Research Article

Mathematical Modeling of Thin-Layer Cassava Leaves Drying for Animal Feed

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Abstract

Cassava is the forage that is high in protein in the leaves, trunk and graphite. The synthesis process of cyanide is self-defense of plants from insect damage, which was can be reduced by thermal processes. The evaluation of mathematical models for prediction of thin-layer cassava leaves drying for animal feed was aimed in this research under combined solar energy and hot-air convective dryer. Additionally, the mathematical models (Henderson and Pabis, Logarithmic, Two-Term) for describing the thin-layer drying behavior was developed, which was conducted using four air temperatures (50, 70, 90, 110^{o}C). Before the drying process, the cassava leaves are taken to aerate at surrounding air temperature for 0, 24, and 72 hr, respectively. The mathematical models were compared according to four statistical parameters, i.e. R, R^2, Adj R^2 and residual error. The results found that the increase of drying air temperature was rapidly decreased of the moisture content and the moisture ratio, which was resulted on the increase of drying rate and decrease drying time. The drying air temperature and desiccated time had the greatest effect on the drying kinetics of cassava leaves. Out of the three models considered, Two term model was found to be the most suitable for describing the drying behavior of the cassava leaves.

Keywords: Cassava leaves, Mathematical model, Solar energy, Hot-air convection

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แบบจำลองทางคณิตศาสตร์ของการอบแห้งใบมันสำปะหลังแบบชั้นบาง เพื่อเตรียมเป็นอาหารสัตว์

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บทคัดย่อ

มันสำปะหลังเป็นพืชอาหารสัตว์ที่มีโปรตีนสูงในส่วนของใบ ลำต้น ก้าน และชิ้นส่วนโดยรวม กระบวนการสังเคราะห์ไซยาไนด์ (cyanogenesis) เป็นการป้องกันตัวเองของพืชจากการถูกทำลายของแมลง ศัตรูพืชหรือสิ่งมีชีวิตที่กินพืช ซึ่งปริมาณไซยาไนด์สามารถลดลงได้ด้วยกระบวนการทางความร้อน วัตถุประสงค์ของงานวิจัยในครั้งนี้คือ การหาแบบจำลองทางคณิตศาสตร์สำหรับการทำนายการอบแห้งแบบชั้นบางของใบมันสำปะหลังเพื่อเตรียมเป็นอาหารสัตว์ภายใต้เครื่องอบแห้งด้วยพลังงานแสงอาทิตย์ร่วมกับการพาอากาศร้อน นอกจากนี้ยังได้มีการพัฒนาแบบจำลองทางคณิตศาสตร์ (Hendersion and Pabis, Logarithmic, Two-Term) สำหรับอธิบายพฤติกรรมของการอบแห้งแบบชั้นบาง เงื่อนไขการทดลองที่อุณหภูมิแตกต่างกัน 4 ระดับ (50, 70, 90, 110^{o}C) ก่อนการอบแห้ง ใบมันสำปะหลังจะนำไปผึ่งที่อากาศแวดล้อมเป็นเวลา 0, 24, and 72 hr ตามลำดับ แบบจำลองทางด้านคณิตศาสตร์จะเปรียบเทียบกับพารามิเตอร์ทางสถิติ เช่น ค่า R, R^2, Adj R^2 และ ค่าความผิดพลาด จากการศึกษาพบว่า การเพิ่มอุณหภูมิของการอบแห้งทำให้ค่าความชื้นและอัตราส่วนความชื้นลดลงอย่างรวดเร็ว ส่งผลต่อการเพิ่มขึ้นของอัตราการอบแห้งและลดระยะเวลาของการอบแห้ง อุณหภูมิ และระยะเวลาการผึ่งมีผลอย่างมากต่อจลนศาสตร์ของการอบแห้งใบมันสำปะหลัง จากการพิจารณาแบบจำลองทางด้านคณิตศาสตร์สามรูปแบบ พบว่า แบบจำลองของ Two term เหมาะสมที่สุดสำหรับอธิบายพฤติกรรมการอบแห้งใบมันสำปะหลัง

