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Mathematical Modelling of Thin Layer Drying of Salak

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Abstract: Thin layer drying kinetics of salak (*Salacca edulis*) in hot air drying was investigated for temperature range of 50 to 80°C. Salak fruits were prepared in two forms; slices with membrane layer and slices without membrane layer on surface. A mathematical model was determined to describe the moisture reduction process during isothermal drying. Theoretical model of Fick's second law, six semi-theoretical models and one empirical model that commonly employed in food dehydration were evaluated. Results showed that the Midilli-Kucuk equation gave the best prediction to the drying kinetics evidenced by coefficient of determination, R^2 ranging from 0.9976-0.9993. A new approach was used for the estimation of drying rate and the commencement point of second falling-rate period by using a semi-theoretical model. Diffusivity coefficients of moisture transfer were found ranging from 4.19×10^{-11} to 2.58×10^{-10} m^2 sec^{-1}. It appears that moisture diffusion is the controlling mechanism of the thin layer drying and it is an increasing function of temperature. Activation energy was determined at 45.27 and 39.78 kJ mol^{-1} for sample with and without surface membrane, respectively. Higher activation energy indicates that the membrane layer is a strong barrier to moisture movement across the sample surface.

Key words: Modelling, drying kinetics, diffusivity, activation energy

INTRODUCTION

Salak (Salacca *edulis*) or also known as snake fruit belongs to Arecaceae family. This palm is native in Indonesia and Malaysia. Nevertheless, cultivation of salak palm can also be found in Thailand and Philippines recently (Abad-García *et al*., 2007). Salak fruit is a good source for dietary fibres and carbohydrate (Lestari *et al*., 2003). This peculiar fruit tastes sweet to sub-acid like combination of pineapple and jackfruit at its ripe stage but immature fruit tastes sour and astringent. Despite the unique smell and taste, salak contains valuable bioactive antioxidants such as vitamin A, vitamin C and phenolic compounds (Setiawan *et al*., 2001; Leong and Shui, 2002; Shui and Leong, 2005; Leontowicz *et al*., 2007). However, salak has a short shelf life of less than a week due to rapid ripening and degradation of the bioactive ingredients.

Drying is one of the common methods used to preserve agricultural products. Removal of moisture from produces may deactivate enzymes or microorganisms that often cause undesired chemical reaction and lead to quality deterioration (Jayaraman and Das Gupta, 2006). Drying kinetics is important in the analysis of moisture migration process in a solid material. Many thermo-physical properties and transport properties that are usually integrated in a drying model can be determined from the analysis of drying kinetics (Marinos-Kouris and Maroulis, 2006). Moreover, movement of moisture within a food material during drying is a complex process with various diffusion mechanisms. Variation in composition and complicated biopolymer structure of the food material may result in unique drying characteristic for different food product (Zogzas *et al*., 1996). Study on the drying kinetics may allow understanding of the controlling mechanism during drying and hence influence of drying parameters on dryer design and dried product quality can be determined.

Nemerous studies have been conducted to the drying kinetics and product quality of foodstuffs that undergoing isothermal convective drying, for instance garlic, pumpkin, grapes, apple and orange skin (Madamba *et al*., 1996; Sawhney *et al*., 1999; Doymaz, 2007; Kaya *et al*., 2007). However, to date there is no literature report on the drying kinetics of salak fruit which is a good source for dietary antioxidant but unexploited. On the other hand, several mathematical models have been proposed for the evaluation of moisture transport behavior by either applying theoretical (Fick's second law of diffusion), semi-theoretical and

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empirical modelling (Crank, 1975; Jayas *et al.*, 1991; Kabganian *et al.*, 2002; Demir *et al.*, 2007; Midilli *et al.*, 2002; Doymaz, 2005). Theoretical model can be used to get an insight on the mechanism of moisture transfer during the falling-rate period in drying. However, simplified assumptions such as constant diffusivity and one-dimension liquid diffusion sometimes resulted in inadequate prediction to the moisture distribution. Meanwhile, a semi-theoretical model may not able to explain the exact mechanism of moisture transport but it often gives good estimation by incorporating lump values of other effects into the model parameters.

