Mathematical Modeling of Thin-Layer Drying of Longan in Hot Air Tunnel

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ABSTRACT

The objectives of this research is to kinematics study of thin layer drying of longan in hot air dryer tunnel. The drying of longan were conducted under three drying temperature of 55, 65, and 75°C with average layer thickness 15 mm with air velocity 1.0 ms^{-1}. Twelve semi-theoretical drying model were investigated and model parameter were determined by non-linear analysis whereas R^2, χ^2, RMSE, and sum of residuals values are used to confirm goodness of fit in models. According to explore, the Midilli's model is the best fit of Longan drying via varying drying temperature. By following Fick's diffusion equation, the effective moisture diffusivity (D_{eff}) of longan drying is in the range 9.47×10^{-10}-20.00×10^{-10} m^2s^{-1} correlating with drying temperature from 55°C to 75°C. By graphical analysis, the activation energy of diffusion (E_a) of Longan is 35.60 kJ/mol and the predicted moisture ratio agreed well with experimental values.

Keywords: Semi-theoretical mathematical model, Thin layer drying, Wind tunnel drying

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Introduction

Longan (Dimocarpus longan Lour.), a genus of the Sapindaceae family, is a most commercially available fruit that is distributed widely in Southeast Asian countries, such as China, Taiwan, Vietnam and Thailand [1]. Especially, statistical data of Thailand in 2017, the cultivated area of longan plant is about 1,093,765 rai (1 rai is equal with 0.16 hectare) with productivity of longan fruit is about 1,019,732 metric tons. Thailand is the major exporter of longan in the world, mainly, more than 95%, exported in fresh longan fruit and dried longan product with export value was 800 million U.S. dollar approximately. The important market longan of Thailand are China, Vietnam, Indonesia, and Hong Kong [2]. Generally, harvesting period of longan is in end of rainy season having high temperature and high humidity therefore it's leads to rapidly of pathological and physical changed of harvested longan as the pericarp browning and fruit disease which significantly affects its storability, difficulty to transport, and short shelf life [3].

Typically, a mature longan fruit has a round or hearth shaped with diameter 15–25 mm. The outer layer of longan is a tinny peel with light brown color is cover to the edible part of longan which is juicy, sweet and white color. The dark brown and round seed is covered with the edible part above [4]. Additionally, the consumption of longan is good for health [5]. Longan contains a number of important vitamins and minerals, including iron, magnesium, phosphorus and potassium, and large amounts of vitamins A and C. Longan has also been used as a traditional Chinese medicine since ancient times, and great attentions have been paid for their great health effects, such as promoting blood metabolism, soothe nerves, relieve insomnia, etc. [6]. Polysaccharides and lignin in the Longan fruit have been considered the main functional compositions for these health effects. Moreover, the different tissues of longan contain high amounts of bioactive compounds, such as phenolic acids, flavonoids and polysaccharides [6-7]. These bioactive compounds exhibit antibacterial, antiviral, antioxidant, anti-inflammatory and anti-carcinogenic properties [6-8]. While, the water extract from Longan seed and peel (WEL) contains high levels of phenolic compounds with antioxidative activities, such as 4-O-methylgallic, (-)-epicatechin, gallic acid and ellagic acid [9].