Keywords: ใบมันสำปะหลัง แบบจำลองทางคณิตศาสตร์ พลังงานแสงอาทิตย์ การพาอากาศร้อน

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Introduction

The cassava (*Manihot esculenta* Crantz) is an important crop in Thailand, which was 5.2% of the export value of agricultural products. Cassava plantations have spread across the country. The acreage of the top 5 in Thailand, including Kamphaeng Phet, Nakhon Ratchasima, Chaiyaphum, Sa Kaeo and Kanchanaburi. Cassava is the forage that is high in protein in the leaves (32.3%), trunk (14.6%), graphite (8.9%) and other parts (32.3%) (Wanapat, 1999). Cassava contains cyanogenic glucosides 2-types of linamarin are approximately 95% and lotaustralin, with approximately 5% of the substance cyanogenic glucosides all sites (Wanapat, 2002). The amount of cyanogenic glucosamine site is based on age species and the environment. The amount of cyanide can be reduced by thermal processes (Wanapat, 2000).

The solar energy is another alternative for drying and easy way, which is not complicated. In Thailand, the solar energy was studied and applied in the drying process, such as; Praphanpong *et al*. (2013), Teeradeth *et al*. (2009-2010), Prateep *et al*. (2012), Thaloengrach *et al*. (2012), Jaruwat *et al*. (2011) and much more.

The simulation models are helpful in designing new or in improving existing drying systems or for the control of the drying operation (Kooli *et al*., 2007). The modeling drying of biomaterials under solar energy are a complex problem, which was involved simultaneous heat and mass transfer in a hygroscopic nature. The drying rate was depended on a number of external variable parameters and internal parameters.

The utilization of cassava leaves are a waste agricultural materials harvested cassava roots are very few. Including research, the use of cassava leaves for animals feed preparation is few. The objective of the present study was to determine experimentally the thin-layer drying characteristics of cassava leaves for animal feed under combined solar energy and hot-air convective dryer. Furthermore, the mathematical models for describing the thin-layer drying behavior were investigated.

Materials and methods

1. Experimental apparatus

The combination of solar energy and hot-air dryer was developed and experimentally used in this study as shown in Fig. 1. It consists of a collector plate with dimensions 180x300 cm, drying chamber with dimensions 30x50x30 cm, 500 Watt electric heating coil which was controlled by PID control system and electrical fan. The K-type thermocouple was used to measure the temperature in the drying chamber, collector plate and surrounding air temperature, an accuracy of ± 2 °C. The cassava leaves sample was placed on a tray inside the drying chamber. The weight of the cassava leaves sample was continuously measured by electrical balance, an accuracy of ± 0.01g.

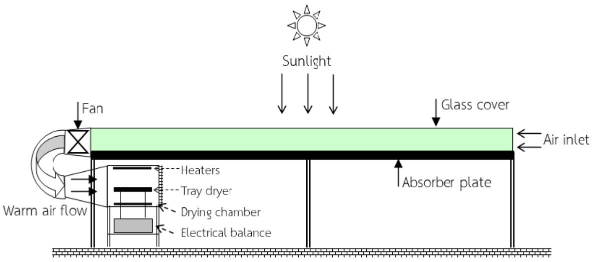


Fig.1 Combined solar energy and hot-air convective dryer

2. Experimental procedure

Experiments were performed to evaluation the effect of process variables on the thin-layer drying characteristics of cassava leaves under combined solar energy and hot-air convective dryer. Before the drying process, the cassava leaves are taken to aerate at surrounding air temperature for 0, 24, and 72 hr. The experiments were carried out at different drying temperature (50, 70, 90 and 110°C). All the experimental conditions, a 300g cassava leaves was used. The weight of cassava leaves was continuously monitored and recorded. The final moisture content in the cassava leaves was 10±1% drybasis (d.b.). Before the start of each drying conditions, a 300g cassava leaves sample was spread in a thin-layer on drying trays and placed in the drying chamber and the test started. The cassava leaves sample weight was continuously monitored and recorded during drying experiments by electrical balance (accuracy of ± 0.01g). Drying was continued until the moisture content of the cassava leaves sample reached 10% d.b.. The average moisture content of the cassava leaves samples for each weighing period was calculated based on the initial mass and final moisture content of the samples. After each drying experiment, the sample was oven-dried at 103°C to determine the moisture content.

