ISSN 2229-5518

Thin layer drying of Black Galingale in Thailand

C. Phusumpao, J. Piwsaoad

Abstract— This article presents the thin-layer drying of Black Galingales, which was conducted under controlled conditions of temperature by using a convective air dryer. The Black Galingales were dried for the temperature of 40°C, 50°C and 60°C, with the air flow velocity fixed at 1 ms^{-1}. It was observed that the drying air temperature has strong influence on the drying rates of Black Galingales, so that the higher the temperature the less the drying time. Seven different thin-layer models were fitted to the experimental data of Black Galingales. The drying parameters of Black Galingales were found to be a function of drying air temperature. The Modified Handerson and Pabis model were revealed to be the best and it was followed by the Two term model. Moisture diffusivities of black galingales have been determined experimentally and moisture diffusivities were found to increase with the increase in drying air temperature. Moisture diffusivities of black galingales can be explained using an Arrhenius-type equation. The mean diffusivity values of black galingales in this study are 9.38×10^{-10} m^2/s.

Keywords — Black Galingale, Thin-layer, Mathematical modeling, Moisture diffusivity

1 Introduction

Black Galingale (*Kaempferia parviflora*) is an herbal from the north of Thailand. The rhizomes of black galingale have been used for centuries in the traditional medicine of Southeast Asia for health promotion and for the treatment of digestive disorders and gastric ulcer. Since freshly harvested black galingale have moisture content of about 142-145% dry basis (db.) for their fresh product was dried to a final moisture content of 3-10% db. Due to its curative abilities, it would be advantageous to keep black galingale for long periods of time so it could be used anytime [1].

Thin layer drying modeling is always used in order to understand and estimate the drying characteristics of agricultural products [2-7]. For proper understanding of transfer processes during drying and production of quality dried black galingale, it is essential to know the thin-layer drying characteristics and the quality of the dried products. This study aims to evaluate thin-layer drying characteristics of the black galingale obtained from north Thailand.

2 Materials and Methods

2.1 Drying Experiments

The black galingales used in this experiment come form north Thailand. They had initial moisture content about 138-140% (db). Fresh rhizomes of black galingale were stored in the refrigerator at temperature of 4 °C until the experiments were carried out. Before the experiments, the samples were removed from the refrigerator and allowed to reach room temperature (about 27 °C). The black galingale was cut into slices of 0.5 cm thickness. The black galingale were placed on a tray in a thin-layer in a laboratory dryer and dried under controlled conditions of temperature. The black galingales were dried at the temperature of 40 °C, 50 °C and 60 °C with the air speed of 1 ms^{-1}.

A schematic diagram of this laboratory dryer is shown in Figure 1. It consists of a fan, heaters, drying chamber, and instruments for measurement. The airflow rate was adjusted by the fan speed control. The heating system consisted of an electric heater placed inside the duct. The drying chamber temperature was adjusted by the heater power control. Prior to an experiment, the laboratory dryer was allowed to run for 30 min to obtain a steady temperature. For each experiment black galingales about 150 g were placed in the drying tray. The thin-layer drying tests were conducted in the temperature of 40 °C, 50 °C and 60 °C. Three sets of experiments were conducted for the black galingales.