The objective of this study is to investigate the kinetics of thin layer drying of salak and to determine mathematical model for the moisture distribution profile of the convective hot air drying. This study also aims to extend the use of semi-theoretical model in the estimation of drying rate at different drying temperature and determination of commencement point of second falling-rate period.

MATERIALS AND METHODS

Sample preparation: Salak fruits (*Salacca edulis*) were purchased from a local fruit supplier. Fruits with similar size (ca. 5-7×5 cm) and skin colour were selected for all experiments to ensure consistency in the samples used. Fresh fruits were kept in refrigerator at about 10°C with storage period not longer than seven days. Salak slices (3×2×2 mm) were prepared in two forms, with surface membrane and without surface membrane. Sample without surface membrane was prepared by removing the membrane layer manually from the fruit surface before slicing.

Drying experiments: Convective hot air drying experiments were performed by using an oven with forced air circulation (Memmert, UFP500, Germany). Heating elements were integrated evenly around the four inner walls to create uniform temperature distribution inside the chamber. Fresh air was pre-heated in a pre-warming chamber and continuously added to the air inside the chamber. Meanwhile, exhaust air was discharged through an opening situated in the middle of back wall. Four levels of hot air temperature (50, 60, 70 and 80°C) were used. Samples (about 100 g) were arranged on flat perforated trays (65×35 cm with 1 cm diameter openings) and placed in the middle section of the oven. The weight of the sample was recorded periodically during the drying with 15 min interval in the first 2 h, 30 min interval in the subsequent next 2 h and hourly thereafter by using a digital balance (Adventurer OHAUS, AR3130, USA). Experiment was terminated when constant weight was obtained in three consecutive measurements. The moisture content obtained at this stage was marked as the Equilibrium Moisture Content (EMC). Dry Matter (DW) weight of the material was determined by drying the sample in oven at 105°C for 24 h.

Mathematical modelling

Moisture ratio: Moisture content was determined as a dimensionless parameter denoted as Moisture Ratio (MR). Equation 1 relates the sample moisture content in real time (X_t) to the initial moisture content (X_o) and equilibrium moisture content (X_e) (Akpinar *et al.*, 2003):

$$MR = \frac{X_1 - X_e}{X_o - X_e} \qquad (1)$$

Theoretical model: Fick's second law was solved analytically for diffusion in a plane sheet by assuming one-dimension diffusion and constant diffusivity (Crank, 1975). Ten terms (n = 10) from the Fick's series in Eq. 2 was used to estimate the moisture content by conducting nonlinear regression analysis using Microsoft Excel SOLVER tool (Microsoft Office Professional 2003, USA). Effective diffusivity constant (D_{eff}) and sample thickness (L) are the model parameters.

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left[\frac{-(2n-1)^2\pi^2 D_{eff}t}{4L^2}\right] \qquad (2)$$

Semi-theoretical and empirical model: Semi-theoretical and empirical models that commonly applied for fruits and vegetables drying were adopted from literatures as shown in Table 1. Three statistical parameters, coefficient of determination (R^2), Chi-square (χ^2) and Root Mean Square Error (RMSE), were used to assess the goodness of fit of the models to experiment data.

Drying rate and falling-rate period: Drying rate at a given temperature was estimated by using first derivation of Midilli-Kucuk model equation while gradient of the drying rate was calculated by conducting second derivation to the same model.

Table 1: Semi-theoretical and empirical models

Model name	Model equation
Newton	$MR = \exp(-kt)$
Page	$MR = \exp(kt^n)$
Midilli-Kucuk	$MR = a\exp(-kt^n) + bt$
Two term	$MR = a\exp(-k_o t) + b\exp(-k_1 t)$
Henderson and Pabis	$MR = a\exp(-kt)$
Logarithmic	$MR = a\exp(-kt) + c$
Wang and Singh	$MR = 1 + at + bt^2$

