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Original Article

Effect of temperature and shape on drying performance of cassava chips

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ABSTRACT

The drying behavior of cassava chips was investigated using two cutting shapes—rectangular and circular—with evaluation under different air temperatures of 60 °C, 80 °C, 100 °C and 120 °C. The results showed that the rectangular chips with a drying air temperature of 100 °C was optimal because they had a soft, white color desirable for cassava flour manufacture and required less drying time compared to the circular chips Four classical drying models—Approximation of Diffusion, Henderson and Pabis, Page, and Verma—were fitted to experimental data and evaluated by comparing the coefficient of determination, reduced chi-square and root mean square error between the experimental and predicted values. The Page model was able to satisfactorily describe the drying behavior of cassava chips.

Introduction

Cassava (*Manihot esculenta* Crantz) is one of the most important staple foods in the world along with rice, wheat and maize (IFAD, 2000). Cassava is one of the most important economic crops in Thailand for domestic use as cassava flour, animal feed or feedstock for bioethanol production, and also for export and its is grown by small-scale farmers right up to business owner factories which are usually located within the cultivating area (Piyachomkwan and Tanticharoen, 2011). Ospina and Wheatl (1992) and Udoro et al. (2008) have described various aspects of processing cassava and this is summarized below. After cassava roots are harvested, they are either loaded into the chopping machine or cut into small pieces manually by farmers. Drying techniques vary among farmers and range from sun drying to artificial hot-air or oven drying. Drying allows safe storage of cassava chips over a long period by reducing the biological degradation rate of raw cassava chips. It also results in a considerable reduction in weight and volume, which helps minimize packaging, storage and transportation costs. Currently, sun drying involves spreading out fresh cassava chips on a cement floor and turning them over with a shovel or rake; it is still the most widely used method in the cassava chip industry. Quality and the drying time of cassava chips in the sun-drying process are influenced by the chips' geometry and the weather conditions. Despite the cost of the oven drying, it is more efficient than the conventional sun-drying due to the control over the drying atmosphere and better control of quality to reduce contamination. The rate of drying depends on the chip size, loading density and initial moisture. The air temperature for the production of cassava chips in oven drying is in the range 45–165 °C (Udoro et al., 2008). Therefore, oven drying of cassava chips is highly recommended. In order to obtain a sellable product, dried cassava chips should pass the following criteria: starch content (68–70% minimum), final moisture content (14–17%), fiber content (5% maximum) and sand content (3% maximum).

Discussion of the drying kinetics of cassava chips can be found in many works such as thin-layer (one to three layers) drying of peeled and diced cassava roots (Kajuna et al., 2001), blanched and unblanched of both sundried and oven dried cassava chips (Udoro et al., 2008) and air-drying of pretreated (soaking and boiling) cassava chips (Tunde-Akintunde and Afon, 2010). However, few works have focused on the influence of cassava chip geometry and air temperature on the oven drying performance. Moreover, the subsequent appearance and starch content of dried cassava chips as well as energy consumption should be taken into consideration when choosing the optimal conditions for a commercial drying plant. Therefore, this paper studied the effect of the shape of cassava chips during oven drying as well as the drying temperature. Moreover, the appearance and starch content after drying were analyzed and discussed to confirm the quality of dried product. Finally, the drying curve obtained from the oven drying experiment

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was fitted to several mathematical models that could explain the drying characteristics.

Materials and methods

Sample preparation and drying experiment

Cassava samples (CM 305-21) were obtained from a local vegetable market in Pathum Thani, Thailand. As shown in Fig. 1, the samples were roughly cleaned to remove adhered mud, and then chipped into two separate shapes, rectangular (length and width in the range 1–2 cm and 4–5 cm, respectively) and circular (diameter in the range 5–8 cm), using a sharp stainless steel knife. The rectangular chips were randomly cut to simulate the dimensions of typical chips produced in the industry such as from using a by chipping machine. The circular chips were sliced along the cassava root with a slice thickness of 5 mm. The loading density was fixed to compare the drying performance between 2 shapes under each set of drying conditions. A sample (200 g) of cassava chips was spread on a tray and kept inside an electric oven (ED series 53; Binder GmbH; Tuttlinggen, Germany) where the drying experiments were performed. Experiments were carried out at four different temperatures (60 °C, 80 °C, 100 °C and 120 °C). During the tests, the samples were taken out of the oven, weighed on a digital balance and then put back into the oven. The weight loss of samples was measured at 15 min intervals during the drying test. When no further changes in three consecutive weights were observed, the experiment was terminated. After the drying test, the dried samples were taken to the Cassava and Starch Technology Research Unit (CSTRU) for determination of the final moisture and starch contents (dry basis) according to the method of Association of Official Agricultural Chemists (1990) and Thailand Industrial Standards Institute (1978), respectively.

