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Proper model of thin layer drying curve for taro (*Colocasia esculenta* L. Schott) chips

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Abstract

The present work reported the determination of the most proper thin layer drying model for the understanding of taro chips drying behaviour. Taro chips with average initial moisture content of 77.28 ± 1.7% (db) were dried in a custom laboratory scale hot-air dryer with static tray type at selected hot air temperatures (50, 60, 70°C). The moisture content, drying rate and moisture ratio during drying were measured and calculated. The calculated moisture ratio data were fitted to the 12 existed thin layer drying models. The results indicated that the drying rate depended on hot air temperature applied in which drying rate increased with increasing hot air temperature. Among the 12 proposed models, the Midilli *et al*. (2002) model precisely represented the hot air drying behaviour of taro chips. By using the Midilli *et al*. (2002) model, higher coefficient of determination (R^2: 0.997, 0.998, 0.998), lower mean square error (*RMSE*: 0.019, 0.016, 0.013) and lower mean square of deviation (χ^2: 4.8e^{-04}, 3.3e^{-04}, 2.2e^{-04}) were obtained for 50, 60, and 70°C, respectively.

Introduction

Taro (*Colocasia esculenta* L. Schott) is a rich-starch corm widely grown in tropical region such as Indonesia. Asian countries contribute 32% of the world production (Arici *et al*., 2016). Taro has high nutritional benefit such as medium glycaemic index and high antioxidant (Simsek and El, 2015), highly digestible (Sefa-Dedeh and Agyir-Sackey, 2002), and includes fibre, protein, vitamins, phosphorous, and calcium (Sefa-Dedeh and Agyir-Sackey, 2004). The corms are consumed in several forms such as flour, paste, cereal bars, beverage powders, canned slices and chips. In Indonesia, Taro is still consumed in limited ways. Its flour is commonly used as raw material for the sweet-sticky cake (locally known as ‘dodol’) and taro-stick snack (Elisabeth, 2015). Taro flour can be turned into various end-products with economic values especially for small and medium enterprises on foods and beverages. Aboubakar *et al*. (2008) investigated the physicochemical and thermal properties as well as microstructure of six varieties of taro starches and flours. Kaushal *et al*. (2012) conducted comparative study of taro flour with rice and pigeonpea flours in terms of physicochemical, functional, anti-nutritional and pasting properties. The study concluded that taro flour has a great potential to be used in food industry for the purpose of formulating new products or the replacement of food products made from various conventional flour sources.

Taro flour production is conducted in sequential processes which include cleaning the raw material, peeling, cleaning the peeled corm, slicing into chips, drying, size reduction with milling, and sieving. Previous studies reported that drying has a major role on taro flour quality and properties (Njintang and Mbofung, 2006). They investigated the effect of precooking time and drying temperature on the physicochemical characteristics and in vitro carbohydrate digestibility of taro flour. They concluded that drying temperature higher than 60°C and high precooking time (>45 min) considerably reduced the relative penetrometric index and in vitro carbohydrate digestibility of reconstituted ‘achu’ (thick porridge obtained by cooking and pounding taro corms). Recent study by Arici *et al*. (2016) suggested that drying conditions (drying temperature, air velocity) played an important role in the physicochemical and nutritional properties of the flours.

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Thin layer drying curve model can help to better understand the heat and mass transfer phenomena and computer simulations for the design of novel food processes and improvement of current drying operation (Kardum *et al*., 2001). Recently, there have been many studies on the thin layer drying and mathematical modelling of various vegetables, fruits and agro-based products such as potato, apple and pumpkin (Akpinar, 2006), fruits and vegetables (Hawa *et al*., 2012), lemon (Hawa *et al*., 2014a, 2014b), cassava chips (Tunde-Akitunde and Afon, 2010) and Gundelia tournefortii L. (Evin, 2012). Previous research on cocoyam slab thin layer drying was reported by Afolabi *et al*. (2015). The most common thin layer drying curve model proposed by some previous studies can be classified as theoretical, semi-theoretical, and empirical. Semi-theoretical models offer a compromise between theory and ease of use. These models are generally derived by simplifying general series solutions of Fick's Second Law (Akpinar, 2006), and are only valid within the drying condition for which they have been developed. However, if compared to theoretical thin layer drying curve model, this model requires short time and do not require assumptions regarding the sample geometry, mass diffusivity and conductivity. Empirical thin layer drying curve model neglects the fundamentals of the drying process and have parameters that have no physical meaning. The reason is that empirical model was derived from direct relationship between moisture content and drying time (McMinn *et al*., 2005).

