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Research Article

Activation Energy of Thin-layer Drying Kinetics of Belimbing Dayak Fruit (*Baccaurea angulata*)

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Abstract: Drying using a hot air chamber was tested on samples of belimbing dayak (*Baccaurea angulata*). The drying experiments were performed at drying air temperature 40, 45 and 50°C, respectivly and at a constant relative humidity of 20% and constant air velocity of 1 m/s. The drying kinetics of *B. angulata* were investigated and obtained. The time required to dry *B. angulata* from an initial moisture content of about 89% (wb) to the final moisture content of around 8% (wb) was 13, 11.5 and 7 h at 45, 50 and 55°C of drying air temperature respectively. The effective moisture Diffusivity (D_{eff}) of *B. angulata* increased from 1.99×10^{-9} to 3.71×10^{-9} m^2/s as the drying air temperature increased from 45 to 55°C. The activation energy of diffusion (E_a) was calculated about 54 kJ/mol.

Keywords: Activation energy, *B. angulata*, belimbing dayak, drying kinetics, hot air chamber

INTRODUCTION

Drying is a traditional method that was used for many centuries to preserve agricultural and marine products (Fudholi *et al*., 2015, 2014a). Most agricultural commodities require drying process in an effort to preserve the quality of the final product. The quality of the products depends on many factors including the drying temperature and duration of drying time (Fudholi *et al*., 2010). Hot air drying is the most frequently used dehydration operation in the food and chemical industry. There have been many reports on drying kinetics of agricultural fruits and vegetables. Thin-layer drying models also have been widely used for analysis of drying of various agricultural products.

Several thin-layer drying model available in the literature for explaining drying of various agricultural and marine products have been used by researchers (Daun *et al*., 2010; Dissa *et al*., 2010; Fudholi *et al*., 2014b, 2012a, 2012b; Gorjian *et al*., 2011; Kilic, 2009; Taheri-Garavand *et al*., 2011; Tahmasebi *et al*., 2011). Three different one-term exponential drying models were compared with experiment data. An excel software was used in the analysis of raw data obtained from the drying experiment. The values of the parameters a, n and k for the models were determined using a plot of curve drying models (Basri *et al*., 2012a, 2012b, 2012c; Fudholi *et al*., 2013, 2012c, 2012d, 2012e, 2011; Othman *et al*., 2012), which the model Page model has been reported to exhibit a better fit than other one-term exponential model thin layer drying models in accurately simulating the drying curves. The main objective of this study is to determine the activation energy of thin-layer drying kinetics of *B. angulata*.

MATERIALS AND METHODS

The fresh *B. angulata* were purchased from a local market in Miri, Sarawak (Malaysia) in February 2012 and stored in ventilated packing bag at a temperature of 4°C. The initial moisture content of *B. angulata* was determined by measuring its initial and final weight using the hot air chamber at 120°C until constant weight was obtained (Meziane, 2011). The average initial moisture content of the fresh *B. angulata* was obtained to be 89.29% w.b.

The experiments are carried out at the Solar Energy Laboratory in Physics Department, Universiti Kebangsaan Malaysia. In this study, a hot air chamber was used to investigate the drying kinetics of *B. angulata*. The hot air chamber (Model DY110,

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Angelantoni Asean Pte Ltd, Singapore) is capable of providing the desired drying air temperature in the range of -40°C to 180°C and air relative humidity in the range of 10 to 98%. *B. angulata* after been cleaned and be cut into ±1.0 cm was inserted into the chamber. The drying experiments were conducted at drying air temperature of 45, 50 and 55°C and at Relative Humidity (RH) 20% and constant air velocity of 1 m/s. The change of weight was recorded at every 5 min. Measurement was discontinued when the heavy weight of the material reaches a constant fixed value. Data obtained from the measurements of weight in a test prior to being used for the analysis of drying kinetics of materials need to be changed first in the form of moisture content data. The moisture content was expressed as a percentage wet basis and then converted to gram water per gram dry matter. The moisture content of materials (X) can be calculated by two methods on the basis of either wet or dry basis using the following equation. The moisture content wet basis:

$$X = \frac{w(t) - d}{w} \times 100\% \tag{1}$$

The moisture content dry basis:

$$X = \frac{w(t) - d}{d} \tag{2}$$

where,
$w(t)$ = Mass of wet materials at instant t
d = Mass of dry materials

From Fick's diffusion equation for infinite slab as given below was used to determine the effective moisture diffusivity at different temperatures of drying:

$$\frac{X_t - X_e}{X_i - X_e} = \sum_{n=0}^{1} \frac{8}{(2n+1)^2 \pi^2} \exp\left(-D_{eff} \frac{(2n+1)^2 \pi^2 t}{4L^2} \right) \tag{3}$$