Effective diffusivity and activation energy: Effective diffusivity constant (D_{eff}) can be determined from the linearized first term from the Fick's infinite equation as shown in Eq. 3 by assuming that constant diffusivity applied to the internal moisture movement during first falling-rate period.

$$\text{InMR} = \text{In}\left(\frac{8}{\pi^2}\right) - \text{Deff}\left(\frac{\pi}{2L}\right)^2 t \qquad (3)$$

Natural logarithm of MR was plotted versus t and D_{eff} can be determined from the slope. Relationship between D_{eff} and temperature can be evaluated with Arrhenius equation as shown in Eq. 4.

$$D_{eff} = D_o \exp\left(-\frac{E_a}{RT}\right) \qquad (4)$$

RESULTS AND DISCUSSION

Drying kinetics: Moisture content of samples at four levels of temperature (50, 60, 70 and 80°C) were monitored over the drying period. Initial moisture content of the salak fruits were recorded at 4.24±0.39 kg water kg DW^{-1}. Figure 1a and b show the moisture ratio versus time for salak slices with and without surface membrane, respectively. Both graphs show exponential trend for the drying curves and it can be observed that the samples reached EMC in a shorter time at higher temperature. Many literatures showed similar results when conducting hot air drying to agricultural products such as red chillies, pineapple and potatoes (Arora *et al*., 2006; Nicoleti *et al*., 2001; Rossello *et al*., 1992). Higher drying temperature would result in higher drying kinetics. However, membrane layer on the fruit surface is a barrier to moisture transfer. Higher moisture content was found in salak with surface membrane when compared with those without membrane at a given time period. Nevertheless, the effect of surface barrier was less pronounce when drying process was conducted at higher temperature. Moisture contents for both samples (with and without membrane) were found close to each other for the hot air drying at temperature 80°C.

Mathematical modelling: Mathematical modelling of the drying curves under various temperatures was conducted by using nonlinear regression analysis coupled with generalized reduced gradient algorithm (GRG2). All the model constants were calculated based on the iterative method and the statistical parameters for the estimation are shown in Table 2. Based on the obtained values for the three statistical parameters, it can be seen that Midilli-Kucuk equation is the best model to describe the drying kinetics of salak slices at all tested temperatures with R^2, χ^2 and RMSE values ranging from 0.9976-0.9993, 0.0001-0.0003 and 0.0068-0.0128, respectively. In agreement with other literatures, Midilli-Kucuk model often gave better prediction on the moisture distribution profile among other semi-theoretical models (Ait Mohamed *et al*., 2005; Haclhaflzoglu *et al*., 2008; Karaaslan and Tunçer, 2008). On the other hand, Fick's equation (theoretical) resulted in lower value of R^2 as compared with semi-theoretical models, while the Wang and Singh model (empirical) presented the lowest R^2 value among the theoretical and semi-theoretical models.

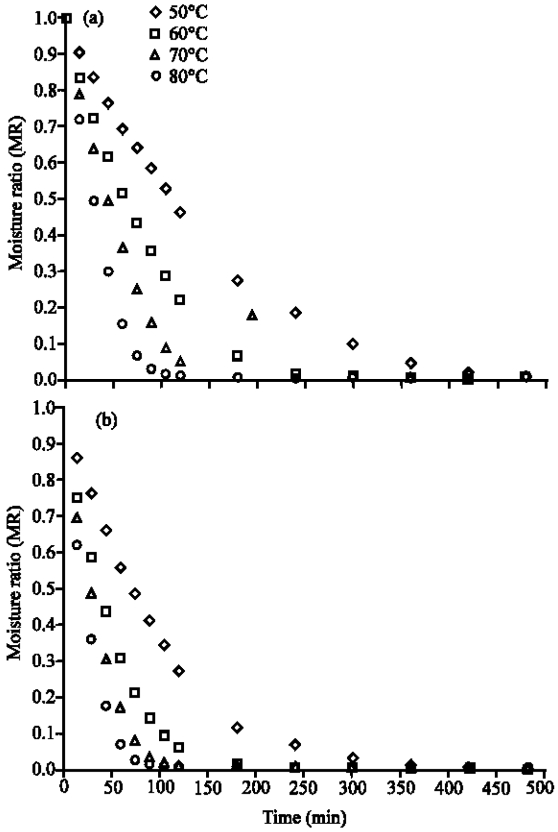

Fig. 1: Moisture ratio of salak slices at different temperature (a) with surface membrane and (b) without surface membrane

