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Drying Kinetics and Modelling of Convective Drying of Kedondong Fruit

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Abstract. Kedondong is an underutilized fruit cultivated in a small scale in Malaysia and it contains nutrients that can be preserved through drying. The dried product can be sold as a premium fruit snack that could generate revenue for the producer. We studied the drying of peeled and unpeeled kedondong fruits using hot air (60-80°C). This study aims to investigate the drying kinetics (drying rates and effective diffusivities) of kedondong fruits and model the drying curves using thin layer models. Ten thin layer models were employed and solved using non-linear regression. Drying kinetics showed that only falling rate periods were observed, which implied that internal diffusion was the dominant mechanism for moisture release. Mathematical models showed that Modified Hii et al. (I) and (II) models were able to predict the drying curve well with the highest R^2 (0.9992-0.9999), the lowest RMSE (8.0×10^{-4} - 2.5×10^{-3}) and the lowest χ^2 (4.0×10^{-5} - 2.0×10^{-4}). Peeled samples showed higher effective diffusivities (average 3.2×10^{-11} m^2/s) than unpeeled samples (average 2.7×10^{-11} m^2/s). The activation energy was lower in peeled samples (25.8 kJ/mol) as moisture diffusion could occur more easily than unpeeled samples (32.1 kJ/mol). Results from this study provide kinetic information that can be used in scaling up of dryer and optimizing dryer performances.

Keywords: Drying rates, Diffusion, Effective diffusivity, Modeling, Thin layer model

INTRODUCTION

Drying requires simultaneous heat and mass transfer. The mass transfer process can be analyzed using Fick's law which is governed by the effective diffusivity (Zogzas et al. 1996, Ghazanfari et al. 2006). Analytical solutions of the Fick's law model are available for various basic shapes (Crank 1975). Additionally, semi-theoretical/empirical models were also reported in the literature to model changes the drying process (Onwude

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et al. 2016). The semi-theoretical/empirical model provides a compromise between theory and ease in the application regardless of shapes and dimensions

Various semi-theoretical/empirical models have been applied for semi-dried and dried food products (Karathanos and Belessiotis 1999) such as apple slices (Sacilik and Elicin 2006), sultana grapes (Yaldiz et al. 2001), pricky pear (Touil et al. 2014), star fruit (Hii et al. 2014), lemon slices (Lee et al. 2020), chicken meat (Hii et al. 2014), herbs (Tham et al. 2017) rice (Bualuang et al. 2011) and edible insect (Seah et al. 2020). Findings from these studies have shown that high prediction accuracy (R^2 > 0.99) could be achieved by selecting the best model (e.g. Page, Verma and others, Midilli-Kucuk and Two-term models) that can meet the criteria of several statistical parameters such as the highest coefficient of determination (R^2), the lowest chi-square (χ^2) and the lowest root mean square error (RMSE). These models have also been reported used in hot air (Hii et al. 2014), vacuum (Lee and Kim 2009), microwave (Prabhanjan et al. 1995), heatpump (Pal et al. 2008) and solar (Yaldiz et al. 2001) drying. Reviews of these models can be seen from the literature (Onwude et al., 2016, Erbay and Icier, 2010, and Jayas et al., 1991).

Kedondong fruit is cultivated in several countries, such as India, Sri Lanka, Indonesia, Vietnam, Laos, Cambodia, Zanzibar, Gabon, Australia, and Malaysia (Jana 2016). The nutritional profile of kedondong fruit (per 100 g basis) includes 0.2 g protein, 12.4 g carbohydrates, 0.1 g fat, 56.0 mg calcium, 67.0 mg phosphorus, 0.3 mg iron, 205.0 µg carotene, 50.0 µg thiamine, 20.0 µg riboflavin and 36.0 mg vitamin C (Jana, 2016). Kedondong fruit is an underutilized fruit cultivated in small volume in Malaysia (around 46.5 ha). Recently, local government agencies have initiated programs to promote planting of underutilized fruits and improve farmers' revenue by diversifying product range production of dried fruit snacks (CFF 2014). Therefore, it is of our interest to carry out a study to investigate the drying kinetics of kedondong fruits and develop an improved mathematical model for drying rates prediction, duration of drying, and effective diffusivities. These parameters are critical in controlling the final product quality (e.g., nutritional). The current work extended the previous study by Hii et al (2009) to obtain a better drying model.