Drying is possibly the oldest and the important method of agriculture products preservation practiced especially in tropical region. Drying is a unit operation to remove water from a product and to reduce its water activity. This would help to inhibit in microorganism growth and deterioration reactions by water activity [10]. Conventionally, fruits and vegetables are dried in open sunlight. However, open sun drying depend on climate condition affecting on the quality control of the final product. Moreover, the products are prone to microbial and other contaminations [11]. Normally longan fruit has moisture content about 350-500% dry basis. Drying of longan is an energy-intensive process. Typically, the drying process employs hot air at temperature in range 55–80°C to remove moisture of longan. In Thailand industrial, convective hot air drying is a common method for drying peeled and unpeeled longan. Drying temperature for unpeeled longan is about 75°C and drying time is 48-52 h while peeled longan require drying temperature about 70°C for 12-15 h in order to achieve final moisture content of product is 22% in dry basis. The energy consumption in drying longan seem to be too much from drying for a long time. The drying of peeled longan using microwave-hot air was studied by Varith et al [12] and results shown that a step-wise drying process using 40°C hot air with 450 W microwave for 1.7 h and followed by 60°C hot air with 300 W microwave for 3.3 h provided the maximum drying efficiency. The drying time and specific energy consumption is decreased by 64.3% and 48.2% respectively comparing with 65°C hot air to obtain golden brown flesh. Nathakaranakule et al. [13] published in evaluation of dried longan using far-infrared radiation assisted drying. FIR combination with hot air and heat pump drying increases the drying rate of longan by reduction the drying time. The result show, FIR helps to create more porous structure in dried longan and consequently leads to lower shrinkage, improved rehydration, lower hardness and lower toughness than samples dried in the absence of FIR. Moreover, in present, solar dryer was applied to dry the agriculture product which is properly for small community. Greenhouse type of solar dryer (parabolic shape) was conducted for drying 500 kg of chili in month of November, 2009. [14]. Drying temperature in greenhouse was generated in the range 30 - 60°C follows the solar intensity. It was found that the chili with the initial moisture content of 74% (wb) were dried in 3 days while the natural sun dried needed 5 days. The mixed mode of solar collector with greenhouse dryer was conducted to experiment investigate and economic evaluation of drying of red pepper and grape [15]. The drying rate in solar greenhouse is higher than open sun drying. The drying time of red pepper and grape is 7 and 17 hours respectively and payback period of dryer was found to be 1.6 years.

However, study on drying kinetics and activation energy of edible part of longan in thin-layer drying under full re-circulation air in hot air tunnel has not been reported yet.

Objectives of the study

The objectives of this study were to fit the experimental data with twelve semi-theoretical models, to calculate effective moisture diffusivity, and determine the activation energy of edible longan under varying drying temperature.

Methodology

A short description of the materials and methods followed must also be included in this section

Material

Typically, the leading cultivation and distribution areas of longan are from northern region of Thailand especially in Chiangmai and Lamphun. Due to the weather conditions corresponding on that area are suitable for doing longan farm. Consequently, the high quality longan is major from the area above. However, grade A "Dor" longan used in the experiments is a seasonal fruit providing from the local market. Good quality in physical of longan was selected for the experiment. The longan was prepared by separate the longan peel and longan seed and uses only edible part of longan (peeled longan) for drying test. Work flow of the experimental can be described as shown in figure below (Figure 1).

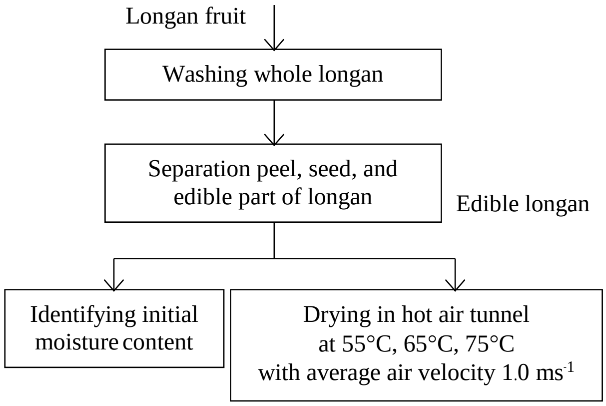

Figure 1 Experiment work flow

For each experiment, 1 kg of peeled longan was used to test. Moisture content of peeled longan was determined in triplicate in heating oven (Binder model FED115) at temperature 103°C, drying for 72 h and initial average moisture content is 487±10% dry basis.

