eq. (4) yields a linear equation of the form

$$\ln(MR) = A - Bt \quad (5)$$

where A and B are constants, and

$$B = \frac{\pi^2 D_e}{r^2} \quad (6)$$

$\ln(MR)$ was plotted against t and the constant B in Equation (5) was obtained from the slope and used in Equation (6) to compute the values of D_e .

The effective diffusivity was assumed to be in an Arrhenius relationship with the temperature (Akpınar et al., 2003, Senadeera et al., 2003, Aviara, 2010, and Aregbesola et al., 2015) in a form that can be expressed as Equation (7).

$$D_e = D_o \exp \left(\frac{-E_a}{RT} \right) \quad (7)$$

where D_o is the reference diffusion coefficient (m^2/s), E_a is the diffusion activation energy (kJ/mol), R is the universal gas constant (0.0083144 kJ/mol K) and T is the air absolute temperature (K).

Equation (7) was linearized through a logarithmic transformation to yield Equation (8) which was used to obtain D_o and E_a , as follows:

$$\ln(D_e) = \frac{-E_a}{RT} + \ln(D_o) \quad (8)$$

A plot of $\ln(D_e)$ against $1/T$ yielded a straight line from which $-E_a$ was obtained as the slope and $\ln(D_o)$ as the intercept on the Y-axis.

Mathematical modeling of drying process

Hii et al. (2008) combined the Page model, which was reported as being able to fit the drying curves of several food products (Jayas et al., 1991) and the Two Term model, which was derived from the first two terms of the analytical solution to Fick's law, to obtain a new equation, stated as follows:

$$MR = ae^{(-kt^n)} + ce^{(-gt^n)} \quad (9)$$

where:

$$MR = \frac{M - M_e}{M_i - M_e} \quad (10)$$

MR is the moisture ratio, which is a dimensionless parameter that normalizes the drying curves, M is the moisture content at a given time (% db), M_i is the initial moisture content of the starch (% db), M_e is the equilibrium moisture content (% db), t is time (min), and a , c , g , k , and n are constants.

Eq. (9) was tested on the natural and artificial thin-layer drying of cocoa (Hii et al., 2008) and found to give a better description of these drying processes than eight other thin-layer drying models, even though the drying temperature was not specifically stated. Further examination of Eq. (9) showed that the predictive performance of the model could be improved by considering the condition where the index of t in the first term is not equal to the index of t in the second term. Taking this condition into consideration, the n index in the first term of Eq. (9) was replaced with m to modify the model and give Eq. (11) which becomes the new model.

$$MR = ae^{(-kt^m)} + ce^{(-gt^n)} \quad (11)$$

where a , c , g , k , m and n are constants.

Eq. (9) and (11), in addition to 13 other popular thin-layer drying models (Table 1), were fitted to the drying data of native cassava starch at different temperatures using the non-linear regression procedure in the STATISTIX 9 statistical analysis software (Analytical Software Inc., 2008). The observed and predicted moisture ratios were compared and statistically analyzed to determine the best-fit equation. The goodness of fit of each model was evaluated using the coefficient of determination and standard error of estimate, calculated by the procedure and residual plots.