where in X_i, X_t and X_e represent the initial moisture content, the moisture content at time t and the equilibrium moisture content, all expressed as Dry Basis (db), L is the half thickness (m) and D_{eff} is the effective moisture diffusivity (m^2/s). For long drying times and small slab thickness (Maiti *et al*., 2011):

$$\frac{X_t - X_e}{X_i - X_e} = MR = \frac{8}{\pi^2} \exp\left(-D_{eff} \frac{\pi^2 t}{4L^2} \right) \tag{4}$$

where, MR is the moisture ratio. Eq. (4) could be rewritten as:

$$MR = A \exp(-kt) \tag{5}$$

where,

$$k = \frac{\pi^2 D_{eff}}{4L^2} \tag{6}$$

The effective moisture diffusivity can be related with temperature by simple Arrhenius equation as given below:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT} \right) \tag{7}$$

where,
D_{eff} = The effective moisture diffusivity (m^2/s)
D_0 = The constant equivalent to the diffusivity at infinitely high temperature (m^2/s)
E_a = The activation energy (kJ/mol)
R = The universal gas constant (8.314×10^{-3} kJ/mol K)
T = The absolute temperature (K).

Eq. (7) can be linearised as:

$$\ln(D_{eff}) = \ln(D_0) - \left(\frac{E_a}{R} \right) \left(\frac{1}{T} \right) \tag{8}$$

The activation energy, E_a and the constant D_0 were determined by plotting $\ln(D_{eff})$ versus 1/T (Kaleemullah and Kailappan, 2006).

RESULTS AND DISCUSSION

The results of the drying kinetic curves of *B. angulata* at relative humidity of 20%. It consists of three curves namely the drying curve, the drying rate curve and the characteristic drying curve. Drying curve showed the profile change in moisture content (X) versus drying time (t). Drying rate curve illustrated the drying rate profile (dX/dt) versus drying time (t). Drying characteristic curves displayed the drying rate profile (dX/dt) versus moisture content dry basis (X). Figure 1 and 2 showed a decrease in moisture content wet basis and dry basis of drying time at different air temperature at relative humidity 20%. From Fig. 1 and 2, it shows that at low air temperature, the moisture content of *B. angulata* is increased, slowing down the drying process as the drying time becomes longer. In contrast, by increasing air temperature, increasing the moisture content caused a reduction in drying time rapidly. This observation is in agreement with other finding reported for drying of tomato (Taheri-Garavand *et al*., 2011). Figure 3 showed the profile of the drying rate versus drying time. From this graph, the drying rate was found higher at high air temperature. This means that the time required to dry the material to reach equilibrium moisture content is shorter. Figure 4 showed the characteristic drying curve obtained at different air temperature.

Eq. (5) can also be written as the following equation:

$$\ln MR = \ln A - kt \tag{9}$$

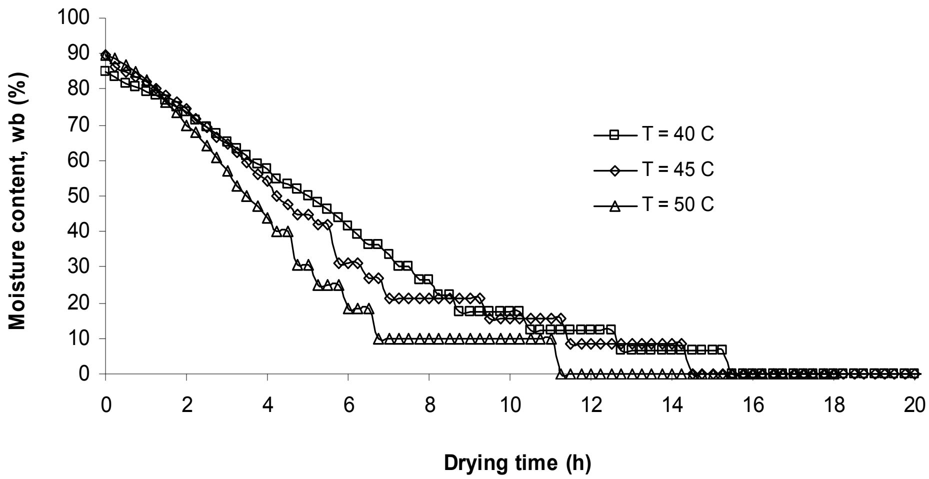

Fig. 1: Drying curve: Wet basis moisture content versus drying time at 20% RH

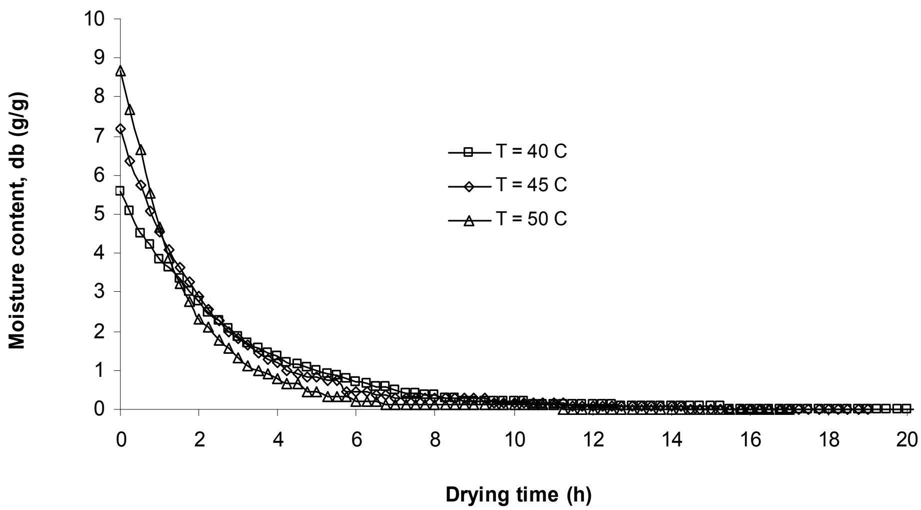

Fig. 2: Drying curve: Wet basis moisture content versus drying time at 20% RH

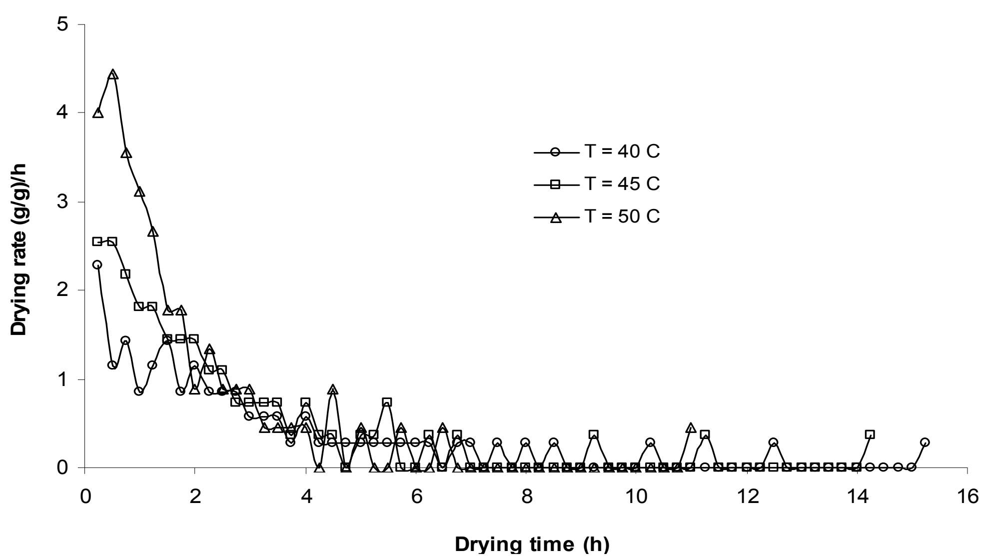

Fig. 3: Drying rate curves: Dry basis moisture content versus drying time at 20% RH

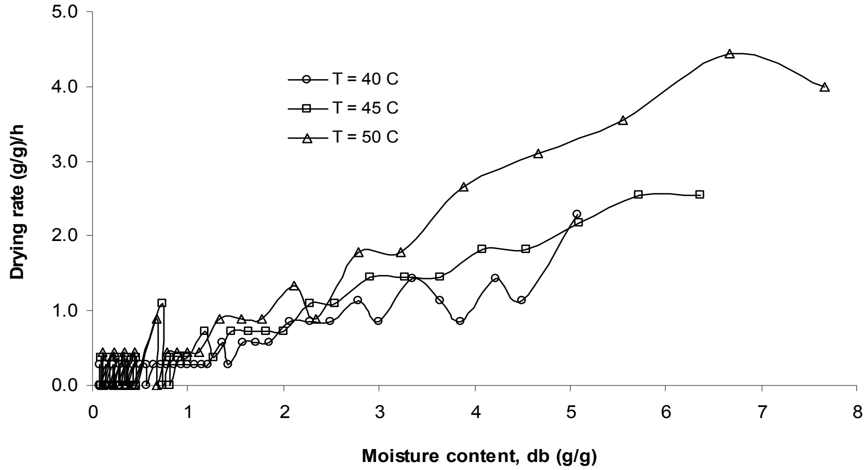

Fig. 4: Drying characteristic curves: A dry basis moisture content versus drying time at 20% RH