Mathematical modeling of drying

The experimental drying data were used to calculate the moisture ratio (MR) according to Equation (1):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

where M_t is the moisture content at any time of drying (grams of water per gram of solid), M_0 is the initial moisture content (grams of water per gram of solid) and M_e is equilibrium moisture content (grams of water per gram of solid). M_t and M_e were calculated using Equations (2) and (3):

$$M_t = \frac{m_t - m_s}{m_s} \quad (2)$$

$$M_e = \frac{m_e - m_s}{m_s} \quad (3)$$

where m_t is the sample weight (grams) at time t, m_s is the solid weight (final weight in grams) of the sample and m_e is the equilibrium mass (grams). Since the samples were not exposed to uniform relative humidity and temperature during the drying process, the values of m_e were very small compared to m_t or m_0. Thus, the moisture ratio can be simplified to M_t/M_0 (Pala et al., 1996; Doymaz, 2004; Goyal et al., 2007).

Four mathematical drying models (Table 1) were tested to select the most suitable model for describing the drying characteristic of the cassava chips. To evaluate the fitting performance of each drying model, three statistical criteria were used—the coefficient of determination (R^2), reduced chi-square (χ^2) and the root mean square error (RMSE) using Equations (4)–(6), respectively (Taheri-Garavand et al., 2011; Darvishi et al., 2012).

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{\sum_{i=1}^{N}\left(\overline{MR}_{pre,i} - MR_{exp,i}\right)^2}\right] \quad (4)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - z} \quad (5)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2\right]^{1/2} \quad (6)$$

where N is the number of observations, z is the number of constants, $MR_{exp,i}$ and $MR_{pre,i}$ are experimental and predicted dimensionless moisture ratio (MR) respectively. The model with the highest R^2 average value and the lowest χ^2 and RMSE average values was selected as the best drying kinetics model.

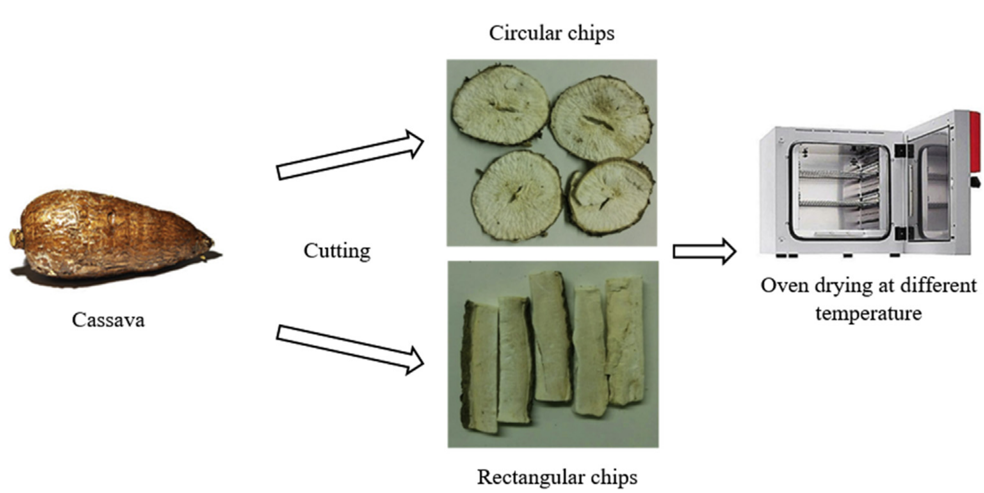

Fig. 1. Schematic diagram of drying experiments.

Table 1
Mathematical models tested for cassava chip oven drying in this study.