Table 1. Thin-layer drying models fitted to cassava starch drying data

S/N	Model Name	Model Equation	Reference
1.	Aghbashlo et al.	$MR = \exp(-kt/1+ct)$	Aghbashlo et al., 2009a
2.	Diffusion Approach	$MR = a \exp(-kt) + (1-a)\exp(-kgt)$	Akpinar and Bicer, 2006
3.	Henderson and Pabis	$MR = a \exp(-kt)$	Akpinar et al., 2003
4.	Hii et al.	$MR = a \exp(-ktn) + c \exp(-gt^n)$	Hii et al., 2008
5.	Logarithmic	$MR = a \exp(-kt) + c$	Yaldiz et al., 2001
6.	Midilli and Kucuk	$MR = a \exp(-ktn) + bt$	Midilli and Kucuk, 2003
7.	Modified Henderson and Pabis	$MR = a \exp(-kt) + \exp(-gt) + c \exp(-ht)$	Hamdami et al., 2006
8.	Modified Hii et al.	$MR = a \exp(-kt^n) + c \exp(-gt^n)$	Present study
9.	Newton	$MR = \exp(-kt)$	Muhidong et al., 1992
10.	Page	$MR = \exp(-kt^n)$	Karathanos and Belessiotis, 1999
11.	Thompson	$t = a \ln(MR) + b[\ln(MR)]^2$	Muhidong et al., 1992
12.	Two term exponential	$MR = a \exp(-kt) + (1-a) \exp(-kat)$	Hii et al., 2008
13.	Two term model	$MR = a \exp(-kt) + c \exp(-gt)$	Yaldiz et al., 2001
14.	Verma et al.	$MR = a \exp(-kt) + (1-a) \exp(-gt)$	Verma et al., 1985
15.	Wang and Singh	$MR = 1 + at + bt^2$	Wang and Singh, 1978

The coefficient of determination is denoted by R^2 and defined as

$$R^2 = 1 - \left[\frac{\sum_{i=1}^n (MR_{obs,i} - MR_{pred,i})^2}{\sum_{i=1}^n (MR_{obs,i} - \overline{MR}_{obs})^2} \right] \quad (12)$$

The standard error of estimate, SE, is defined as

$$SE = \sqrt{\frac{\sum_{i=1}^n (MR_{obs,i} - MR_{pred,i})^2}{df}} \quad (13)$$

where MR_{obs} is the measured moisture ratio, MR_{pred} is the predicted moisture ratio, \overline{MR}_{obs} is the average measured moisture ratio, n is the number of data points, and df is the degree of freedom in the regression model.

A model is regarded as being acceptable if the residuals are uniformly scattered around the horizontal value of zero, are randomized, and exhibit no systematic tendency towards a clear pattern. One model is regarded as being better than another if produces a higher coefficient of determination and a lower standard error of estimate (Ajibola, 1989).

The moisture ratios predicted by the best-fitting model at each temperature were then plotted alongside the measured values against time. The reliability of the model for describing the drying curve of the starch was evaluated

by comparing the predicted moisture ratios with the measured values (Onuoha et al., 2013). This was carried out by plotting the predicted moisture ratios against the measured moisture ratios. A model is regarded as being reliable if the predicted moisture ratios fall near the line $y = x$ (Syarif et al., 1984).

Results and Discussion

Drying time and equilibrium moisture of cassava starch in tray dryer

The average initial moisture content of the starch was 82% (db). During the drying of the starch at different temperatures over a range of 40-60°C, the moisture content decreased with time (Figure 2) until the dynamic equilibrium moisture content for each drying temperature was attained. As the drying temperature increased in the above range, the drying time and dynamic equilibrium moisture content (EMC) decreased from 480 to 270 min and from 7.70 to 1.70% (db), respectively (Table 2). Similar results were obtained for the drying of eggplant (Ertekin and Yaldiz, 2004), potato (Aghbashlo et al., 2009a), and coroba slices (Corzo et al., 2010).

The relationship between the drying time and drying temperature was found to be linear and can be represented by Eq. (14):

$$t = -9.8 T + 858, \quad R^2 = 0.973 \quad (14)$$

where t is the drying time (min), T is the drying temperature ($^{\circ}\text{C}$), and R^2 is the coefficient of determination.

The value of EMC decreased linearly with an increase in the drying temperature within a temperature range of 40-55 $^{\circ}\text{C}$, according to a relationship that can be expressed with the following equation.

$$40\text{-}55^{\circ}\text{C} : \text{EMC} = -0.0838T + 11.003, R^2 = 0.986 \quad (15)$$

where EMC is the dynamic equilibrium moisture content (% (db)), and T is the drying temperature ($^{\circ}\text{C}$). Beyond the above temperature range, the EMC declined sharply and the relationship between it and the temperature varied. This may be due to the commencement of the physical modification that normally occurs when wet starch is heated to an elevated temperature.