In order to get a better understanding on the drying phenomenon of taro chips, the present work examined the most proper thin layer drying curve model. The objective of the present work was therefore to determine the most suitable thin layer drying model to understand the drying behaviour and to quantify the moisture removal characteristic of taro chips subjected to selected temperatures of hot air drying.

Materials and methods

Material preparation

Taro corms were purchased from the local market in Malang, Indonesia, washed with water, manually peeled, re-washed and sliced into chips (±1 mm thickness) using sharp stainless steel knife. The initial average moisture content of the chips was 77.28 ± 1.7% (db), which was measured with standard gravimetric method according to AOAC (Standard No. 925.10) (1995). After preparation, the chips were divided into small groups of similar weight (1 g) and subjected to drying.

Procedure

A custom laboratory scale hot-air dryer with static-tray type (Fig. 1) which was developed at the Department of Agricultural Engineering, Universitas Brawijaya, Indonesia, with insulated drying chamber (55 cm length × 50 cm width × 45 cm height), was used in the present work. The dryer was powered by an electric heater (2,000 W) placed at the bottom of the drying chamber. The generated hot air was blown with an electric fan with a constant speed (1.5 m/s), and was electronically controlled. A perforated tray was used to allow airflow, and placed inside the drying chamber. A K-type thermocouple (Omron, Japan) was placed near the product inside the tray to measure the actual temperature of hot air. The temperature inside the drying chamber was controlled by digital thermo-controller (Omron, Japan) linked with the heater. The dryer was installed in an environment of ≈70-75% relative air humidity and ≈28°C surrounding temperature.

Before drying, the dryer system was started in order to achieve a desirable steady state for each examined temperature (50°C, 60°C, 70°C). The prepared samples were loaded into the drier and removed at regular intervals for weight measurement. At initial stage, weighing was made at short interval (every 10 min) and gradually increased to every 30 min using precision balance (PL303 series, Mettler Toledo, USA) with 0.001 g accuracy. The manual weighing measurement was conducted until three consecutive weights were constant, indicating equilibrium condition. Moisture contents of the samples at each weighing intervals were determined according to standard method by AOAC (Standard No. 925.10) (1995). Drying experiment for each temperature was conducted in triplicate, and mean values were reported.

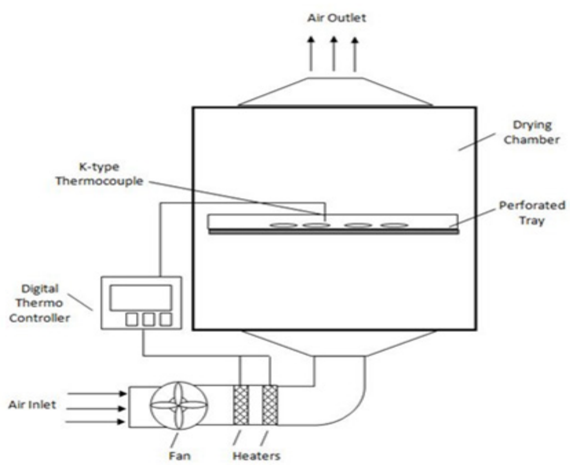

Figure 1. A schematic diagram of hot-air dryer with static-tray type (111 × 107 mm).