3. Evaluation of thin-layer drying curves

The equation describes the drying rate of a thin-layer is necessary for simulation of deep bed drying, due to simulation models are usually based on the assumption that the deep bed is composed of a series of thin-layers (Kashaninejad *et al*., 2007). Besides, Jayas *et al*., (1991) reported that the behavior of moisture loss with time in drying is best characterized by an inverse exponential relationship. Numerous models have been proposed to describe the rate of moisture loss during drying of materials (McMinn, 2006; Sharma *et al*., 2005; Midilli *et al*., 2003; Akbulut *et al*., 2010; Duc *et al*., 2011; Hiia *et al*., 2009; Hii *et al*., 2012; Meziane, 2011; Singh, 2011; Kooli *et al*., 2007). A few selected thin layer drying models, which might be adequate to describe thin-layer drying data for the cassava leaves are reviewed as follow.

Henderson and Pabis (Chhinman, 1984) model has been used to model thin-layer drying characteristics of various agricultural products. The slope of model, coefficient k, is related to effective diffusivity when drying process takes place only in the falling rate period and liquid diffusion controls the process. The model of Henderson and Pabis was calculated using the following Eq. (1).

$$MR = a \exp(-kt) \qquad (1)$$

Two term model (Henderson, 1974) has proved to be the most widely popular. This model is a part of infinite series of negative exponentials derived from a general solution to the diffusion equation. Two term model was calculated using the following Eq. (2).

$$MR = a \exp(-k_1 t) + b \exp(-k_2 t) \qquad (2)$$

Logarithmic model (Chandra and Singh, 1995) has been used to model thin-layer drying characteristics of various agricultural products, which was calculated using the following Eq. (3).

$$MR = a \exp(-kt) + c \qquad (3)$$

4. Correlation coefficients and error analyses

The goodness of fit of the tested thin-layer models to the experimental data of cassava leaves under combined solar energy and hot-air drying was evaluated with the R, R^2, Adj R^2 and residual error. The linear or nonlinear regression analysis was performed with statistical software. The higher the R, R^2, Adj R^2 and lowest residual error values is the goodness of fit.

Results and Discussion

The moisture content change of cassava leaves under combined solar energy and hot-air convective dryer versus drying time at various hot-air temperature and time of aerate are as shown in Fig. 2. As seen from this figure that the moisture content was decreased with the increase of hot-air temperature, which was rapidly reduced in the first period and then slowly decreased. The drying time was deceased with the increase of hot-air temperature; it can be seen in the Table 1 While the moisture content was gradually decreased at 50°C in overall drying conditions, a sharp decrease occurs in moisture content with the highest hot-air temperature of 110°C.

Table 1 The drying time of cassava leaves under difference drying conditions.

Drying condition	Drying time (min)			
	50°C	70°C	90°C	110°C
0 hr of aerate	540	180	90	60
24 hr of aerate	330	120	60	30
72 hr of aerate	50	15	7	5

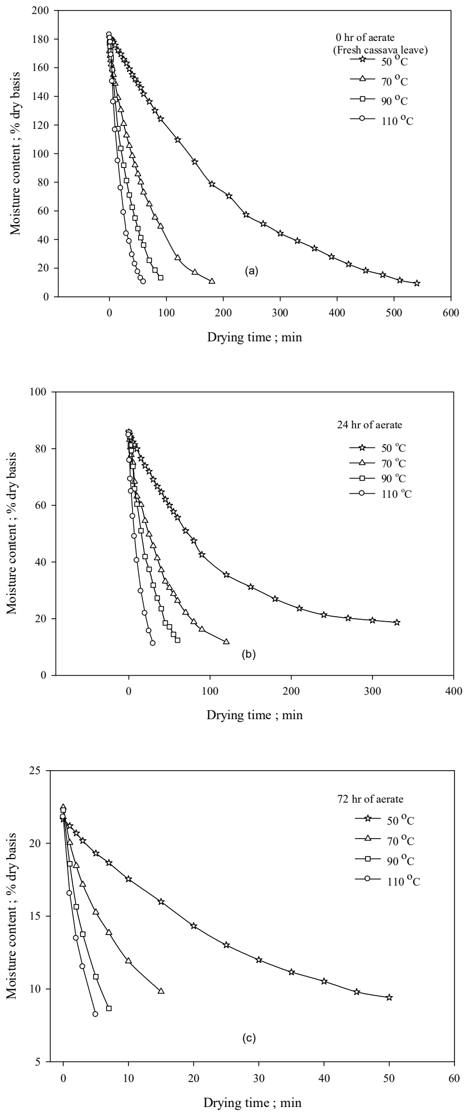


Fig. 2 Change of moisture content versus drying time under difference drying conditions (a) 0 hr of aerate (Fresh cassava leave) (b) 24 hr of aerate (c) 72 hr of aerate