The variation in the drying rate of the starch according to the moisture content is shown in Figure 3. This figure shows that, for a temperature range of 40-55 $^{\circ}\text{C}$, the drying rate increased with the temperature and was initially constant over a wide range of moisture values. Subsequently, however, the drying rate decreased continuously

with the moisture content until the completion of the drying process. For a drying temperature of 60 $^{\circ}\text{C}$, the drying rate was high and decreased with the moisture content from the very start of the drying process. A constant rate phase was therefore observed in the drying of the starch over a temperature range of 40-55 $^{\circ}\text{C}$. When the critical moisture content was exceeded at each temperature, the drying process began to occur in the falling rate phase. The starch dried throughout the falling rate phase at a drying temperature of 60 $^{\circ}\text{C}$. The variation in the critical moisture content with the drying temperature is presented in Table 2. This shows that the critical moisture content of the starch increased with the drying temperature over a temperature range of 40-55 $^{\circ}\text{C}$. The relationship between the critical moisture content and temperature in the above range was found to be linear and can be represented by the following equation:

$$40\text{-}55^{\circ}\text{C} : M_{crit} = 0.4276T + 46.259, R^2 = 0.986 \quad (16)$$

where M_{crit} is the critical moisture content, in % (db), and T is the drying temperature, in $^{\circ}\text{C}$.

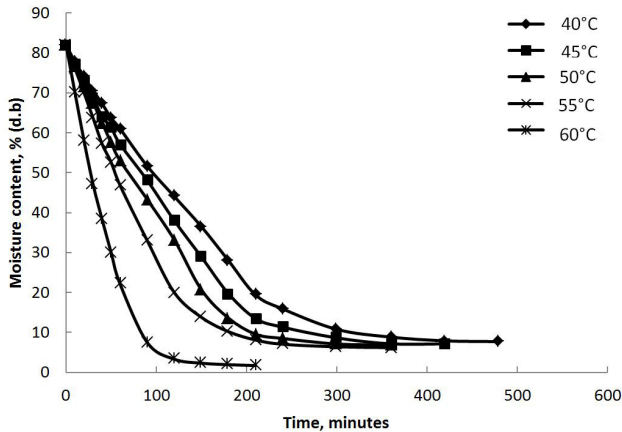


Figure 2. Drying curves of native cassava starch at different temperatures.

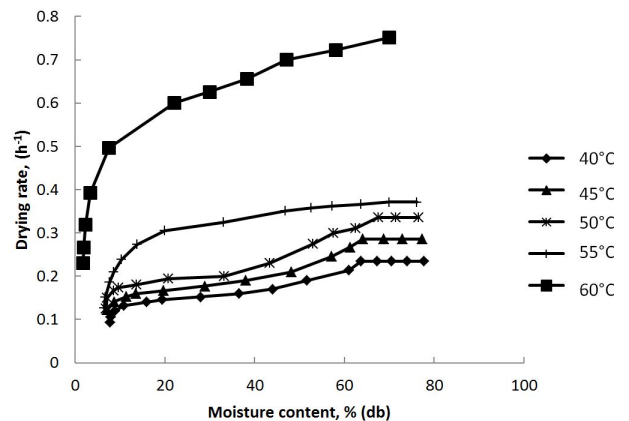


Figure 3. Thin-layer drying rate periods of native cassava starch at different temperatures in tray dryer.

Table 2. Variation in drying time, dynamic equilibrium moisture content, critical moisture content, and effective diffusivity of cassava starch with drying temperature in tray dryer

Temperature $^{\circ}\text{C}$	Drying time min	Dynamic equilibrium moisture content % (db)	Critical moisture content % (db)	Effective diffusivity m^2s^{-1}
40	480	7.7	63.67	3.109×10^{-10}
45	400	7.14	66.11	3.811×10^{-10}
50	360	6.85	67.5	4.364×10^{-10}
55	330	6.4	70.00	5.593×10^{-10}
60	270	1.7	-	6.502×10^{-10}

Effective diffusivity, diffusion coefficient, and activation energy

The variation in the effective diffusivity of native

cassava starch with drying temperature is presented in Table 2. This shows that the effective diffusivity of the starch increased exponentially with the drying temperature,