Table 1. The proposed thin layer drying curve models and their classification

Model No.	Model	Mathematical model	Classification*	Reference
1	Lewis	$MR = \exp(-kt)$	Semi-theoretical	Lewis (1921)
2	Page	$MR = \exp(-kt^n)$	Semi-theoretical	Page (1949)
3	Modified Page	$MR = \exp\left(-(kt)^n\right)$	Semi-theoretical	Overhults *et al*. (1973)
4	Henderson-Pabis	$MR = a\exp(-kt)$	Semi-theoretical	Henderson and Pabis (1961)
5	Logarithmic	$MR = a\exp(-kt) + c$	Semi-theoretical	Temple and Boxtel (1999)
6	Midilli *et al*.	$MR = a\exp(-kt^n) + bt$	Semi-empirical	Midilli *et al*. (2002)
7	Two-term	$MR = a\exp(-k_0 t) + b\exp\left(-k_1 t\right)$	Semi-theoretical	Sharaf-Eldeen *et al*. (1980)
8	Two-term Exp.	$MR = a\exp(-kt) + \left(1-a\right)\exp\left(-kat\right)$	Semi-theoretical	Sharaf-Eldeen *et al*. (1980)
9	Mod. Henderson-Pabis	$MR = a\exp(-kt) + b\exp\left(-gt\right) + c\exp\left(-ht\right)$	Semi-theoretical	Karathanos (1999)
10	Wang and Singh	$MR = 1 + at + bt^2$	Empirical	Wang and Singh (1978)
11	Diffusion approach	$MR = a\exp(-kt) + \left(1-a\right)\exp\left(-kbt\right)$	Semi-theoretical	Yaldiz and Ertekin (2001)
12	Verma *et al*.	$MR = a\exp(-kt) + \left(1-a\right)\exp\left(-gt\right)$	Semi-empirical	Verma *et al*. (1985)

*Jayas *et al*., 1991; McMinn *et al*., 2005; Pakowski and Mujumdar, 2006

Mathematical modelling of drying curves

The moisture ratio of taro chips during thin layer drying experiment was calculated using the following equation (Akpinar *et al*., 2003), where M_t was the moisture content of product at time *t*, M_o was the initial moisture content of the product and M_e was the equilibrium moisture content. *MR* represented the dimensionless moisture ratio.

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

The drying rate (*DR*) of taro chips can be defined as moisture content variation with time, and calculated using the following equation (Evin, 2012), where M_t and $M_{t+\Delta t}$ were the moisture content at *t* and moisture content at *t+Δt*, respectively, and *t* was drying time.

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (2)$$

For mathematical modelling, 12 models consisted of semi-theoretical and empirical thin layer drying curve models which are commonly used in previous studies were tested to select the best model for describing the drying curve of taro chips (Table 1). Non-linear regression analysis was performed using SPSS 16.0 (SPSS Inc., USA) and Microsoft Excel 2010 (Microsoft Inc., USA). The coefficient of determination (R^2) was one of the main criteria for selecting the best equation expressing the drying curves of the sample. In addition to the coefficient of determination, the goodness of fit was also determined by statistical parameters such as reduced mean square of deviation (χ^2) and root mean square error (*RMSE*) analysis (Akpinar *et al*., 2003). These parameters were calculated as follows, where $MR_{ex,i}$ was the *i*-th experimentally observed moisture ratio, $MR_{pr,i}$ was the *i*-th predicted moisture ratio, *N* was the number of observations and *np* was the number constants. For determining the fittest model, the coefficient of determination (R^2) value should be higher and reduced mean square of deviation (χ^2) and root mean square error (*RMSE*) values should be lower (Tunde-Akitunde and Afon, 2010).

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{ex,i} - MR_{pr,i}\right)^2}{N - np} \quad (3)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pr,i} - MR_{ex,i})^2\right]^{1/2} \quad (4)$$

Results and discussion

Drying curves

The hot air drying curve of taro chips is shown in Fig. 2(A) which illustrates the variation of moisture contents with drying times. The drying process was characterised by a progressive decrease in moisture content with time. The data also revealed that drying time decreased with increasing hot air temperature. By increasing the hot air temperature, the initial negative slope of moisture content curves became more significant, and made smaller time periods needed to remove the moisture content of the chips. The moisture content of chips gradually decreased at 50°C, while a sharp decrease occurred in moisture content at 70°C. The more significant decrease of moisture content caused by higher hot air temperature was previously reported by several researches in red pepper (Akpinar *et al*., 2003), eggplant (Ertekin and Yaldiz, 2004), potato, apple and pumpkin (Akpinar, 2006), sweet sorghum stalk (Shen *et al*., 2011), and paddy (Doungporn *et al*., 2012).