Hot air drying tunnel

In the experiment, closed return wind tunnel is used to conduct the kinetic experiments. There are five main parts of closed return wind tunnel consists of 1) wind tunnel structure is made from galvanized steel sheet forming as a square duct (cross section) size 40 cm × 40 cm. The structure of tunnel is combined with small parts to be the closed loop tunnel. 2) Axial blower (direct drive) with air flow rate manual adjustable dimmer (SCR regulator) is installed and used for forcing air move along the tunnel path whereas hot wire anemometer (Testo 435) is used to measure the velocity of air in tunnel. 3) Set of fin air heater electric power totally 6,000 watts are installed placing before the chamber to heat up air temperature. PID temperature controller with thermocouple K type sensor is used for control drying temperature up to 90°C. 4) Air distributor is placed at one end of returning air section to distribute air flow while a few layer of wire-mesh screen be installed to reduce air turbulence before entering chamber, and 5) testing section or chamber is located at the bottom-center of the tunnel containing volume size is 40 × 40 × 50 cm^3. The samples were dried on the perforated square tray placing over the tray supporter. The product tray is placed over the digital scale which is an automatically record weight having maximum capacity 20 kg with 10-gram precision.

Mathematical modeling of drying curve

The moisture content of longan obtained from experiment in the range of drying temperatures of 55°C, 65°C, and 75°C were converted to be the dimensionless of moisture ratio:

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

Experimental results of moisture ratio with drying time were fitted to the collected semi-theoretical models, widely used in the scientific literature to describe the kinetics of the drying process. The selected mathematical models are identified in Table 1. Non-linear regression techniques were used to obtain the different constants in each selected model, using Statistica 6.0 software based in the Levenberg–Marquardt method. The coefficient of determination

(R^2), reduced chi-square (χ^2), root mean square error (RMSE) and sum of residuals were calculated to evaluate the fitting of each model to experimental data.

Table 1 semi-theoretical models for thin layer drying considered in the study

Model No.	Model	Analytical expression
1	Lewis	$\mathrm{MR} = \exp(-kt)$
2	Page	$\mathrm{MR} = \exp(-kt^{y})$
3	Henderson and Pabis	$\mathrm{MR} = a\exp(-kt)$
4	Wang and Singh	$\mathrm{MR} = 1 + at + bt^2$
5	Logarithmic	$\mathrm{MR} = a\exp(-kt) + c$
6	Two term	$\mathrm{MR} = a\exp(-k_1 t) + b\exp(-k_2 t)$
7	Two term exponential	$\mathrm{MR} = a\exp(-kt) + (1-a)\exp(-kat)$
8	Modified Henderson and Pabis	$\mathrm{MR} = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$
9	Midilli	$\mathrm{MR} = a\exp(-kt^{n}) + bt$
10	Approximation of diffusion	$\mathrm{MR} = a\exp(-kt) + (1-a)\exp(-kbt)$
11	Verma et al.	$\mathrm{MR} = a\exp(-kt) + (1-a)\exp(-gt)$

The higher values of the coefficient of determination (R^2) and the lower values of the reduced chi-square (χ^2), RMSE and sum of residuals were chosen for goodness of fit, according to the criterion followed by Midilli and Kucuk [16] and by Akpinar et al. [17]. These parameters can be calculated as

$$R^2 = \left\{ \frac{N(\Sigma_{i=1}^{N} \mathrm{MR}_{\exp,i} \times \mathrm{MR}_{\mathrm{pre},i}) - (\Sigma_{i=1}^{N} \mathrm{MR}_{\exp,i})(\Sigma_{i=1}^{N} MR_{\mathrm{pre},i})}{\sqrt{[N\Sigma_{i=1}^{N} \mathrm{MR}_{\exp,i}^2 - (\Sigma_{i=1}^{N} \mathrm{MR}_{\exp,i})^2][N\Sigma_{i=1}^{N} \mathrm{MR}_{\mathrm{pre},i}^2 - (\Sigma_{i=1}^{N} \mathrm{MR}_{\mathrm{pre},i})^2]}} \right\}^2 \quad (2)$$

$$\chi^2 = \frac{\Sigma_{i=1}^{N} (\mathrm{MR}_{\exp,i} - \mathrm{MR}_{\mathrm{pre},i})^2}{N - p} \quad (3)$$

$$\mathrm{RMSE} = \left[\frac{1}{N} \Sigma_{i=1}^{N} (\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\exp,i})^2 \right]^{1/2} \quad (4)$$

$$\mathrm{residuals} = \Sigma_{i=1}^{N} (\mathrm{MR}_{\exp,i} - \mathrm{MR}_{\mathrm{pre},i}) \quad (5)$$

where $\mathrm{MR}_{\exp,i}$ and $\mathrm{MR}_{\mathrm{pre},i}$ is the experiment and predicted moisture ratio respectively, while N is the number of data point and p is the number of constants in the regression model.