Table 3. Parameter estimates and comparison criteria for selected thin-layer models and cassava starch dried at 40°C

S/N	Model name	Model Constants	R ²	S.E.	Nature of Residual Plots
1.	Aghbashlo et al.	c = -1.892×10^{-3} k = 4.84×10^{-3}	0.9985	0.014	Randomized
2.	Diffusion approach	a = 1.000 g = 1.000 k = 6.95×10^{-3}	0.9748	0.0596	Patterned
3.	Henderson and Pabis	a = 1.0732 k = 7.632×10^{-3}	0.9911	0.0482	Randomized
4.	Hii et al.	a = 0.4637 c = 0.4637 g = 4.431×10^{-4} k = 4.431×10^{-4} n = 1.5341	0.9970	0.0226	Randomized
5.	Logarithmic	a = 1.1908 c = -0.1578 k = 5.547×10^{-3}	0.9976	0.0220	Randomized
6.	Midilli and Kucuk	a = 0.0176 b = -1.616×10^{-3} k = -4.5218 n = -0.0452	0.9592	0.0792	Randomized
7.	Modified Henderson and Pabis	a = 0.3577 b = 0.3577 c = 0.3577 g = 7.632×10^{-3} h = 7.632×10^{-3} k = 7.632×10^{-3}	0.9822	0.0579	Randomized
8.	Modified Hii et al.	a = 0.4568 c = 0.4719 g = 4.691×10^{-4} k = 4.530×10^{-4} m = 1.5293 n = 1.5240	0.9994	0.0123	Randomized
9.	Newton	k = 6.95×10^{-3}	0.9937	0.0552	Patterned
10.	Page	k = 1.696×10^{-3} n = 1.2869	0.9987	0.0292	Randomized
11.	Thompson	a = -140.24 b = -12.107	0.9838	17.217	Randomized
12.	Two term exponential	a = 1.0000 k = 6.950×10^{-3}	0.9748	0.0573	Patterned
13.	Two term	a = 0.5366 c = 0.5366 g = 7.632×10^{-3} k = 7.632×10^{-3}	0.9911	0.0524	Randomized
14.	Verma et al.	a = 16.192 g = 0.0132 k = 0.0126	0.9987	0.030	Randomized
15.	Wang and Singh	a = -5.28×10^{-3} b = 6.931×10^{-6}	0.9995	0.0168	Randomized

which agrees with the findings of Akpınar and Bicer (2006). The effective diffusivity values were found to be within a range of 10^{-11} to 10^{-9} m²/s. This range is generally

considered acceptable for agricultural and food products (Madamba et al., 1996).

The diffusion coefficient D_0 and activation energy E_a of the

Table 4. Parameter estimates and comparison criteria for selected thin-layer models and cassava starch dried at 45°C

S/N	Model name	Model Constants	R ²	S.E.	Nature of Residual Plots
1.	Aghbashlo et al.	c = -2.249×10^{-3} k = 5.660×10^{-3}	0.9985	0.014	Randomized
2.	Diffusion approach	a = 1.000 g = 1.000 k = 8.209×10^{-3}	0.9720	0.0632	Patterned
3.	Henderson and Pabis	a = 1.0845 k = 9.124×10^{-3}	0.9953	0.0498	Randomized
4.	Hii et al.	a = 0.4619 c = 0.4618 g = 5.296×10^{-4} k = 5.296×10^{-4} n = 1.5483	0.9966	0.0242	Randomized
5.	Logarithmic	a = 1.2026 c = -0.1652 k = 6.504×10^{-3}	0.9924	0.0329	Randomized
6.	Midilli and Kucuk	a = 0.0188 b = -1.916×10^{-3} k = -4.4683 n = -0.0480	0.9806	0.0780	Randomized
7.	Modified Henderson and Pabis	a = 0.3615 b = 0.3615 c = 0.3615 g = 9.124×10^{-3} h = 9.124×10^{-3} k = 9.124×10^{-3}	0.9810	0.0610	Randomized
8.	Modified Hii et al.	a = 0.4676 c = 0.4575 g = 5.466×10^{-4} k = 5.525×10^{-4} m = 1.5403 n = 1.5417	0.9995	0.0125	Randomized
9.	Newton	k = 8.209×10^{-3}	0.9930	0.0581	Patterned
10.	Page	k = 1.975×10^{-3} n = 1.2996	0.9986	0.0299	Randomized
11.	Thompson	a = -118.85 b = -10.340	0.9830	14.890	Randomized
12.	Two term exponential	a = 1.0000 k = 8.209×10^{-3}	0.9720	0.0605	Patterned
13.	Two term	a = 0.5422 c = 0.5422 g = 9.124×10^{-3} k = 9.124×10^{-3}	0.9905	0.0545	Randomized
14.	Verma et al.	a = 14.241 g = 0.0158 k = 0.0150	0.9931	0.0314	Randomized
15.	Wang and Singh	a = -6.217×10^{-3} b = 9.615×10^{-6}	0.9996	0.0172	Randomized