Fig. 2(A) also shows the total drying times required to reach moisture equilibrium of taro chips which were 330, 330 and 360 min at 50°C, 60°C and 70°C, respectively. It also shows the final moisture contents which were 3.03% (db), 1.40% (db), and 2.03% (db) at 50°C, 60°C and 70°C, respectively. The variation of drying rates with moisture contents which described the hot air drying behaviour of taro chips is given in Fig. 2(B) in which it is apparent that the higher hot air temperature used, the higher the drying rate. As can be seen in Fig. 2(B), the initial drying process was preceded by a warming-up period indicated by increasing of drying rate and followed by falling rate period, i.e. decreasing of drying rate. The highest temperature examined (70°C) yielded the shortest warming-up period (45 min) with peak drying rate at 1.13 g water/g dry matter/min. Fig. 2(B) also reveals that the lowest hot air temperature examined (50°C) yielded the longest warming-up period (140 min) with lowest achieved drying rate at 0.76 g water/g dry matter/min. It was also observed that the drying rate impacted on the drying time, i.e., drying time required until the moisture ratio (*MR*) decreased to below 0.5 was 120, 85, and 45 min at 50°C, 60°C and 70°C, respectively. Therefore, it took about 64%, 74%, and 87.5% of total drying time to remove the half remaining of taro chips water content at 50°C, 60°C and 70°C, respectively.

Fig. 2(C) shows the drying rates versus the moisture contents for all hot air temperatures examined. The initial moisture content value was 77.28 g water/g dry matter in average. All the curves indicate two zones which are characterised by the different trend of drying rates with the decrease of moisture contents. Initially, a gradual increase in drying rates occurred until the moisture contents of the chips reached 28, 46 and 45 g water/g dry matter at 50°C, 60°C and 70°C, respectively. As the moisture contents decreased, the drying rate also decreased until reaching moisture equilibrium. This trend of drying rate was in good comparison with that reported by Afolabi *et al*. (2014) who conducted experiment to investigate the drying behaviour of untreated and pretreated cocoyam slices under convective hot-air drying process.

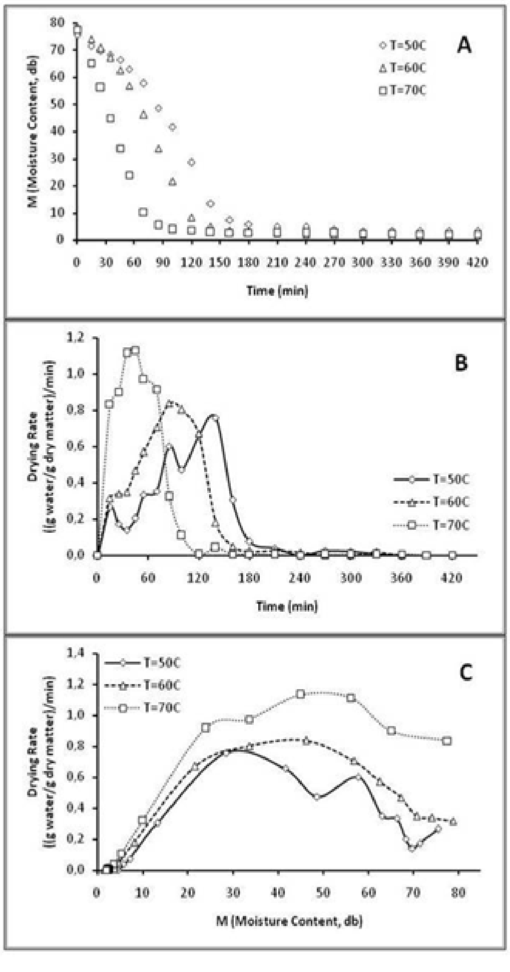

Figure 2. Variation of (A) moisture content with drying time, (B) drying rate with drying time, and (C) drying rate with moisture content under hot air drying process at different temperatures.

Mathematical modelling

Thin layer drying curve models are clearly beneficial for food engineers, and have found wide application due to their ease of use and less data required if compared to more complex theoretical models. Many correlations were proposed on various literatures with relative mathematically simple form to describe the rate of moisture removal during thin layer drying of agricultural and biological materials (Kardum *et al*., 2001). In the present work, 12 models were considered as they represent the most commonly used and adopted. The measured moisture content data were converted into non-dimensional parameter, i.e. *MR* using Eq. 1. Non-linear regression analyses were conducted on the 12 different thin layer drying curve models by relating the drying time and dimensionless moisture ratio (*MR*) for each hot air temperature examined. Regression coefficients for each thin layer drying curve model for taro chips during hot air drying are given in Table 2 for all the hot air temperatures examined.

Table 2. Thin layer drying curve model constants and statistical analysis result at all hot air temperature with asterisk (*) indicates the most suitable thin layer drying curve model.