Model name	Expression of moisture ratio (MR)	Reference
Henderson and Pabis	MR = a exp (-kt)	(Henderson and Pabis, 1962)
Page	MR = exp (-kt^n)	(Karathanos and Belessiotis, 1999)
Verma et al.	MR = a exp (-kt) + (1-a) exp (-gt)	(Verma et al., 1985)
Approximation of Diffusion	MR = a exp (-kt) + (1-a) exp (-kgt)	(Sacilik et al., 2006)

Results and discussion

Appearance and property of dried cassava chips

Figs. 2 and 3 show the appearance of all samples after drying at different air temperatures. Samples dried at 120 °C tended to have a darker color compared to the samples at 60 °C, 80 °C and 100 °C, and also had the familiar odor of burned sugar. As indicated in Table 2, all results showed that dried cassava in both shapes at all temperature tested in this experiment satisfied the standards required by the cassava industry in Thailand—namely, a final moisture content less than 14% and a minimum starch content of 68%—except for rectangular chips dried at 60 °C, circular chips dried at 120 °C and rectangular chips dried at 120 °C which contained 67.08%, 66.99% and 67.61% starch content, respectively. It could be said that with the higher drying temperature (120 °C), the starch content was reduced regardless of the shape of the samples. In addition, the final moisture content decreased as the temperature increased. The samples dried at 100 °C had a satisfactory final moisture content and a high starch content compared to other samples at 60 °C and 80 °C that passed the standards. It should be noted that the analyzed samples might contain some peel that resulted in the lower starch content as can be seen with the rectangular chips dried at 60 °C. Considering the effect of drying temperature in more detail, the higher the air temperature, the more starch or carbohydrates that would break down into sugar and when the carbohydrates are cooked, the sugars in those carbohydrates are browned. This results from the non-enzymatic Browning reaction, where sugars react with amino acids when heated to create the brown color (Yildiz, 2009). As this process has a high temperature coefficient, the rate of browning increases with the rising temperature. Lowering the temperature during drying cassava chips can help to minimize the process (Yildiz, 2009). Fig. 4 shows the overall mean diameter and length of all samples before and after drying regardless of the drying conditions. From Fig. 4A, the mean diameter of circular chips was reduced by 21% after drying. Similarly, the mean length of rectangular chips after drying was reduced by 18.5%, as shown in Fig. 4B.

Drying performance

As seen in Fig. 5, the MR decreased non-linearly with increased drying time for all samples due to the different forms of water (that is free water and bound water) in cassava roots (Tunde-Akintunde and Afon, 2010). From Fig. 5A and B, the drying temperature strongly affected the drying performance of the cassava samples,