Determination of effective moisture diffusivity

The effective moisture diffusivity is an important transportation property in food and used to describe the drying characteristics of food. Fick's second diffusion law can be used to estimate the effective moisture diffusivity of the edible longan flesh. The solution of Fick's second diffusion law for slab geometry is defined by following equation [18]:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}t}{4L^2}\right) \tag{6}$$

where D_{eff} is the effective moisture diffusivity (m^2s^{-1}), t is drying time (s), L is the half of thickness of the samples (m) and n is a positive integer. For long drying period, the equation (6) can be simplified to only the first term of the series. The natural logarithmic form is

$$\ln MR = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff}t}{4L^2} \tag{7}$$

From equation (7), effective moisture ratio can be calculated by plotting $\ln MR$ varying with drying time, the experimental data gives a straight line with slope expressed as

$$\text{Slope} = \frac{\pi^2 D_{eff}}{4L^2} \tag{8}$$

Determination of activation energy

The effective moisture diffusivity is related with temperature by the Arrhenius equation:

$$D_{eff} = D_0\exp\left(-\frac{E_a}{R(T+273.15)}\right) \tag{9}$$

where D_0 is pre-exponential factor of Arrhenius equation in m^2s^{-1}, E_a is the activation energy in $kJ\,mol^{-1}$, R is the universal gas constant in $kJ\,mol^{-1}K^{-1}$, and T is the drying air temperature in $^{\circ}$C.

Taking natural logarithms, Eq. (9) can be linearized as

$$\ln D_{eff} = \ln D_0 - \frac{E_a}{R(T+273.15)} \tag{10}$$

Results and Discussion

Experimental drying curves

The variation of moisture ratio with drying time are shown in Figure 2. The longan peeled moisture ratio decreases with increasing drying time following an exponential decay.

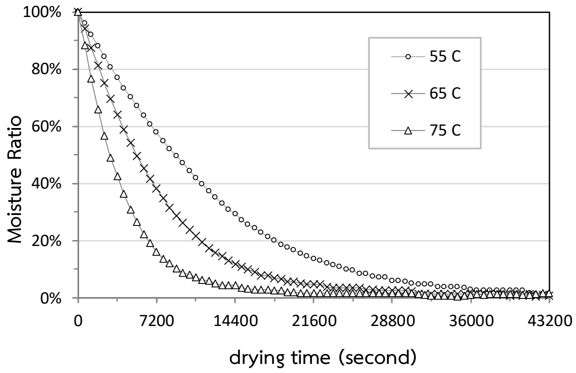

Figure 2 Drying curves of dried longan at different temperature

Figure 3 shows the changes in drying rate as a function of moisture content at experiment temperatures. It was shown that drying rate decrease continuously versus with the moisture content. There is no constant drying rate period while the falling rate period occurs in all drying process. This means that diffusion is an important mechanism for controlling the movement of moisture in longan.

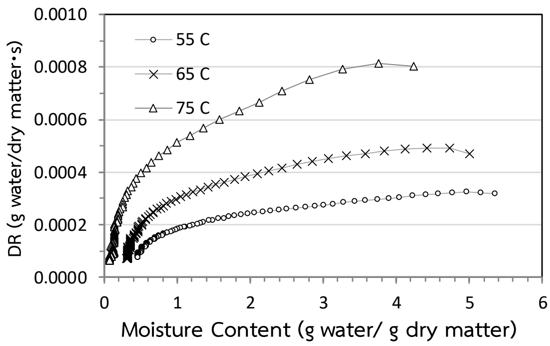

Figure 3 Variation of drying rate as a function of moisture content at different temperature