Models	Temperature		
	50°C	60°C	70°C
Lewis			
k	0.008	0.111	0.022
R²	0.940	0.949	0.969
RMSE	0.128	0.108	0.062
χ^2	0.017	0.012	0.004
Page			
k	$1.52e^{-05}$	$5.05e^{-05}$	$1.22e^{-3}$
n	2.237	2.209	1.739
R2	0.995	0.997	0.998
RMSE	0.029	0.021	0.014
χ^2	$9.60e^{-04}$	$5.10e^{-04}$	$2.20e^{-04}$
Modified Page			
k	0.008	0.011	0.021
n	1.000	1.000	1.000
R²	0.940	0.949	0.968
RMSE	0.128	0.108	0.062
χ^2	0.018	0.013	0.004
Henderson-Pabis			
a	1.188	1.178	1.103
k	0.010	0.013	0.023
R²	0.932	0.946	0.968
RMSE	0.108	0.091	0.055
χ^2	0.012	0.009	0.003
Logarithmic			
a	1.280	1.223	1.118

Table 2. (Cont.)

k	0.008	0.011	0.022
c	-0.121	-0.063	-0.019
R²	0.941	0.949	0.969
RMSE	0.097	0.085	0.054
χ^2	0.010	0.008	0.003
*Midilli et al.**			
a	0.947	0.958	0.979
k	$9.78e^{-07}$	$1.24e^{-05}$	$9.00e^{-04}$
n	2.906	2.513	1.809
b	$8.45e^{-06}$	$1.24e^{-05}$	$1.03e^{-05}$
R²	0.997	0.998	0.998
RMSE	0.019	0.016	0.013
χ^2	$4.80e^{-04}$	$3.30e^{-04}$	$2.2e^{-04}$
Two-term			
a	0.594	0.588	0.551
k0	0.010	0.013	0.023
b	0.594	0.588	0.551
k1	0.010	0.013	0.023
R²	0.932	0.946	0.968
RMSE	0.108	0.091	0.055
χ^2	0.014	0.010	0.003
Two-term Exp.			
a	0.008	0.008	0.012
k	0.996	1.366	1.756
R²	0.939	0.948	0.967
RMSE	0.129	0.109	0.063
χ^2	0.018	0.013	0.004
Mod. Henderson-Pabis			
a	0.396	0.392	0.367
k	0.010	0.013	0.023
b	0.396	0.392	0.367
g	0.010	0.013	0.023
c	0.396	0.392	0.367
h	0.010	0.013	0.023
R²	0.932	0.804	0.968
RMSE	0.108	0.457	0.055
χ^2	0.016	0.292	0.004
Wang-Singh			
a	-0.006	-0.007	-0.009
b	$9.77e^{-06}$	$1.31e^{-05}$	$1.80e^{-05}$
R²	0.957	0.943	0.801
RMSE	0.093	0.090	0.174
χ^2	0.009	0.009	0.033
Diffusion Approach			
a	-15.378	-16.335	-6.922
k	0.022	0.029	0.052
b	0.920	0.925	0.858
R²	0.978	0.986	0.994
RMSE	0.060	0.045	0.022
χ^2	0.004	0.002	$5.90e^{-04}$

Table 2. (Cont.)

Verma et al.			
a	-5.851	-5.327	-5.217
k	0.023	0.031	0.054
g	0.019	0.025	0.044
R^2	0.978	0.986	0.994
RMSE	0.060	0.045	0.022
χ^2	0.004	0.002	$5.90e^{-04}$

For all the hot air temperatures examined, the model which has the fittest to the measured moisture ratio (*MR*) data was the Midilli *et al*. (2002) model. The model, which is written in Eq. 5, has mathematical form as follows, where *MR* and *t* are the moisture ratio and drying time, respectively. The estimated parameters of this model, i.e. *a* (dimensionless drying constant); *k* (drying constant, min^{-1}); *n* (dimensionless drying constant); *b* (dimensionless drying constant); and values of R^2, *RMSE* and χ^2 are highlighted in Table 2.

$$MR = a\exp\left(-kt^n\right) + bt \qquad (5)$$

Midilli *et al*. (2002) thin layer drying curve model can be considered as the most suitable drying model for taro chips with the highest R^2 and lowest RMSE and χ^2 values for all the hot air temperatures examined. The comparison between measured and predicted by Midilli *et al*. (2002) thin layer drying curve model of moisture ratio (*MR*) is depicted by Fig. 3(A). It was also observed that the drying constant (*k*) in the Midilli *et al*. (2002) thin layer drying curve model increased with increasing hot air temperature. The higher *k* value demonstrates the elevated moisture removal rates which indicate an enhancement of the drying potential (McMinn *et al*., 2005).