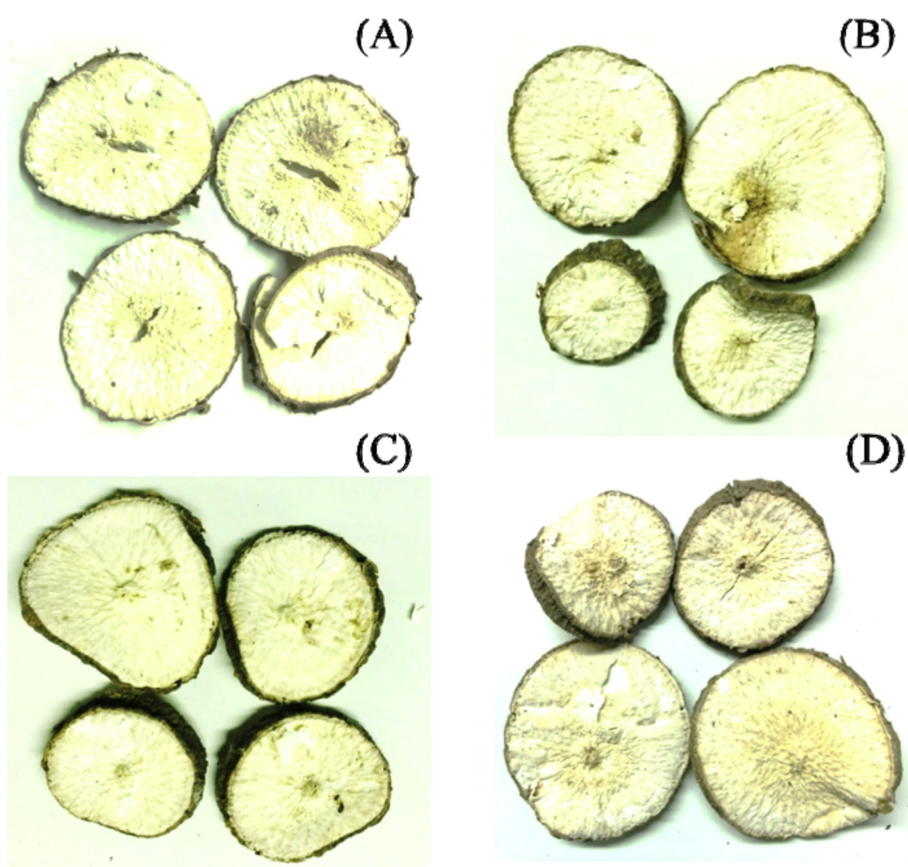

Fig. 2. Appearance of circular chips after drying at: (A) 60 °C; (B) 80 °C; (C) 100 °C; (D) 120 °C.

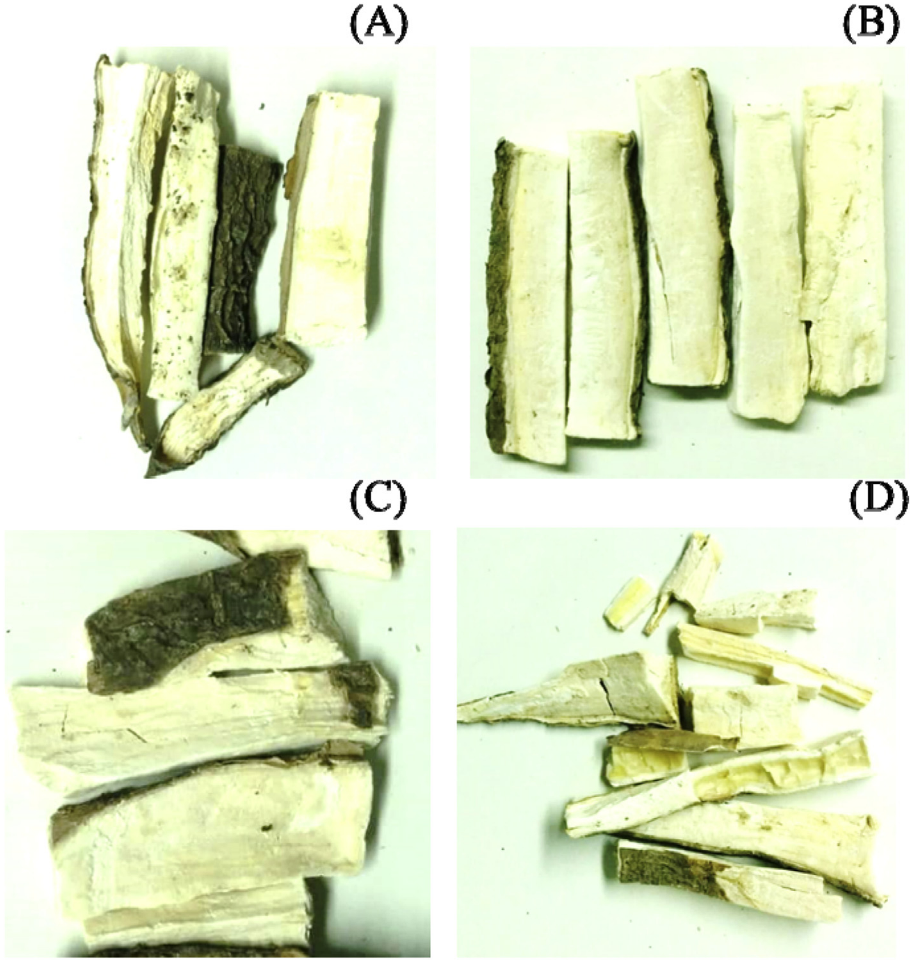

Fig. 3. Appearance of rectangular chips after drying at: (A) 60 °C; (B) 80 °C; (C) 100 °C; (D) 120 °C.