starch were found to be $0.0000958 \text{ m}^2\text{s}^{-1}$ and $32.933 \text{ kJmol}^{-1}$, respectively. The moisture diffusion coefficient is that which is needed to actuate the flow during moisture removal

through drying, while the activation energy is the amount of energy needed to trigger moisture removal from a solid matrix during drying (Tanko et al., 2005). The relationship

Table 5. Parameter estimates and comparison criteria for selected thin-layer models and cassava starch dried at 50°C

S/N	Model name	Model Constants	R ²	S.E.	Nature of Residual Plots
1.	Aghbashlo et al.	c = -2.6782×10^{-3} k = 6.488×10^{-3}	0.9981	0.0158	Randomized
2.	Diffusion approach	a = 1.000 g = 1.000 k = 9.541×10^{-3}	0.9669	0.0693	Patterned
3.	Henderson and Pabis	a = 1.0982 k = 0.0108	0.9890	0.0537	Randomized
4.	Hii et al.	a = 0.4606 c = 0.4606 g = 6.016×10^{-4} k = 6.016×10^{-4} n = 1.5705	0.9955	0.0285	Randomized
5.	Logarithmic	a = 1.2256 c = -0.1838 k = 7.396×10^{-3}	0.9972	0.0347	Randomized
6.	Midilli and Kucuk	a = 0.0192 b = -2.269×10^{-3} k = -4.4444 n = -0.0495	0.9626	0.0776	Randomized
7.	Modified Henderson and Pabis	a = 0.3661 b = 0.3661 c = 0.3661 g = 0.0108 h = 0.0108 k = 0.0108	0.9781	0.0674	Randomized
8.	Modified Hii et al.	a = 0.4568 c = 0.4673 g = 6.389×10^{-4} k = 6.599×10^{-4} m = 1.5527 n = 1.5579	0.9980	0.0134	Randomized
9.	Newton	k = 9.541×10^{-3}	0.9669	0.0633	Patterned
10.	Page	k = 2.150×10^{-3} n = 1.3240	0.9920	0.0325	Randomized
11.	Thompson	a = -98.933 b = -8.5448	0.9730	16.073	Randomized
12.	Two term exponential	a = 1.0000 k = 9.541×10^{-3}	0.9669	0.0661	Patterned
13.	Two term	a = -15.240 c = 16.164 g = 0.9429 k = 0.0201	0.9932	0.0331	Randomized
14.	Verma et al.	a = 36.973 g = 0.0184 k = 0.0108	0.9915	0.0350	Randomized
15.	Wang and Singh	a = -7.192×10^{-3} b = 1.278×10^{-5}	0.9973	0.0189	Randomized

between the effective diffusivity and drying temperature can therefore be expressed for native cassava starch, using the following equation:

$$D_e = 9.58 \times 10^{-5} \exp\left(\frac{-32.933}{8.3144 \times 10^{-3} T}\right) R^2=0.9935 \quad (17)$$

Table 6. Parameter estimates and comparison criteria for selected thin-layer models and cassava starch dried at 55°C