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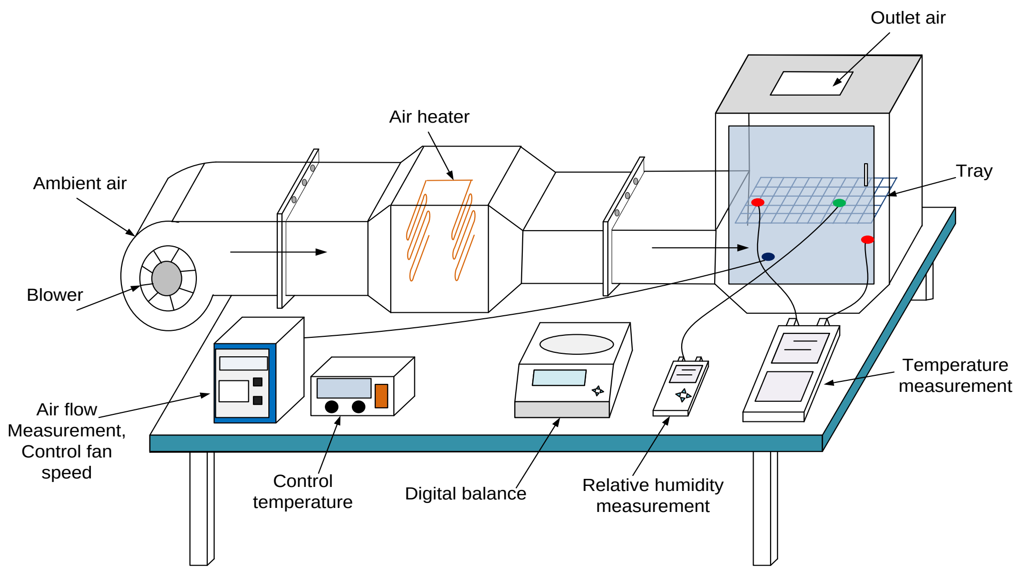

Fig. 1. Schematic diagram of the laboratory dryer.

2.2 Mathematical Modeling

The moisture ratio of the black galingales slices during the thin layer drying experiments was calculated using the following equation:

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

where MR is the dimensionless moisture content ratio; and M, M_0 and M_e are the moisture content at any given time, the initial moisture content and the equilibrium moisture content, respectively.

In general, an agricultural moist product is composed of water and dried solid mass. The moisture content (M) of the product in dry basis (% db.) can be calculated from the following equation:

$$M = \frac{m - m_{solid}}{m} \times 100\% \quad (2)$$

where m is mass of the product and m_{solid} is mass of dried solid mass of the product. m can be obtained by using a balance. In order to obtain dried solid mass (m_{solid}), the water in the product must be totally removed by drying the product in an oven at the temperature of 103 °C for 24 hours [8].

To select a suitable model for describing the drying process of black galingales, seven different thin-layer drying models were selected to fit the thin-layer experimental data of black galingales. The selected thin-layer drying models are presented in table 1. The models were fitted to the experimental data by direct least square. The coefficient of determination (R^2) was one of the main criteria for selecting the best equation. In addition to R^2, the goodness of fit was determined by root mean square error ($RMSE$). For the best fit, the R^2 value should be high and $RMSE$ values should be low. $RMSE$ and R^2 are defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})^2}{N}} \quad (3)$$

$$R^2 = 1 - \frac{Residual\ sum\ of\ squares}{Corrected\ total\ sum\ of\ squares} \quad (4)$$

where $MR_{exp,i}$ and $MR_{model,i}$ are the moisture ratio derived from the experiment and the moisture ratio derived from the model. $\overline{MR}_{exp}$ is mean moisture ratio obtained from experiments. N is the number of observations.

ISSN 2229-5518

TABLE 1
THE 7 SELECTED THIN-LAYER DRYING MODEL

Serial no	Model equation	Name of the model
1	MR=exp(-kt)	Newton
2	MR=exp(-kt^n)	Page
3	MR=exp(kt^n)	Modified Page
4	MR=$a$exp(-kt)	Handerson and Pabis
5	MR=$a$exp(-kt)+c	Logarithmic
6	MR=$a$exp(-kt)+$b$exp(-gt)	Two term
7	MR=$a$exp(-kt)+$b$exp(-gt)+$c$exp(-pt)	Modifile Handerson and Pabis

2.3 Diffusivities of the Black Galingales

Fick's second law of the unsteady state diffusion, neglecting the effects of temperature and total pressure gradient, can be used to describe the drying behavior of fruits .