regardless of shape as observed from the drying curves at 100 °C and 120 °C. The drying time decreased as the air temperature increased for both circular and rectangular chips. For example, at the desired moisture ratio of 0.1, the drying time of circular chips at 60 °C, 80 °C, 100 °C and 120 °C was 520 min, 350 min, 210 min and 170 min respectively. Table 3 presents the energy consumption and its cost associated with cassava drying. The amount of energy consumed by the oven drying process at 60 °C was higher than the amount of energy consumed at 120 °C as it required a substantially longer drying period to reach the targeted condition. The drying time spent on removing the moisture content in the rectangular cassava chips was less than that for the circular chips indicating that the former was a more effective oven drying process. For example, after drying for 120 min at 60 °C, 80 °C, 100 °C and 120 °C in an oven, the MR was 0.73, 0.59, 0.37 and 0.24 for circular chips, respectively and was 0.70, 0.48, 0.33 and 0.19 for rectangular chips, respectively. In general, rectangular chips shrank faster than circular chips by 5–15%. The most plausible reason for this was that the mean size of rectangular samples was lower than the mean size of the circular chip samples. The shorter the distance traveled from within to the surface of the chips, the more moisture is removed in a shorter time (Olowoyeye, 2014). Therefore, the chip shape should allow air and moisture to readily pass through the mass for effective drying. Moreover, even though the surface area of the two types of samples was arbitrarily controlled and the total surface area of the circular chip seemed to be higher than that of the rectangular chip, the latter had a higher lateral surface area than the former; thus, the exposure to the air flow of the rectangular chip was relatively

Table 2
Moisture and starch content (±SD) of dried cassava chips.

Drying temperature (°C)	Sample shape	Final moisture content (%)	Starch content (%)
60	Circular	6.34 ± 0.90	74.62 ± 0.45
	Rectangular	10.69 ± 0.04	67.08 ± 0.04
80	Circular	4.02 ± 0.93	68.26 ± 0.61
	Rectangular	4.45 ± 0.64	69.63 ± 0.11
100	Circular	2.24 ± 0.08	74.34 ± 0.02
	Rectangular	4.45 ± 0.06	72.59 ± 0.22
120	Circular	1.74 ± 0.11	66.99 ± 0.16
	Rectangular	1.62 ± 0.27	67.61 ± 0.05

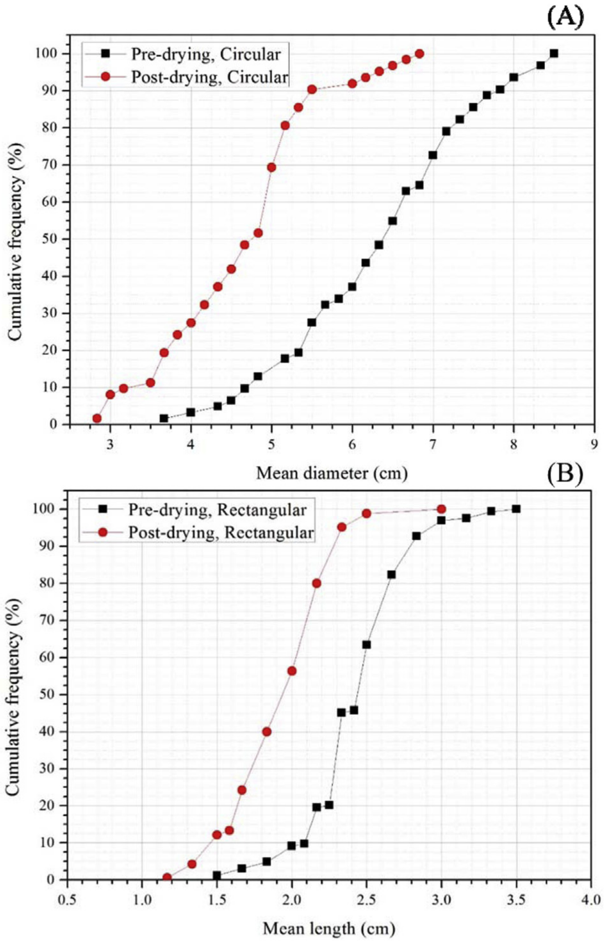

Fig. 4. Overall size distribution of pre-drying and post-drying from all drying conditions: (A) circular chips (B) rectangular chips.

higher leading to the enhancement of the moisture evaporation rate (Naderinezhad et al., 2016). Possible errors in the experimental data might have occurred in the measurement of the weight of the samples and of the initial moisture content of cassava chips. The moisture content on a wet basis of freshly harvested cassava roots can vary in the range 62.5–75.4% (Kajuna et al., 2001; Mlingi, 1995). Cassava roots tend to develop water-soaked tissues and begin to deteriorate rapidly after they are harvested and kept in the laboratory (Kajuna et al., 2001).