Modeling of drying curves

The average moisture ratio of longan at various drying air temperature at 55, 65, 75°C were fitted in eleven thin layer drying models and the statistical results from model are summarized in Table 2. The best model describing the thin-layer drying characteristic of peeled longan was chosen as one of the highest R^2 values and lowest χ^2, RMSE, and sum of residuals at all drying temperatures. By the statistical results on Table 2, Midilli's model (model no. 9) corresponds to the experiment data and describes the best drying behavior with values of R^2 over 0.999 for 55 and 65°C and over 0.998 for 75°C, values of χ^2 between 1.4013×10^{-5} and 5.8425×10^{-5}, RMSE between 0.00373 and 0.00761, and values of sum of residuals between 0.00572 and 0.19729. Figure 4 compare experiment data with predicted with Midilli's model for peeled longan at 55, 65, 75°C along diagonal line which suitability described the drying characteristic of peeled longan.

Table 2 Statistical results on mathematical models for thin layer drying of longan

No.	Temp	Model constants	R^2	χ^2	RMSE	residuals
1	55°C	k = 0.00008590	0.9979	3.3167×10^{-4}	0.01813	-0.40446
	65°C	k = 0.00013756	0.9981	1.2150×10^{-4}	0.01097	0.17619
	75°C	k = 0.00024227	0.9982	8.7896×10^{-5}	0.00933	0.63461
2	55°C	k = 0.00002057, y = 1.14920348	0.9997	1.8128×10^{-5}	0.00424	-0.04918
	65°C	k = 0.00005768, y = 1.09563234	0.9994	4.0275×10^{-5}	0.00632	0.38442
	75°C	k = 0.00020017, y = 1.02241917	0.9985	8.5254×10^{-5}	0.00919	0.66975
3	55°C	a = 1.05302072, k = 0.00009021	0.9976	1.9409×10^{-4}	0.01387	-0.49871
	65°C	a = 1.03960270, k = 0.00014287	0.9986	7.1505×10^{-5}	0.00842	0.14402
	75°C	a = 1.01531780, k = 0.00024599	0.9985	8.3176×10^{-5}	0.00908	0.62685
4	55°C	a = -0.00004786, b = 5.2971×10^{-10}	0.9436	6.8542×10^{-3}	0.08242	-2.16617
	65°C	a = -0.00005374, b = 6.3526×10^{-10}	0.8172	2.2567×10^{-2}	0.14955	-4.45907
	75°C	a = -0.00005685, b = 6.9202×10^{-10}	0.6186	4.6598×10^{-2}	0.21490	-7.05811
5	55°C	a = 1.05609402, k = 0.00008659, c = -0.01212041	0.9979	1.4045×10^{-4}	0.01180	0.00000
	65°C	a = 1.03914369, k = 0.00014399, c = 0.00217467	0.9986	6.8680×10^{-5}	0.00825	0.00000
	75°C	a = 1.01350307, k = 0.00025280, c = 0.00736482	0.9987	4.1493×10^{-5}	0.00641	0.00000
6	55°C	a = -1.90434281, b = 2.95736360, $k_1 = k_2$ = 0.00009021	0.9976	1.9409×10^{-4}	0.01387	-0.49871
	65°C	a = -1.75061443, b = 2.79021712, $k_1 = k_2$ = 0.00014287	0.9986	7.1505×10^{-5}	0.00842	0.14402
	75°C	a = -3.56161779, b = 4.57693558, $k_1 = k_2$ = 0.00024599	0.9985	8.3176×10^{-5}	0.00908	0.62685
7	55°C	a = 1.67401535, k = 0.00011148	0.9998	1.2434×10^{-5}	0.00351	-0.05624
	65°C	a = 1.58640213, k = 0.00017073	0.9995	4.1636×10^{-5}	0.00642	0.41487
	75°C	a = 0.70693604, k = 0.00026951	0.9981	8.5788×10^{-5}	0.00922	0.57847
8	55°C	a = -1.25854900, b = -1.25854900, c = 3.57011958, $k = g = h$ = 0.00009021	0.9976	1.9409×10^{-4}	0.01387	-0.49869
	65°C	a = -1.32805179, b = -1.32805179, c = 3.69570628, $k = g = h$ = 0.00014287	0.9986	7.1505×10^{-5}	0.00842	0.14402
	75°C	a = -3.94271843, b = -3.94271843, c = 8.90075460, $k = g = h$ = 0.00024599	0.9985	8.3176×10^{-5}	0.00908	0.62685
9	55°C	a = 0.98694666, b = 7.1089×10^{-9}, k = 0.00001640, n = 1.17152758	0.9998	1.4013×10^{-5}	0.00373	0.00572
	65°C	a = 1.00460449, b = 9.8176×10^{-8}, k = 0.00005677, n = 1.09847674	0.9995	2.6370×10^{-5}	0.00511	0.07382
	75°C	a = 1.01143302, b = 1.3008×10^{-7}, k = 0.00021417, n = 1.01632011	0.9982	5.8425×10^{-5}	0.00761	0.19729
10	55°C	a = 11.40328614, b = 1.05013151, k = 0.00013169	0.9998	1.0896×10^{-5}	0.00329	0.00528
	65°C	a = 16.88985555, b = 0.98762028, k = 0.00011204	0.9983	1.0431×10^{-4}	0.01017	0.37218