Drying rate and falling-rate period: High value of R^2 and low value of χ^2 and RMSE obtained from the regression analyses indicate that the Midilli-Kucuk model fitted well with the experiments data. Thus, it can be used to represent the drying curve for salak slices under isothermal drying and the drying rate can be calculated by applying first derivative to the Midilli-Kucuk equation. Drying rate curves for salak slices with and without surface membrane are shown in Fig. 2a and b, respectively. It was observed hat there was no constant-

Table 2: Results of statistical parameters estimated from regression analyses for temperature of 50-80°C

		50°C		60°C		70°C		80°C	
Model	Parameters	With	Without	With	Without	With	Without	With	Without
Fick's second law	R^2	0.9577	0.9745	0.9725	0.9803	0.9614	0.9739	0.9670	0.9826
	χ^2	0.0054	0.0029	0.0031	0.0018	0.0042	0.0025	0.0029	0.0013
	RMSE	0.0717	0.0523	0.0539	0.0416	0.0626	0.0479	0.0525	0.0355
Newton	R^2	0.9941	0.9974	0.9954	0.9970	0.9882	0.0007	0.9882	0.9951
	χ^2	0.0007	0.0002	0.0005	0.0002	0.0012	0.0261	0.0010	0.0003
	RMSE	0.0267	0.0164	0.0220	0.0160	0.0345	0.0000	0.0313	0.0188
Page	R^2	0.9987	0.9992	0.9981	0.9990	0.9974	0.9984	0.9988	0.9993
	χ^2	0.0001	0.0001	0.0002	0.0001	0.0003	0.0001	0.0001	0.0001
	RMSE	0.0124	0.0091	0.0138	0.0090	0.0161	0.0116	0.0098	0.0069
Midili-Kucuk	R	0.9991	0.9993	0.9984	0.9991	0.9976	0.9985	0.9988	0.9993
	χ^2	0.0001	0.0001	0.0002	0.0001	0.0003	0.0001	0.0001	0.0001
	RMSE	0.0104	0.0086	0.0128	0.0087	0.0153	0.0114	0.0096	0.0068
Two term model	R^2	0.9991	0.9982	0.9963	0.9980	0.9931	0.9962	0.9966	0.9986
	χ^2	0.0001	0.0002	0.0005	0.0002	0.0009	0.0004	0.0004	0.0001
	RMSE	0.0104	0.0137	0.0197	0.0129	0.0263	0.0182	0.0185	0.0105
Henderson and Pabis	R^2	0.9941	0.9974	0.9954	0.9970	0.9882	0.9922	0.9903	0.9954
	χ^2	0.0008	0.0003	0.0005	0.0002	0.0013	0.0007	0.0011	0.0004
	RMSE	0.0267	0.0164	0.0220	0.0160	0.0345	0.0261	0.0313	0.0188
Logarithmic	R^2	0.9959	0.9975	0.9955	0.9970	0.9882	0.9922	0.9903	0.9954
	χ^2	0.0006	0.0003	0.0005	0.0003	0.0014	0.0008	0.0012	0.0004
	RMSE	0.0223	0.0161	0.0217	0.0160	0.0345	0.0261	0.0313	0.0188
Wang and Singh	R^2	0.9640	0.7499	0.7338	0.1095	0.4238	0.5987	0.5299	0.1820
	χ^2	0.0049	0.0302	0.0319	0.0885	0.0674	0.1104	0.1361	0.3427
	RMSE	0.0660	0.1639	0.1678	0.2795	0.2418	0.3093	0.3466	0.5499

rate period in all drying rate curves. All drying experiments comprised of only falling-rate period. The rate of drying fell steadily with time. It appears that higher drying rate was obtained at high temperature and sample without surface membrane attained higher drying rate when compared with those with membrane layer at a given temperature.