Mathematical modeling

The experimental results of the MR variation with drying time at different air temperatures in the oven-drying process and the cassava chip geometry were fitted to Approximation of Diffusion, Henderson and Pabis, Page, and Verma models, which have been widely used in the literature to predict the behavior and depict the kinetics of the drying process (Akpinar and Bicer, 2005; Sonmete et al., 2017; Zhao et al., 2014). The drying constants and the results of statistical analysis for the four models are shown in Tables 4 and 5 for dried circular cassava chips and dried rectangular cassava chips, respectively. The R^2 values varied from 0.97794 to 0.99010, from 0.97393 to 0.99408, from 0.96325 to 0.90182 and from 0.99448 to 0.99910 for the Approximation of Diffusion, Henderson and Pabis, Page, and Verma models, respectively. The values of R^2 were greater than 0.97 for all models except for the Verma model, and the Page model had the highest value. It seemed that the

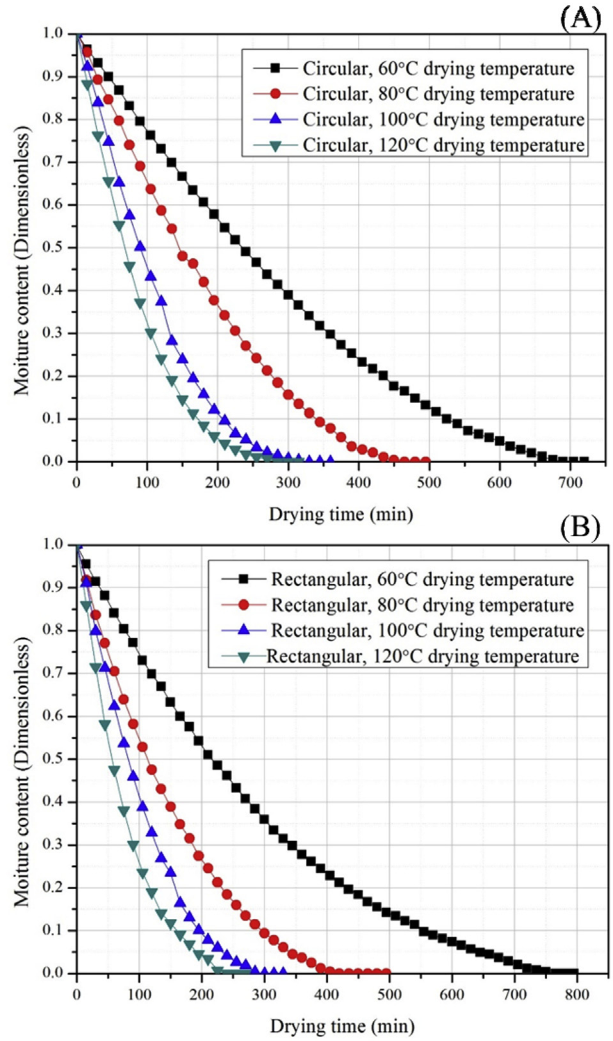

Fig. 5. Drying curves: (A) circular chips and (B) rectangular chips.

predicted MR curve derived from the Page model precisely fitted the MR curve from the drying experiment. Figs. 6 and 7 show the experimental and prediction moisture ratio, respectively, for the Page model versus time. The χ^2 values varied from 0.00010 to 0.00249, from 0.00065 to 0.00257, from 0.00095 to 0.00549 and from 0.0001 to 0.00054 for the Approximation of Diffusion, Henderson and Pabis, Page, and Verma models respectively. The RMSE values were between 0.00932 and 0.07076 for all examined models.

Table 3
Energy utilization and cost of cassava drying.