S/N	Model name	Model Constants	R ²	S.E.	Nature of Residual Plots
1.	Aghbashlo et al.	c = -2.926x10 ⁻³ k = 8.620x10 ⁻³	0.9989	0.0124	Randomized
2.	Diffusion approach	a = 1.000 g = 1.000 k = 0.0119	0.9922	0.0579	Patterned
3.	Henderson and Pabis	a = 1.1173 k = 0.0136	0.9945	0.0379	Randomized
4.	Hii et al.	a = 0.4771 c = 0.4771 g = 1.665x10 ⁻³ k = 1.665x10 ⁻³ n = 1.5341	0.9996	0.0118	Randomized
5.	Logarithmic	a = 1.1519 c = -0.0698 k = 0.0115	0.9940	0.0293	Randomized
6.	Midilli and Kucuk	a = 4.916x10 ⁻³ b = -1.746x10 ⁻³ k = -6.0996 n = -0.0580	0.9736	0.0918	Randomized
7.	Modified Henderson and Pabis	a = 0.3724 b = 0.3724 c = 0.3724 g = 0.0136 h = 0.0136 k = 0.0136	0.9890	0.0475	Randomized
8.	Modified Hii et al.	a = 0.4788 c = 0.4755 g = 1.605x10 ⁻³ k = 1.727x10 ⁻³ m = 1.4273 n = 1.4410	0.9992	0.0120	Randomized
9.	Newton	k = 0.0119	0.9767	0.0528	Patterned
10.	Page	k = 3.004x10 ⁻³ n = 1.3153	0.9984	0.0146	Randomized
11.	Thompson	a = -77.886 b = -4.6834	0.9909	9.3397	Randomized
12.	Two term exponential	a = 1.0000 k = 0.0119	0.9767	0.0552	Patterned
13.	Two term	a = 0.5587 c = 0.5587 g = 0.0136 k = 0.0136	0.9890	0.0419	Randomized
14.	Verma et al.	a = 9.6658 g = 0.0240 k = 0.0221	0.9982	0.016	Randomized
15.	Wang and Singh	a = -8.656x10 ⁻³ b = 1.825x10 ⁻³	0.9940	0.0279	Randomized

Drying model evaluation

The parameter estimates and comparison criteria for the thin-layer drying models, tested on the native cassava

starch drying kinetics over a temperature range of 40-60°C, are presented in Tables 3-7.

These tables show that only three of the fifteen models

Table 7. Parameter estimates and comparison criteria for selected thin-layer models and cassava starch dried at 60°C

S/N	Model name	Model Constants	R ²	S.E.	Nature of Residual Plots
1.	Aghbashlo et al.	c = -4.167×10^{-3} k = 0.0158	0.9976	0.0158	Randomized
2.	Diffusion approach	a = 1.000 g = 1.000 k = 0.0213	0.9958	0.0441	Patterned
3.	Henderson and Pabis	a = 1.1268 k = 0.0244	0.9961	0.0285	Randomized
4.	Hii et al.	a = 0.4628 c = 0.4628 g = 3.259×10^{-3} k = 3.259×10^{-3} n = 1.4643	0.9996	0.0105	Randomized
5.	Logarithmic	a = 1.1319 c = -0.0246 k = 0.0228	0.9980	0.0260	Randomized
6.	Midilli and Kucuk	a = 7.858×10^{-4} b = -1.159×10^{-3} k = -8.4848 n = -0.0790	0.9396	0.0885	Randomized
7.	Modified Henderson and Pabis	a = 0.3756 b = 0.3756 c = 0.3756 g = 0.0244 h = 0.0244 k = 0.0244	0.9922	0.0368	Randomized
8.	Modified Hii et al.	a = 0.4569 c = 0.4688 g = 3.406×10^{-3} k = 3.114×10^{-3} m = 1.4729 n = 1.4559	0.9998	0.0104	Randomized
9.	Newton	k = 0.0213	0.9831	0.0399	Randomized
10.	Page	k = 7.339×10^{-3} n = 1.2792	0.9981	0.0141	Randomized
11.	Thompson	a = -36.096 b = -0.6232	0.9833	10.679	Randomized
12.	Two term exponential	a = 1.0000 k = 0.0213	0.9831	0.0419	Patterned
13.	Two term	a = 0.5634 c = 0.5634 g = 0.0244 k = 0.0244	0.9984	0.0319	Randomized
14.	Verma et al.	a = 11.075 g = 0.0408 k = 0.0381	0.9980	0.0153	Randomized
15.	Wang and Singh	a = -0.0135 b = 4.083×10^{-5}	0.9838	0.0821	Randomized