$$\frac{\partial M}{\partial t} = \nabla.\left(D \nabla M\right) \quad (5)$$

This equation can be solved for different standard shapes of the drying material. Mass transfer due to moisture migration takes place through the product so as to reach moisture equilibrium between the product and the ambient environment. The mechanisms involved can be commonly expressed by Fick's second law of diffusion for drying porous materials during the falling rate period [9]. Assuming the black galingales being represented by a sphere and the shell by a slab, assuming uniform initial moisture content distribution, one-dimensional moisture diffusion, no shrinkage, negligible external resistance, and a constant effective moisture diffusion coefficient throughout the drying period, the analytical solutions of Eq. (6), for the black galingales samples are derived as follows [11]. For slab of half thickness z:

$$\frac{M - M_e}{M_0 - M_e} = \frac{8}{p^2} \sum_{n=1}^{\infty} \frac{4}{(2n-1)^2} exp(-(2n-1)^2 \frac{D_{eff}\, t}{z^2}) \quad (6)$$

where D_{eff} is effective moisture diffusion coefficient (square meter per minute), n is the number of terms of the Fourier series and r is the average radius of the nuts, z is the average slab of half thickness. t is time.

3 RESULTS AND DISCUSSION

3.1 Drying Characteristics of Black Galingales

The changes in moisture contents with time for different drying air temperatures are shown in figure 2. The final moisture content of samples dried under different conditions ranged from 10% to 22% (db). The drying rate is higher for higher air temperature. As a result, the time taken to reach the final moisture content is less, as shown in figure 2. Therefore, the drying air temperature has an important effect on the drying of black galingales.

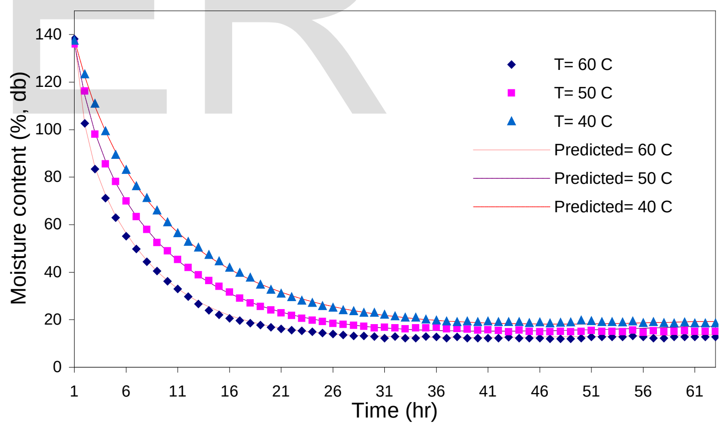

Fig. 2. Predicted and observed moisture content of black galingales using Modified Handerson and Pabis model at the temperatures of 40 ˚C, 50 ˚C and 60 ˚C

TABLE 2
PARAMETER VALUE, COEFFICIENT OF DETERMINATION (R^2) AND ROOT MEAN SQUARE ERROR (*RMSE*) VALUE OF THE DIFFERENT MODELS.

Models	T (°C)	k	a	b	c	n	g	p	R^2	RMSE (%)
Newton	40	0.0952							0.9924	1.9728
	50	0.1383							0.9881	2.2148
	60	0.1887							0.9852	2.2576
Page	40	0.1323				0.8740			0.9978	1.0713
	50	0.2094				0.8140			0.9992	0.5641
	60	0.2816				0.7879			0.9972	0.9730
Modified Page	40	-0.1322				0.8740			0.9978	1.0713
	50	-0.2095				0.8140			0.9992	0.5641
	60	-0.2817				0.7879			0.9972	0.9730
Henderson and Pabis	40	0.0883	0.9299						0.9969	1.2584
	50	0.1260	0.9177						0.9937	1.6139
	60	0.1746	0.9326						0.9886	1.9757
Logarithmic	40	0.0921	0.9282		0.0101				0.9976	1.1012
	50	0.1332	0.9168		0.0124				0.9957	1.3365
	60	0.1896	0.9315		0.0180				0.9948	1.3339
Two-term	40	0.0851	0.8957	0.1043			2.1726		0.9990	0.7330
	50	0.1069	0.7589	0.2353			0.5755		0.9989	0.6595
	60	0.2623	0.7723	0.2115			0.0679		0.9985	0.7074
Modified Henderson and Pabis	40	0.2788	0.3968	0.0190	0.7001		0.0866	0.0355	0.9993	0.5850
	50	0.4287	0.5636	0.0292	0.8056		0.1265	0.1224	0.9994	0.4825
	60	0.4316	0.6704	0.0446	0.9283		0.2273	0.5191	0.9994	0.4650