Many literatures suggested that moisture diffusion in solid material during falling-rate period is diffusion-controlled and moisture diffusion in first falling-rate period is more prominent and significant as compared with diffusion in second falling-rate period. This is because second falling-rate period is the period of unsaturated surface evaporation and usually the amount of moisture removed is relatively small but the time required may be long. Hence, moisture diffusivity can be estimated from the first falling-rate period and the calculated effective diffusivities are lump values over the range of moisture content (Geankoplis, 1993). Nevertheless, in most cases, the commencement of second falling-rate period is difficult to be estimated from the drying rate curve due to unobvious curve change especially when data points are closed to each other at low moisture content.

Thus, plots for drying rate gradient against drying time were constructed by applying second derivation to the Midilli-Kucuk model. Figure 3a and b show the curves for the dying rate gradient with and without membrane layer, respectively. Overall, drying rate gradient was found increased with time before reaching a constant value and decreased with time thereafter. The obtained constant value is an indication of first falling-rate period

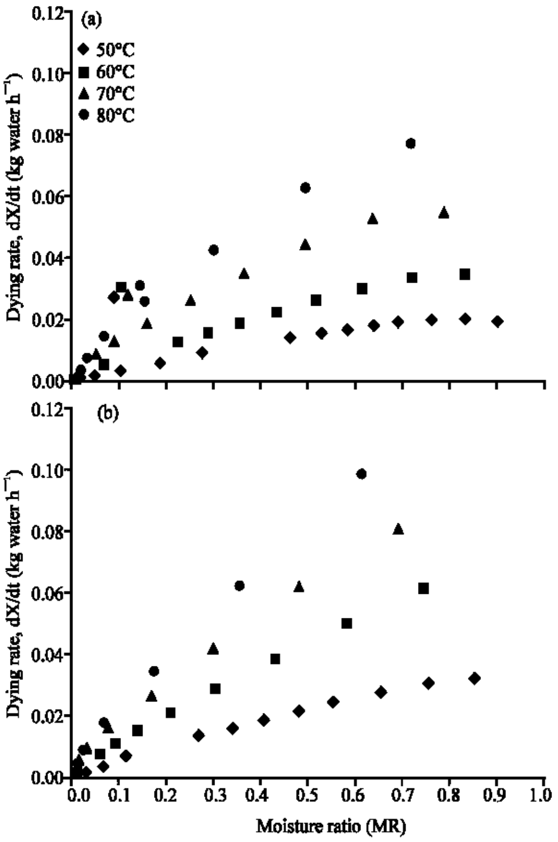

Fig. 2: Drying rate curves for salak slices (a) with surface membrane and (b) without surface membrane

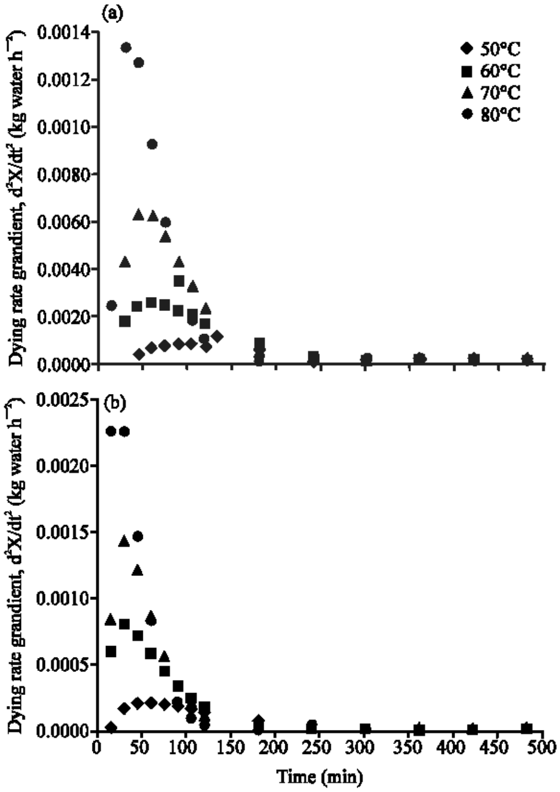

Fig. 3: Drying rate gradient for salak slices (a) with surface membrane and (b) without surface membrane