The mathematical modelling result of the present work was different when compared with previous report by Afolabi *et al*. (2015) that concluded the Logarithmic and Parabolic model were the best model to describe the thin layer drying characteristics of pre-treated cocoyam slab for oven and sun drying, respectively. The different result might be due to pre-treatment, dimension of dried cocoyam, drying method and condition used.

Validation of the most suitable thin layer drying curve model was made by comparing the measured moisture ratio values with predicted ones of the hot air temperatures examined. It was found that the predicted data generally band around the straight line (Fig. 3(B)) which indicates the suitability of Midilli *et al*. (2002) thin layer drying curve model for describing thin layer drying behaviour of taro chips. It is thus clear that the model could be used to explain thin layer drying behaviour of taro chips.

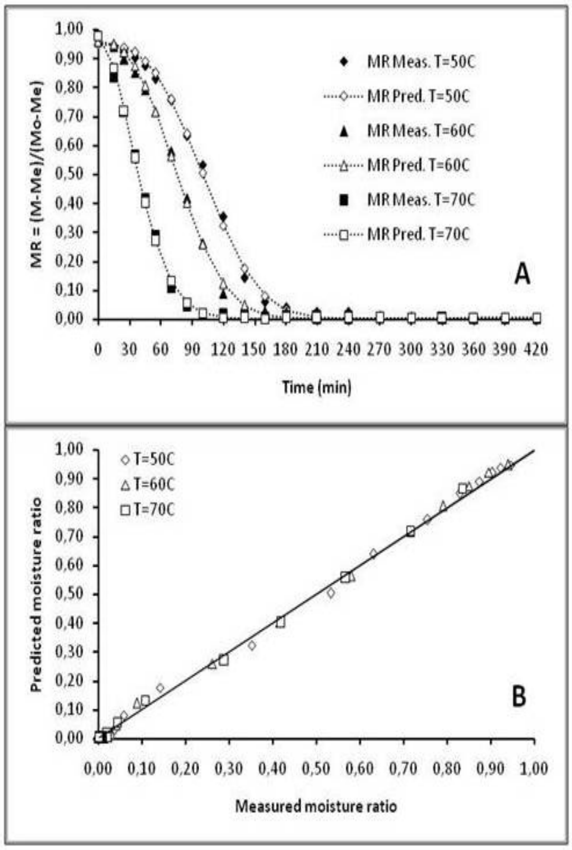

Figure 3. Measured and predicted moisture ratio using Midilli et al. thin layer drying curve model (A) and its comparison (B) for each examined hot air temperature

Conclusions

Thin layer drying of taro chips was conducted at different temperatures of hot air (50°C, 60°C, 70°C) and the drying characteristics of the taro chips were determined. Based on the results, it is concluded that the drying rate depended on the hot air temperature applied in which the drying rate increased with increasing hot air temperature. Initial drying process of taro chips proceeded by warming up period and followed by falling rate period, with different time required for both periods at different hot air temperatures. The 12 thin layer drying curve model were fitted to the measured data. For all hot air temperature conditions considered, the Midilli *et al*. (2002) thin layer drying curve model was demonstrated as the best model for describing the thin layer drying of taro chips.

Nomenclature

a, b, c, g, h, n	Empirical constants in the drying models
k, k0, k1	Empirical coefficients in the drying models
MR	Moisture ratio (dimensionless)
DR	Drying rate ((g water/g dry matter)/min)
$MR_{ex,i}$	*i*-th experimentally moisture ratio (dimensionless)
$MR_{pr,i}$	*i*-th predicted moisture ratio (dimensionless)
N	Number of observations
np	Number of constant in model
RMSE	Root mean square error
t	Time (min)
M_t	Moisture content at time t (% dry basis)
M_0	Initial moisture content (% dry basis)
M_e	Equilibrium moisture content (% dry basis)
$M_{t+\Delta t}$	Moisture content at time t + Δt (% dry basis)
χ^2	Reduced mean square of deviation

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