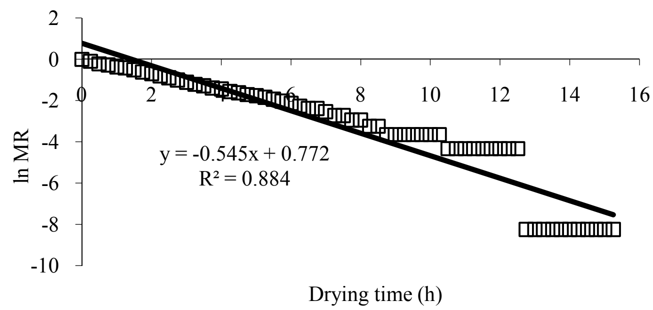

Fig. 5: Plot of ln MR versus drying time at temperature of 45°C

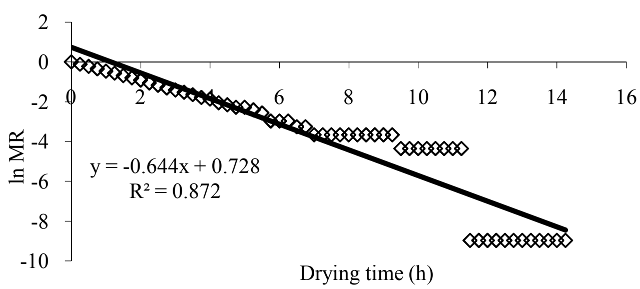

Fig. 6: Plot of ln MR versus drying time at temperature of 50°C

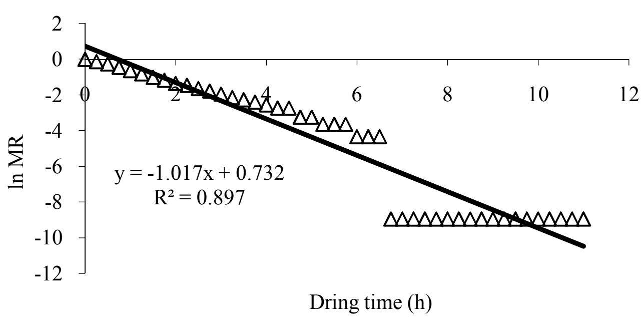

Fig. 7: Plot of ln MR versus drying time at temperature of 55°C

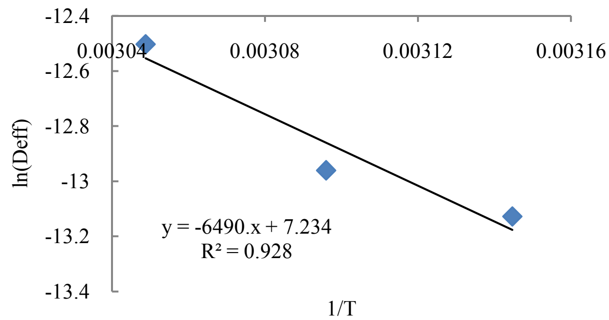

Fig. 8: Arrhenius type relationship between effective moisture diffusivity and reciprocal of absolute temperature

From Eq. (9), a plot of ln MR versus drying time gives a straight line with intercept = ln A and slope = k. Graf MR versus ln t, as shown in Fig. 5 to 7, obtained the value k = 0.545, k = 0.644 and k = 1.017 for air temperature of 45, 50 and 55°C, respectively.

The plot depicting the relationship between ln(D_{eff}) and 1/T was found to be a straight line in the range of temperatures investigated, indicating Arrhenius dependence as shown in Fig. 8. The activation energy (E_a) was calculated of 53.96 kJ/mol.

CONCLUSION

Drying using a hot air chamber was tested on belimbing dayak (*Baccaurea angulata*). Drying kinetics of *B. angulata* was investigated within a temperature range of 45, 50 and 55°C, respectivly. The time required to dry *B. angulata* from an initial moisture content of about 89% (wb) to the final moisture content of around 8% (wb) was 13, 11.5 and 7 h at 45, 50 and 55°C of drying air temperature respectively. The effective moisture diffusivity (D_{eff}) of *B. angulata* increased from 1.99×10^{-9} to 3.71×10^{-9} m^2/s as the drying air temperature increased from 45 to 55°C. The activation energy of diffusion (E_a) was calculated of 53.96 kJ/mol.

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