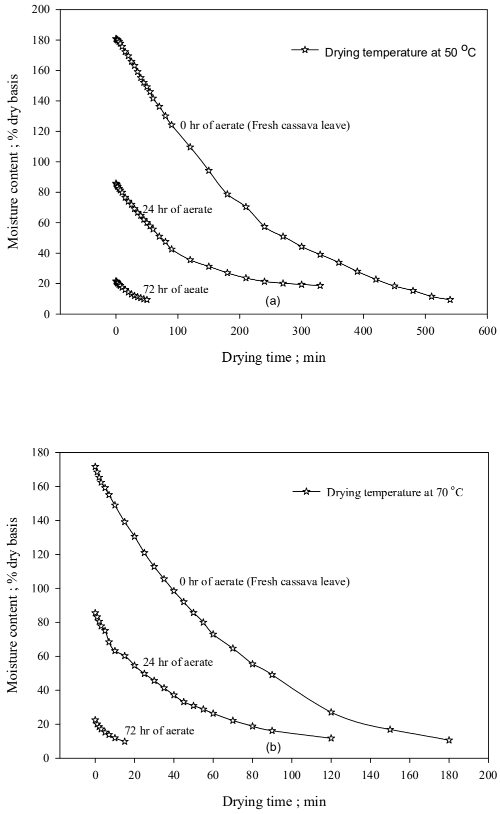


Fig. 3 Effect of time of aerate on the change of moisture conte

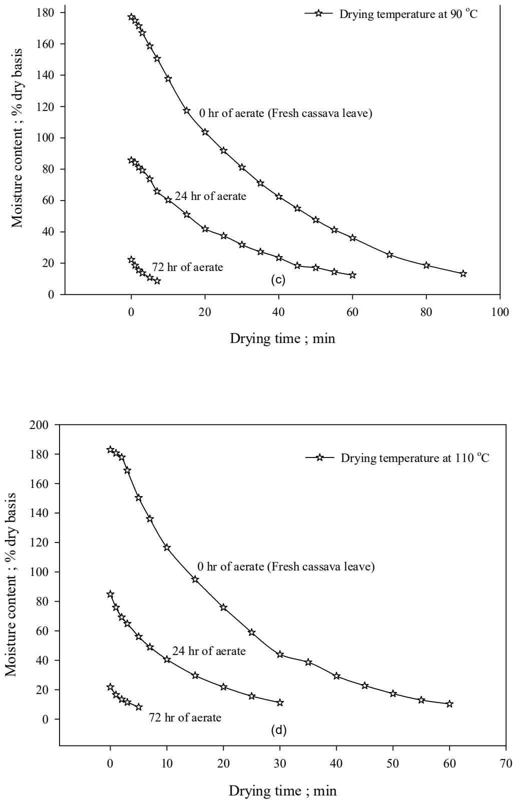


Table 2 Results of statistical analysis on the modeling

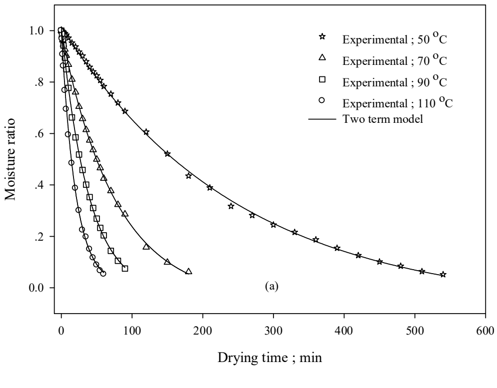
Mathematical model	Drying conditions		Regression coefficient		
	Temperature (°C)	Aerate (hr.)	R	R^2	Adj R^2
Henderson and Pabis	50	0	0.9990	0.9980	0.9980
		24	0.9923	0.9848	0.9842
		72	0.9967	0.9934	0.9928
	70	0	0.9995	0.9990	0.9989
		24	0.9966	0.9932	0.9929
		72	0.9859	0.9720	0.9673
	90	0	0.9996	0.9993	0.9992
		24	0.9991	0.9982	0.9981
		72	0.9941	0.9883	0.9854
	110	0	0.9996	0.9991	0.9991
		24	0.9980	0.9961	0.9956
		72	0.9923	0.9846	0.9795
	Average		***0.9960***	***0.9921***	***0.9909***

Table 2 Results of statistical analysis on the modeling (Con.)