Table 2 Statistical results on mathematical models for thin layer drying of longan (Cont.)

No.	Temp	Model constants	R^2	χ^2	RMSE	residuals
	75°C	a = 0.50414708, b = 1.00688227, k = 0.00024144	0.9982	8.7895×10^{-5}	0.00933	0.63454
11	55°C	a = -26.70483411, k = 0.00005935, g = 0.00006011	0.9983	1.4237×10^{-4}	0.01188	0.31923
	65°C	a = -16.36988878, k = 0.00011067, g = 0.00011202	0.9983	1.0431×10^{-4}	0.01017	0.37220
	75°C	a = -1.52531588, k = 0.00024217, g = 0.00024221	0.9982	8.7896×10^{-5}	0.00933	0.63462

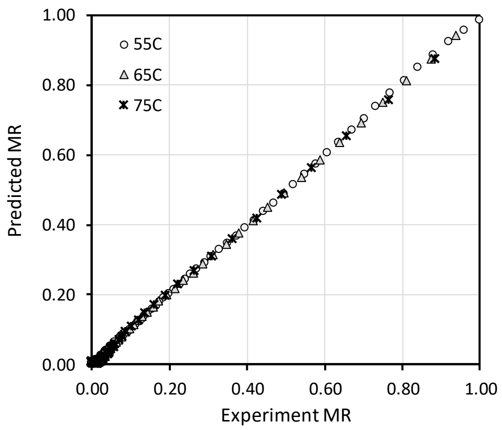

Figure 4 Comparison of experimental and predicted moisture ratio by Midilli's model in all drying temperatures

Determination of moisture diffusivity and activation energy

The moisture diffusivity for each drying temperature was determined by plotting experimental data in terms of $\ln \mathrm{MR}$ versus drying time as shown in Figure 5.

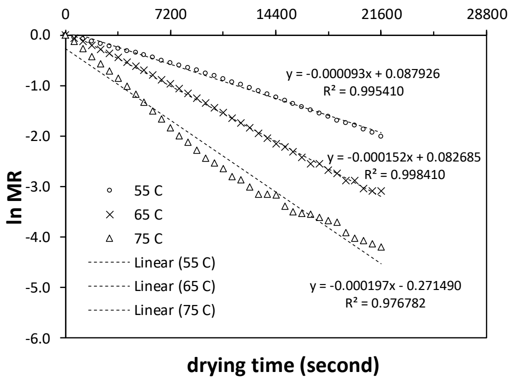

Figure 5 Plot of $\ln \mathrm{MR}$ vs. drying time.

The values of the moisture diffusivity were calculated using Eqn. (8) and slope values from Figure 5. The moisture diffusivity D_{eff} values were varied in the range of 9.47×10^{-10} and 20.00×10^{-10} m^2/s. It was noted that D_{eff} values increased with increasing drying temperature. While peeled longan were dried in high temperature, heating energy would increase the activity of water molecules inside effecting to higher effective moisture diffusivity. The value of D_{eff} are comparable with the reported value of 3.32 to 90.0×10^{-10} m^2/s for berberis fruits at 50-60°C [19], 6.27 to 35.0×10^{-10} m^2/s for orange slice at 40-80°C [20], and 2.6 to 5.4×10^{-10} m^2/s for persimmon slice at 50-80°C [21]. The values of D_{eff} found from the experiment lie within in general range 10^{-12}-10^{-8} m^2/s for drying of food materials [22].