3.2 Mathematical Modeling of Thin-Layer Drying

Seven thin-layer drying (Table 1) models were fitted to the experimental data of moisture ratio of black galingales dried at different temperatures and relative humidity. The parameter values, R^2 and *RMSE*, are also shown in Table 2. The Modified Handerson and Pabis model was found to be the best, followed by the Two term model. The value of R^2 of the Modified Handerson and Pabis model was 0.9993-0.9994, indicating good fit and *RMSE* were also good (0.47-0.59%). Empirical expressions were developed for the drying parameters of the Modified Handerson and Pabis model and the drying parameters were found to be a function of drying air temperature (T in °C).

$$k = -1.32690 + 0.04327T - 0.06373rh - 0.00022Trh - 0.00049T^2 - 0.0027224rh^2 \quad (7)$$

$$a = 0.530722 + 0.011611T - 0.073347rh + 0.000725Trh + 0.000208T^2 + 0.000504rh^2 \quad (8)$$

$$b = 1.844231 + 0.026047T - 0.583286rh + 0.003369Trh - 0.000227T^2 + 0.007765rh^2 \quad (9)$$

$$c = 1.604367 - 0.048950T + 0.082477rh + 0.000267Trh - 0.000571T^2 - 0.005243rh^2 \quad (10)$$

$$g = 1.205501 - 0.047973T - 0.044575rh + 0.0009867Trh + 0.00034T^2 + 0.005292rh^2 \quad (11)$$

$$p = -0.603453 + 0.087975T - 0.084546rh - 0.009750Trh - 0.003367T^2 + 0.0054814rh^2 \quad (12)$$

3.3 Diffusivities of Black Galingales

The diffusivities of black galingales were found to be dependent on temperatures and can be expressed as function of temperature by using the Arrhenius-type equations as follows:

$$D_{black\ galingale} = 5.63 \times 10^{-6} e^{\left(-2115.84/T_{ab}\right)} \quad (13)$$

Figure 3 presents the variations of moisture diffusivities of black galingales as functions of the reciprocal of absolute drying air temperature. The mean diffusivities of black galingales in the range of 6.74×10^{-10} to 1.35×10^{-09} m²/s are found in this study.

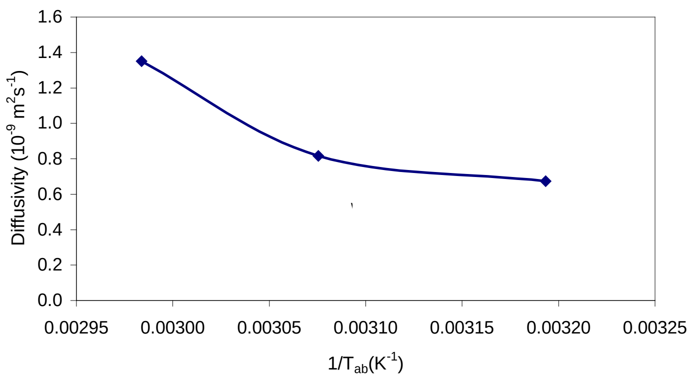

Fig. 3. Variations of moisture diffusivity of black galingales as a function of the reciprocal of absolute drying air temperature (T_{ab}).

study and the drying rate increases with the increase of air temperatures. The entire drying process occurred in the falling rate period and constant rate period was not observed. Seven thin-layer drying models were fitted to the experimental data of black galingales to describe the drying characteristics of black galingales. Drying parameter of Modified Handerson and Pabis model were found to be a function of drying air temperature. The Modified Handerson and Pabis model was the best, followed by the Two term model.

Moisture diffusivities of black galingales have been determined experimentally and moisture diffusivities were found to increase with the increase in drying air temperature. Moisture diffusivities of black galingales can be explained using an Arrhenius-type equation. The mean diffusivity values of black galingales in this study are 9.38×10^{-10} m^2/s.

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