Table 8. Five best models for expressing drying characteristics of native cassava starch in tray dryer at different temperatures

Temperature, °C	S/N	Model Name	R ²	Standard error of estimate
40	1.	Modified Hii et al.	0.9994	0.0123
	2.	Wang and Singh	0.9995	0.0168
	3.	Aghbashlo et al.	0.9985	0.0140
	4.	Page	0.9987	0.2920
	5.	Verma et al.	0.9987	0.0300
45	1.	Modified Hii et al.	0.9995	0.0125
	2.	Wang and Singh	0.9996	0.0172
	3.	Aghbashlo et al.	0.9985	0.0140
	4.	Page	0.9986	0.0299
	5.	Hii et al.	0.9966	0.0242
50	1.	Modified Hii et al.	0.9980	0.0134
	2.	Aghbashlo et al.	0.9981	0.0158
	3.	Wang and Singh	0.9973	0.0189
	4.	Logarithmic	0.9972	0.0347
	5.	Hii et al.	0.9955	0.0285
55	1.	Hii et al.	0.9996	0.0118
	2.	Modified Hii et al.	0.9992	0.0120
	3.	Aghbashlo et al.	0.9989	0.0121
	4.	Page	0.9984	0.0146
	5.	Verma et al.	0.9982	0.0160
60	1.	Modified Hii et al.	0.9998	0.0104
	2.	Hii et al.	0.9996	0.0105
	3.	Two Term	0.9984	0.0319
	4.	Page	0.9981	0.0141
	5.	Logarithmic	0.9980	0.0260

evaluated, namely, the Diffusion approach, and the Newton and Two term exponential models (with patterned residual plots at each drying temperature), were unacceptable for predicting the drying behavior of the starch in a tray dryer. Of the remaining twelve models that were acceptable (with randomized residual plots), the Modified Hii et al. model proposed in this study consistently gave better prediction results with the highest value of R² and the lowest standard error of estimate among the models.

The five best models for the starch drying behavior at each drying temperature in the above range are presented in Table 8. The Table shows that, at 40°C, the best model is the Modified Hii et al., followed by Wang and Singh, Aghbashlo et al., and then Page and Verma et al. The above order of performance was repeated at 45°C, with the Hii et al. model displacing Verma et al. as the fifth. The Modified Hii et al. model maintained its position as the best model at 50°C, but was displaced to second position by Hii et al. at 55°C, regaining the best position at 60°C, making it the overall best. At each drying temperature, the Modified Hii et al. model for native cassava starch can be stated as follows:

$$40^{\circ}\text{C} : MR = 0.4568 \exp(-4.53 \times 10^{-4} t^{1.5293}) + 0.4717 \exp(-4.491 \times 10^{-4} t^{1.5240}), R^2 = 0.9994 \quad (18)$$

$$45^{\circ}\text{C} : MR = 0.4676 \exp(-5.525 \times 10^{-4} t^{1.5403}) + 0.4575 \exp(-5.466 \times 10^{-4} t^{1.5417}), R^2 = 0.9995 \quad (19)$$

$$50^{\circ}\text{C} : MR = 0.4568 \exp(-6.599 \times 10^{-4} t^{1.5527}) + 0.4673 \exp(-6.389 \times 10^{-4} t^{1.5417}), R^2 = 0.9980 \quad (20)$$

$$55^{\circ}\text{C} : MR = 0.4788 \exp(-1.727 \times 10^{-3} t^{1.4273}) + 0.4755 \exp(-1.605 \times 10^{-3} t^{1.441}), R^2 = 0.9992 \quad (21)$$

$$60^{\circ}\text{C} : MR = 0.4569 \exp(-3.114 \times 10^{-3} t^{1.4729}) + 0.4688 \exp(-3.406 \times 10^{-3} t^{1.4559}), R^2 = 0.9998 \quad (22)$$