Two term	50	0	0.9990	0.9980	0.9979
		24	0.9993	0.9987	0.9985
		72	0.9998	0.9995	0.9994
	70	0	0.9995	0.9990	0.9988
		24	0.9991	0.9981	0.9978
		72	0.9998	0.9997	0.9994
	90	0	0.9996	0.9993	0.9992
		24	0.9995	0.9989	0.9987
		72	0.9999	0.9998	0.9994
	110	0	0.9997	0.9995	0.9994
		24	1.0000	0.9999	0.9999
		72	0.9999	0.9998	0.9993
	Average		***0.9995***	***0.9991***	***0.9989***
Logarithmic	50	0	0.9997	0.9994	0.9994
		24	0.9993	0.9987	0.9986
		72	0.9998	0.9995	0.9995
	70	0	0.9998	0.9997	0.9997
		24	0.9983	0.9966	0.9962
		72	0.9979	0.9958	0.9941
	90	0	0.9997	0.9995	0.9994
		24	0.9994	0.9988	0.9986
		72	0.9995	0.9991	0.9985
	110	0	0.9996	0.9992	0.9991
		24	0.9988	0.9976	0.9970
		72	0.9987	0.9975	0.9950
	Average		***0.9992***	***0.9984***	***0.9979***

The effect of time of aerate at surrounding air temperature on the moisture content found that the time of aerate was significantly affected on the initial moisture content, namely the initial moisture content of cassava leaves before drying was reduced from 181% d.b. to 85 % d.b and 22 % d.b. for 24 hr and 72 hr, respectively. During operation, the trend of moisture content was similarly changed as shown in Fig. 3.

The moisture content of cassava leaves were converted into moisture ratio (MR), and then fitted against drying time, using the various models (Henderson and Pabis, Logarithmic, and Two-Term models). It can be seen that the Two term model has the average highest value for the R, R^2, Adj R^2 of 0.9995, 0.9991 and 0.9989, respectively. The results of statistical analysis on the modeling under all drying condition were presented in the table 2.



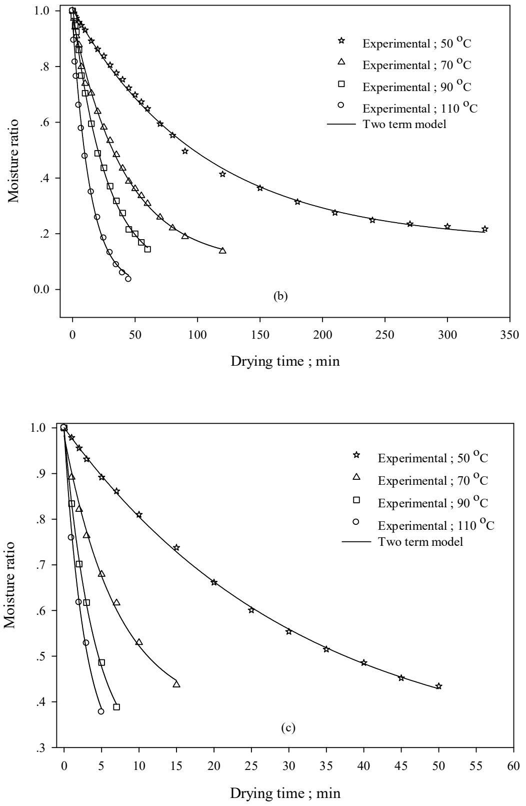


Fig. 4 Moisture ratio versus drying time, comparing experimental curve with the predicted one based on Two term model under the hot-air temperature range of 50–110°C.
(a) 0 hr of aerate (b) 24 hr of aerate
(c) 72 hr of aerate

Fitted drying curves based on Two term model which was found to provide excellent fits of the experimental data for 50, 70, 90 and 110°C can be seen in Fig. 4. Besides, it has the average lowest residual error as shown in Fig. 5, under specific drying condition. Therefore, Two term model was successfully described the thin-layer drying behavior of the cassava leaves under combined solar energy and hot-air convective drying.