Drying temperature (°C)	Sample shape	Drying time (hr)	Unit[a] (kWh)	Cost[b] (THB)
60	Circular	12	2.88	8.64
	Rectangular	13	3.12	9.36
80	Circular	8	2.56	7.68
	Rectangular	7.5	2.4	7.20
100	Circular	5.5	2.2	6.60
	Rectangular	4.5	1.8	5.40
120	Circular	4.5	2.16	6.48
	Rectangular	4.5	2.16	6.48

[a] Unit was calculated from multiplication of utilization factor (target temperature/maximum temperature), electric power of electric oven (1.2 kW), and drying time.
[b] Cost was calculated by multiplying unit by electricity cost (THB 3/unit).

Table 4
Constants and statistical results—coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (RMSE)—from mathematical models for dried circular cassava chips.

Model	Approximation of Diffusion				Henderson and Pabis				Verma				Page			
Temperature (°C)	Constant	R^2	χ^2	RMSE	Constant	R^2	χ^2	RMSE	Constant	R^2	χ^2	RMSE	Constant	R^2	χ^2	RMSE
60	k = 0.00677 a = −17.31348 g = 0.95489	0.99305	0.00070	0.02564	k = 0.00381 a = 1.09742	0.97393	0.00257	0.04968	k = 0.00347 a = 0.01 g = 0.01	0.96325	0.00370	0.05894	k = 0.00037 n = 1.38501	0.99448	0.00054	0.02285
80	k = 0.00678 a = −16.76077 g = 0.95347	0.99305	0.00104	0.03078	k = 0.00600 a = 1.09959	0.97566	0.00256	0.04906	k = 0.00347 a = 0.00538 g = 0.00347	0.96325	0.00549	0.07076	k = 0.00067 n = 1.39277	0.99569	0.00045	0.02063
100	k = 0.01801 a = −16.78671 g = 0.95180	0.99733	0.00031	0.01645	k = 0.00998 a = 1.09512	0.97991	0.00223	0.04524	k = 0.00919 a = 0.09430 g = 0.00919	0.97097	0.00338	0.05435	k = 0.00134 n = 1.39462	0.99833	0.00019	0.01305
120	k = 0.02108 a = −15.41202 g = 0.95608	0.99897	0.00011	0.00989	k = 0.01239 a = 1.06566	0.98905	0.00114	0.03220	k = 0.00578 a = 0 g = 0.01170	0.98483	0.00166	0.03789	k = 0.00327 n = 1.27329	0.99883	0.0001	0.00934

Table 5
Constant and statistical results—coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (RMSE)—from mathematical models for dried rectangular cassava chips.

Model	Approximation of Diffusion				Henderson and Pabis				Verma				Page			
Temperature (°C)	Constant	R^2	χ^2	RMSE	Constant	R^2	χ^2	RMSE	Constant	R^2	χ^2	RMSE	Constant	R^2	χ^2	RMSE
60	k = 0.05397 a = −0.10669 g = 0.07298	0.98994	0.00093	0.02960	k = 0.00384 a = 1.06720	0.98720	0.00116	0.03337	k = 0.0036 a = 0.00556 g = 0.0036	0.98229	0.00163	0.03925	k = 0.00089 n = 1.24078	0.99685	0.00028	0.01654
80	k = 0.01215 a = −4.39198 g = 0.88144	0.99612	0.00038	0.01857	k = 0.00719 a = 1.05244	0.98789	0.00115	0.03281	k = 0.00684 a = 0.00937 g = 0.00684	0.98488	0.00149	0.03664	k = 0.00228 n = 1.21165	0.99586	0.00039	0.01918
100	k = 0.00984 a = 1 g = 1	0.97794	0.00249	0.04651	k = 0.01054 a = 1.07721	0.98401	0.00172	0.03962	k = 0.00984 a = 0.001 g = 0.00984	0.97794	0.00249	0.04651	k = 0.0021 n = 1.3202	0.99776	0.00024	0.0148
120	k = 0.02412 a = −2.90632 g = 0.84007	0.99910	0.00010	0.00932	k = 0.01406 a = 1.04636	0.99408	0.00065	0.02395	k = 0.013480 a = 0.00951 g = 0.01348	0.99182	0.00095	0.02814	k = 0.00591 n = 1.18269	0.99910	0.0001	0.00933