The variation in the predicted and observed moisture ratios over time for native cassava starch is given in Figure 4. This figure shows that the moisture ratio of the

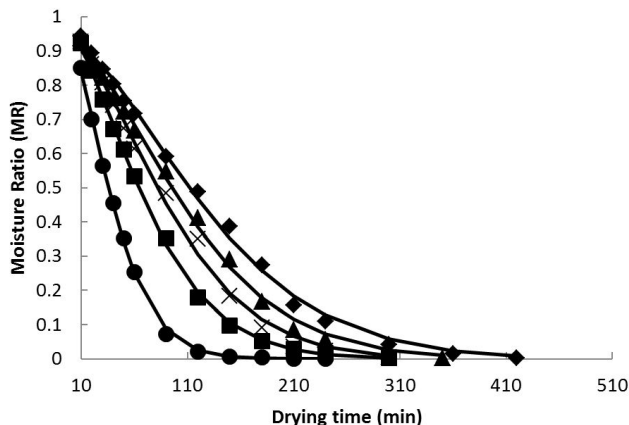


Figure 4. Variation in moisture ratios of native cassava starch predicted at various temperatures using Modified Hii et al. model and observed data with drying time: \blacklozenge 40°C, \blacktriangle 45°C, \times 50°C, 55°C, and \bullet 60°C.

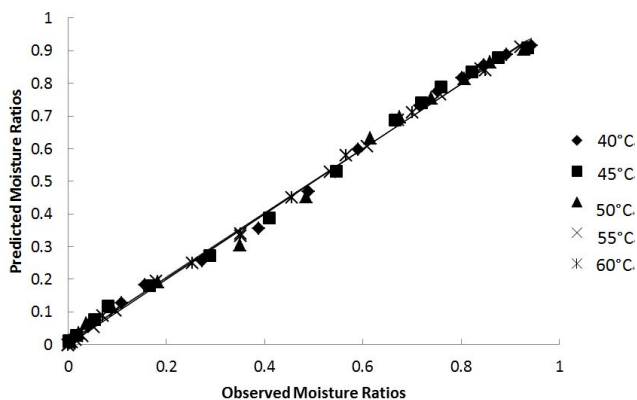


Figure 5. Plots of predicted against observed moisture ratios of native cassava starch, dried at different temperatures

starch decreased with time. Towards the end of the drying, the trend tended to become asymptotic to the time axis. The figure also shows that the Modified Hii et al. model closely predicted the observed moisture ratios of the starch at drying temperatures of 40, 45, 50, 55 and 60°C.

The reliability of the Modified Hii et al. model for describing the drying curves of native cassava starch, tested by comparing the predicted moisture ratios of the starch with those obtained experimentally at each drying temperature (Figure 5), showed that the predicted moisture ratios of the starch banded around a straight line with a high value of R^2 , indicating that the model tracked the drying curves well throughout the drying periods. This further proves that the proposed model was suitable for use in describing the drying behavior of the starch.

Conclusion

From the results of this study, we can conclude that, for native cassava starch, the drying time and dynamic EMC decrease as the temperature increases, while the drying rate increases with temperature. The constant rate phase occurs without the period of induction over a temperature range of 40-55°C, prior to the occurrence of the falling rate phase, while drying at 60° occurs entirely in the falling rate phase. The critical moisture content is observed when drying the starch within a temperature range of 40-55°C and increases with the temperature. The effective diffusivity increased with the drying temperature and was within the values acceptable for agricultural and food products. The diffusion coefficient and drying activation energy of the starch were $9.58 \times 10^{-5} \text{ m}^2\text{s}^{-1}$ and $32.933 \text{ kJmol}^{-1}$, respectively. The proposed Modified Hii et al. model produced the most accurate prediction of the drying characteristics of the starch from among the fifteen thin-layer drying models that were tested for a drying temperature range of 40-60°C.

Conflict of Interest

The authors have no conflicting financial or other interests to declare.

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