The activation energy were calculated from the slope (E_a / R) of Arrhenius plot between $\ln D_{eff}$ versus $1/(T+273.15)$ Eq. (10) while the intercept is $\ln D_0$ as shown in Figure 6. The final value was found to be 35.60 kJ/mol. Whereas the value of activation energy stands within the general range of 12.7 to 110 kJ/mol for various food materials. By the literature by several authors for difference fruit, the activation energy was obtained as 22.66 – 30.92 kJ/mol for apples [23] and 67.29 kJ/mol for seedless grapes [24].

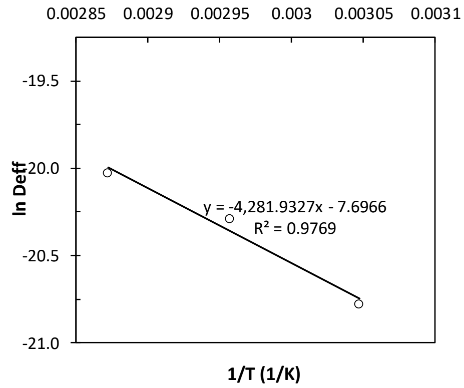

Figure 6 Arrhenius-type relationship of the effective moisture diffusivity and inversely proportional temperature

Conclusions

According to the experiment, the drying kinetics of peeled longan in thin-layer dryer was investigated. The drying time used to dry peeled longan from initial moisture content around 500% (d.b.) to the equilibrium moisture content around 600, 390, and 330 minutes at drying temperature 55, 65, and 75°C respectively. The experiment shows that there is no constant drying rate period, while the falling rate period that occurs in all drying process as shown in Figure 3. The diffusion is dominant mechanism for controlling the movement of moisture in longan.

Midilli's is the best model describing the thin-layer drying characteristic of peeled longan with statistical results including of values of R^2 over 0.999 for 55 and 65°C and over 0.998 for 75°C, values of χ^2 between 1.4013×10^{-5} and 5.8425×10^{-5}, value of RMSE between 0.00373 and 0.00761, and values of sum of residuals between 0.00572 and 0.19729.

The approximations of effective moisture diffusivity varied in the range of 9.47×10^{-10} and 20.00×10^{-10} m^2/s which is in the normal range of drying of food materials. Finally, by Arrhenius plot relative between $\ln D_{eff}$ versus with $1/(T+273.15)$, the activation energy for moisture diffusion was found to be 35.60 kJ/mol which is in the normal range of food materials.