Hence, convective air drying was carried out on peeled and unpeeled kedondong fruit slices (*Spondias dulcis*). To date, studies on thin-layer drying of kedondong fruits have not been well studied.

MATERIALS AND METHODS

Sample preparation

Fresh and ripe kedondong fruits were bought from a nearby supermarket (Semenyih, Malaysia) and stored in a chiller (4±1°C) before experiments. The fruits were oval, and their length was about 3-5 cm. The fruits were cut crosswise (1 cm thick) into slices (16 pieces). The samples were classified into peeled (without skin) and unpeeled (with skin) (see Fig. 1). The fruit slices were spread on a stainless steel tray for drying.

Fig. 1: Kedondong fruit and samples (with and without skin)

Drying experiment

Fig. 2 shows a schematic diagram of the hot air oven used (Memmert, Germany). The temperatures were set at 60°C, 70°C, and 80°C using an air velocity of 0.3 m/s.

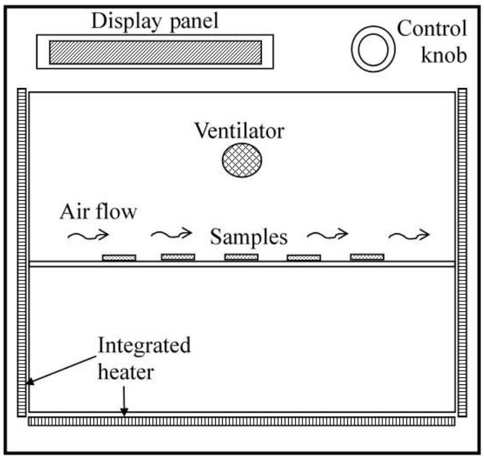

Fig. 2: Schematic of hot air oven

The dimensions of the drying chamber was 0.3 m × 0.3 m × 0.6 m, and the direction of the airflow was parallel to the drying tray. The weight of the samples was measured hourly until a constant weight condition was obtained. The moisture content was determined according to the oven method (Hii et al. 2012). The experiments were performed in duplicate.

Drying kinetics

Moisture content (*X*) and drying rate (*dX/dt*) were calculated using Eq. (1) and (2), respectively.

$$X_i = \frac{M_i - M_{ds}}{M_{ds}} \quad (1)$$

$$\frac{dX_i}{dt} = \frac{M_i - M_{i+1}}{t_i - t_{i+1}} \quad (2)$$

where *M* = weight of sample (g), *t* = time (s), *i* = time *i* and *ds* = dry solid weight (g), respectively. Moisture content (dry basis) was converted to moisture ratio using Eq. (3).

$$MR = \frac{X_i - X_e}{X_0 - X_e} \quad (3)$$

where subscripts *i, e, 0* represent time *i*, equilibrium and initial, respectively.

Effective diffusivity

Effective diffusivity was determined using Eq. (4) (Crank, 1975).

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} exp\left[\frac{-(2n+1)^2 \pi^2 D_e t}{4L^2}\right] \quad (4)$$

where *MR* = moisture ratio, D_e = effective diffusivity (m^2/s), *L* = half-thickness (m) and *t* = time (s), respectively.