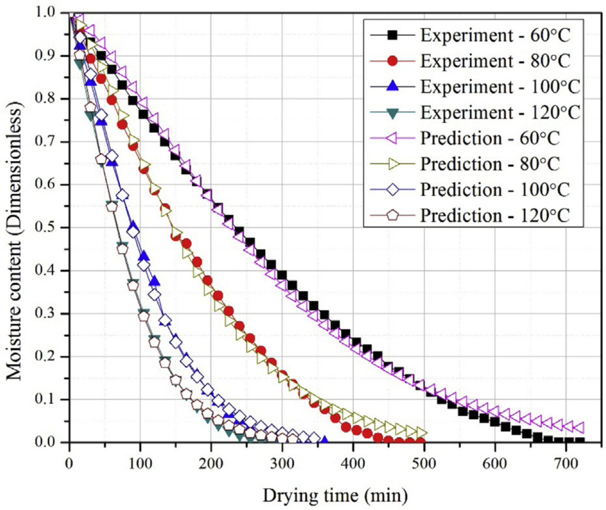

Fig. 6. Experimental and prediction moisture content for Page model versus time for circular chips.

However, for the Page model, the RMSE values were between 0.00933 and 0.02285. With its R^2 closest to 1, its χ^2 around 0.0001–0.0005 and its RMSE values of 0.00933–0.02285, the Page model was clearly satisfactory for drying behavior prediction with both rectangular and circular cassava chips. These results were in agreement with other literature reported for drying of cassava chips (Tunde-Akintunde and Afon, 2010) and for various food products (AHMED and Shivhare, 2001; Akpinar and Bicer, 2005; Dissa et al., 2008; Doymaz, 2007; Doymaz and Pala, 2002; Karathanos and Belessiotis, 1999; Kashaninejad and Tabil, 2004). However, at the end of the drying process, the experimental and predicted drying profiles diverged slightly. This might have been due to the amount of evaporated moisture at the end of experiment being small and so the balance could not accurately measure the weight of the sample.

This work experimentally investigated the influence of the cassava chip shape and the air temperature in the oven drying process. The moisture removal rate was observed to increase with increased oven drying temperature. However, it should be noted that the dried cassava chips seemed to have a darker color at higher air temperature, which is undesirable for the cassava flour and starch industry. Rectangular samples reduced the moisture content faster than did circular samples. Chopping cassava chips into rectangular shapes would also help increase the moisture removal ratio in the oven drying process. Rectangular chips had lower shrinkage after drying, (18.5% reduction of mean length compared to 21% reduction in mean diameter for the circular chips). The drying kinetics study indicated that the Page model was the most appropriate for describing the drying curve of cassava chips, as it had an R^2 value closest to 1 and the lowest χ^2 and RMSE values. After all information had been examined, including the appearance, the starch content and final moisture content from the CSTRU analysis and the drying curve, it could be concluded that the rectangular chips dried at an air temperature of 100 °C produced the best cassava chips using oven drying because these conditions yielded a soft, white color favored by cassava flour manufacturers and required less drying time compared to the circular chips at the same drying air temperature with negligible differences of 2.21% in the starch content and 1.75% in the final moisture content.

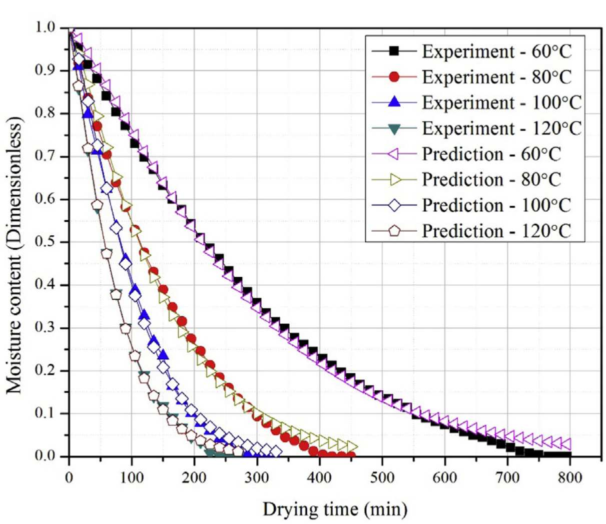

Fig. 7. Experimental and prediction moisture content for Page model versus time for rectangular chips.

Conflict of interest

The authors declare that there is no conflict of interest.

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