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References

1. Lin Y, Chen M, Lin H, Hung Y, Lin Y, Chen Y, et al. DNP and ATP induced alteration in disease development of Phomopsis longanae Chinoculated longan fruit by acting on energy status and reactive oxygen species production-scavenging system. Food Chemistry. 2017; 228: 497-505.
2. Office of Agriculture Economics. Ministry of Agriculture and Cooperatives. Agro-product situation and forecast in 2018. 2017; 109-116.
3. Zhang S, Lin Y, Lin H, Lin Y, Chen Y, Wang H, et al. Lasiodiplodia theobromae (Pat.) Griff.&Maubl.-induced disease development and pericarp browning of harvested longan fruit in association with membrane lipids metabolism. Food Chemistry. 2018; 244: 93–101.
4. Tippayawong N, Tantakitti C, Thavornun S, Peerawanitkul V. Energy conservation in drying of peeled longan by forced convection and hot air recirculation. Biosystems Engineering. 2009; 104: 199–204.
5. Rangkadilok N, Sitthimonchai S, Worasuttayangkurn L, Mahidol C, Ruchirawat M, Satayavivad J. Evaluation of free radical scavenging and antityrosinase activities of standardized longan fruit extract. Food and Chemical Toxicology. 2007; 45: 328-336.
6. Yang B, Zhao MM, Shi J, Yang N, Jiang YM. Effect of ultrasonic treatment on the recovery and DPPH radical scavenging activity of polysaccharides from longan fruit pericarp. Food Chemistry. 2008; 106: 685–690.
7. Rangkadilok N, Worasuttayangkurn L, Bennett RN, Satayavivad J. Identification and quantification of polyphenolic compounds in Longan (Euphoria longana Lam.) fruit. Journal of Agricultural and Food Chemistry. 2005; 53: 1387-1392.
8. Pan YM, Wang K, Huang SQ, Wang HS, Mu XM, He CH, et al. Antioxidant activity of microwave-assisted extract of longan (Dimocarpus longan Lour.) peel. Food Chemistry. 2008; 106: 1264–1270.
9. Lerici CR, Dalla Rosa M, Pinnavia G. Direct osmotic as pre-treatment to fruit drying. In Proceedings of European Conference on Food Chemistry; 1983 March 15–18; Rome, Italy. p.287–296.
10. Castro AM, Mayorga EY, Moreno FL. Mathematical modelling of convective drying of fruits: A review. Journal of Food Engineering. 2018; 223: 152-167.
11. Doymaz I. Evaluation of some thin-layer drying models of persimmon slices (Diospyros kaki L.). Energy Conversion and Management. 2012; 56: 199–205.
12. Varith J, Dijkanarukkul P, Achariyaviriya A, Achariyaviriya S. Combined microwave – hot air drying of peeled longan. Journal of Food Engineering. 2017; 81: 459–468.
13. Nathakaranakule A, Jaiboon P, Soponronnarit S. Far-infrared radiation assisted drying of longan fruit. Journal of Food Engineering. 2010; 100: 662–668.

14. Kaewkiew J, Nabnean S, Janjai S. Experimental investigation of the performance of a large-scale greenhouse type solar dryer for drying chilli in Thailand. Procedia Engineering. 2012; 32: 433-439.
15. Elkhadraoui A, Kooli S, Hamdi I, Farhat A. Experimental investigation and economic evaluation of a new mixed mode solar greenhouse dryer for drying red pepper and grape. Renewable Energy. 2015; 77: 1-8.
16. Midilli A, Kucuk H. Mathematical modelling of thin layer drying of pistachio by using solar energy. Energy Conversion and Management. 2003; 44: 1111-1112.
17. Akpinar EK, Bicer Y, Centikaya F. Modelling of thin layer drying of parsley leaves in a convective dryer and under open sun. Journal of Food Engineering. 2006; 75: 308-315.
18. Crank J. The mathematics of diffusion. 2nd ed. Oxford: Clarendon Press; 1975.
19. Aghbashlo M, Kianmehr MH, Samimi-Akhijahani H. Influence of drying conditions on the effective moisture diffusivity, energy of activation and energy consumption during the thin layer drying of berberis fruit (Berberidaceae). Energy Conversion and Management. 2008; 49: 2865-2871.
20. Rafiee S, Sharifi M, Keyhani A, Omid M, Jafari A, Mohtasebi SS, et al. Modeling effective moisture diffusivity of orange slices (Thompson Cv.). Int Journal of Food Property. 2010; 13: 32-40.
21. Teris-Romero J, Gabas AL, Menegalli FC, Telis VRN. Drying of persimmon: mathematical model for diffusivity as a simultaneous function of moisture content and shrinkage. Proceedings of the second Inter-American Drying Conference; 2001; Veracruz, Mexico. 243-251.
22. Zogzas NP, Maroulis ZB, Marinos-Kouris D. Moisture diffusivity data compilation in foodstuffs. Drying Technology. 1996; 14: 2225-2253.
23. Meisami-asl E, Rafiee S, Keyhani A, Tabatabaeefar A. Drying of apple slice (var. Golab) and effect on moisture diffusivity and activation energy. Plant Omics Journal. 2010; 3(3): 98-102.
24. Xiao HW, Pang CL, Wang LH, Bai JW, Yang WX, Gao ZJ. Drying kinetics and quality of Monukka seedless grapes dried in an air-impingement jet dryer. Biosystem Engineering. 2010; 105: 233-240.