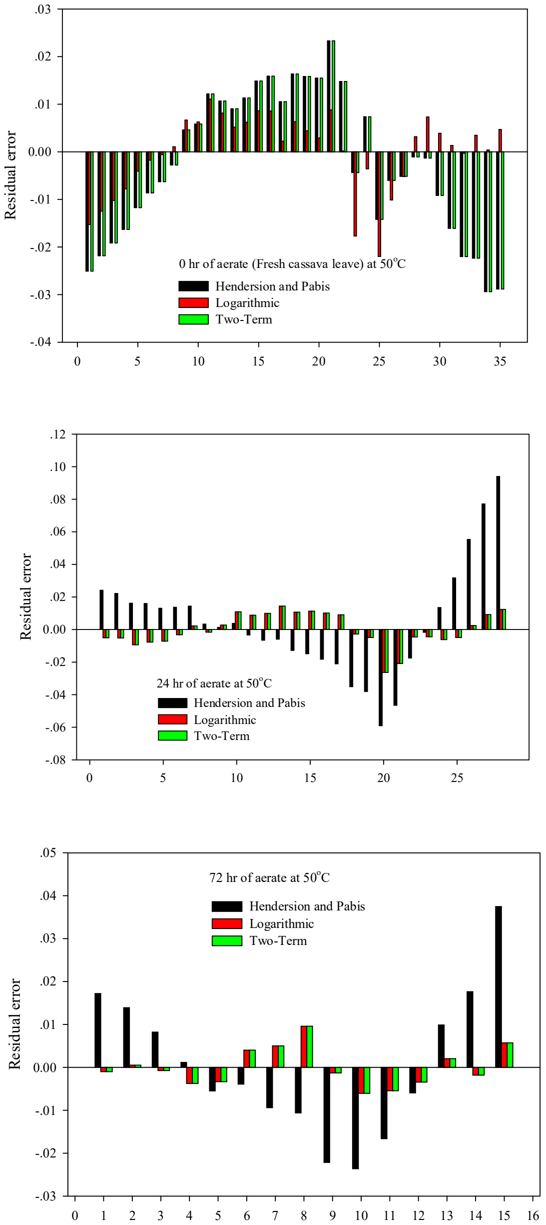


Fig. 5 Values of residual error under specific drying conditions (50°C) (a) 0 hr of aerate (b) 24 hr of aerate (c) 72 hr of aerate

The validation of the Two term model was confirmed by comparing the estimated or predicted moisture ratio at any particular drying condition as shown in Fig. 6. The predicted data generally banded around the straight line which showed the suitability of the Two term model in describing the combined solar energy and hot-air drying behavior of the cassava leaves.

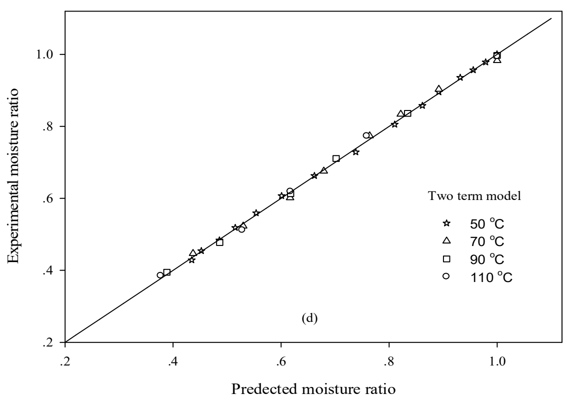


Fig. 6 The comparison of the experimental moisture ratio with the data predicted by Two term model

Conclusion

Base on this research for cassava leaves drying under combined solar energy and hot-air convective dryer for animal feed preparation, the following conclusions can be stated: 1) Drying air temperature and desiccate time are significant factors in drying of cassava leaves, 2) The higher drying air temperature and the desiccate long-time is resulted on the reduce of the drying time, 3) The change of moisture content is takes place in the falling rate period and 4) Two term model was successfully described the thin-layer drying behavior of the cassava leaves under combined solar energy and hot-air convective dryer.

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