due to the characteristic of the first falling-rate curve which is usually a straight line with slope. It appears that time period for the occurrence of the first falling-rate is dependent on the temperature. For instance, the beginning points for the second falling-rate period (also the end points for first falling-rate period) were found at 120, 75, 60 and 45 min at temperature of 50, 60, 70 and 80°C, respectively, for the drying of salak with membrane layer. It seems that at higher temperature the first falling-rate period will be shorten.

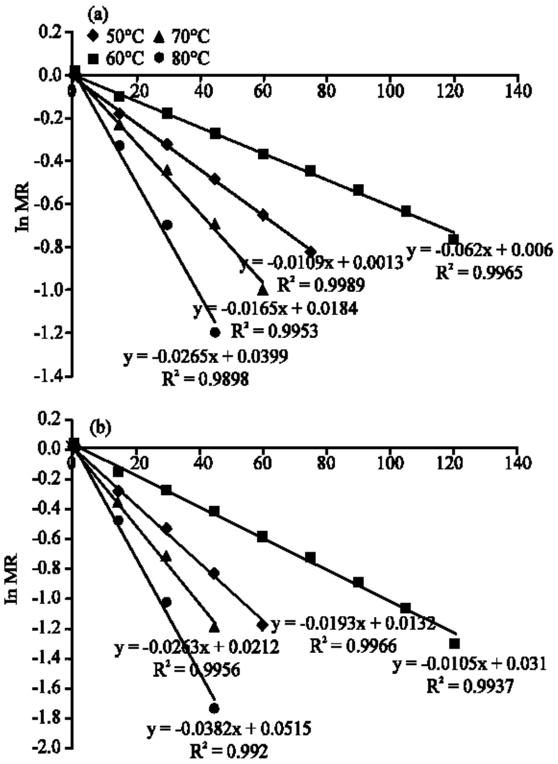

Fig. 4: Plot of lnMR versus t for salak slices (a) with surface membrane and (b) without surface membrane

Table 3: Effective diffusivity, constant diffusivity and activation energy for salak with or without membrane

Sample	Temperature (°C)	D_{eff} (m^2 sec^{-1})	D_o ($m^2 sec^{-1}$)	E_a (kj mol^{-1})
With surface membrane	50	4.19E-11	8.93E-04	45.27
	60	7.36E-11		
	70	1.11E-10		
	80	1.79E-10		
Without surface membrane	50	7.09E-11	2.04E-04	39.78
	60	1.30E-10		
	70	1.78E-10		
	80	2.58E-10		

Effective diffusivity and activation energy: Plots of lnMR versus t for the four drying temperatures were constructed by using only the data fell within the first falling-rate period and the results are shown in Fig. 4a and b. The constant diffusivity (D_o) and activation energy (E_a) were determined from the y-intercept and slope of the linearized Arrhenius equation curve, respectively. Table 3 shows the summary of the D_{eff}, D_o and E_a. The estimated D_{eff} ranging from 4.19×10^{-11} to 2.58×10^{-10} m sec^{-1} and the obtained values are fall within the range of values reported in other literatures (Madamba *et al.*, 1996; Nicoleti *et al.*, 2001; Biju Cletus and Carson, 2008; Garau *et al.*, 2006). Apparently, the effective diffusivity increased with drying temperature. On the other hand, activation energy for sample with surface membrane was found higher than those without surface membrane. This could be resulted by the existence of the membrane on the sample surface that had become the resistance for the moisture movement. Thus higher energy required to overcome the resistance.

CONCLUSION

Elevated air temperature resulted in higher drying kinetics. Effective diffusivity constant was found increased with temperature and correlated well with the Arrhenius equation. Higher activation energy showed that the surface membrane was a strong barrier to moisture diffusion from internal to surrounding air. Midilli-Kucuk model gave better prediction to the moisture distribution profile as compared to other semi-theoretical models.

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