The equation was simplified (taking n = 0) as shown in Eq. (5) and linearized by multiplying the natural log at both sides (Eq. (6)). The equations can be used for long drying, (MR reduces beyond 0.8 and lower), drying under falling rate period, and for sample with Biot number < 0.1. Bi < 1 means that the moisture content and product temperature development can be assumed uniform within the sample. Eq. (4)-(7) have been reported used in drying of banana (Baini and Langrish 2007, Azharul and Hawlader 2005) and figs (Doymaz 2005).

$$MR = \frac{8}{\pi^2} exp\left(\frac{-\pi^2 D_e t}{4L^2}\right) \quad (5)$$

$$ln\, MR = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_e t}{4L^2}\right) \quad (6)$$

By plotting *ln MR* versus time *t*, the slope ($\pi^2 D_e t/4L^2$) can be used to calculate the effective diffusivity (D_e). The effective diffusivities can be correlated to drying temperatures using Eq. (7).

$$D_e = D_{eo} exp\left(\frac{-E}{RT}\right) \quad (7)$$

where D_{eo} = diffusion constant (m^2/s), E = activation energy (kJ/mol) and R = universal gas constant (8.314 J/(mol.K)). Eq. (7) can be linearized (*ln* D_e versus *1/T*), and the slope of the graph *(E/R)* can be used to determine the activation energy (*E*).

Mathematical Modeling

Moisture ratio data from each experiment was fitted into the thin layer drying models (Table 1). Modified Hii et al.(I) and Hii et al. (II) are improved models from Hii et al. (2009). Non-linear regression analysis was used by minimizing Sum of the Square of the Residuals (SSR) (Eq. (8)) to estimate the constants/coefficients of the models using Excel Solver (Microsoft Office, USA).

Table 1. Thin layer drying models

Model	*Equation*
Newton	$MR = exp^{-kt}$
Page	$MR = exp^{-kt^n}$
Henderson & Pabis	$MR = aexp^{-kt}$
Midilli & others	$MR = aexp^{-kt^n} + bt$
Logarithmic	$MR = aexp^{-kt} + c$
Two-term	$MR = aexp^{-kt} + bexp^{-gt}$
Verma & others	$MR = aexp^{-kt} + (1 - a)exp^{-gt}$
Hii et al.	$MR = aexp^{-k_1t^n} + bexp^{-k_2t^n}$
Modified Hii et al.(I)	$MR = aexp^{-k_1t^n} + (1 - a)exp^{-k_2t^n}$
Modified Hii et al. (II)	$MR = aexp^{-k_1t^{n_1}} + bexp^{-k_2t^{n_2}} + cexp^{-k_3tn_3}$

where *a, b, c,* and *n* (including subscripts 1-3) are dimensionless coefficients and g and *k* (including subscripts 1-3) are drying constant (1/s) in the models.

Initial guess values were set according to the coefficients/constants in the models and changed to achieve the objective (SSR) through several iterations. This was done by minimizing the SSR (Eq. (8)) to the lowest value (global minima). Constraint was also set such that the predicted moisture ratios should be all positive real numbers. This resulted in the prediction of the moisture ratio at each time interval (Hii and Ogugo 2014, Hii et al. 2009). The solving method used was the GRG non-linear method (Generalized Reduced Gradient). This is done by looking at the gradient of the objective function based on the initial guess values until it reaches an optimum solution (global minima).

$$SSR = \sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2 \qquad (8)$$

where subscripts *pre* and *exp* are predicted and experimental values, respectively.

Statistical parameters were employed to evaluate the model namely Coefficient of Determination (R^2), Chi-Square (χ^2), and Root Mean Square Error (*RMSE*) (Eq. (9) –(11)).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{\sum_{i=1}^{N}\left(\overline{MR}_{pre,i} - MR_{exp,i}\right)^2} \qquad (9)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - z} \qquad (10)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2} \qquad (11)$$

The best drying model was decided based on the highest R^2 and the lowest χ^2 and *RMSE* values (Doymaz 2005).

RESULTS AND DISCUSSION

Drying Kinetics

Fig. 3 shows the drying curves where unpeeled samples (14 - 23 hours) required a longer drying time than peeled samples (12 -

19 hours). The reduction in moisture ratios followed an exponential decaying trend, which was quite similar to what was found in the drying of many food products (Hii et al. 2009, Hii and Ogugo 2014, Doymaz 2017, Ee et al. 2019). A larger reduction of the moisture in the beginning of the drying was mainly due to the greater driving force for mass transfer. At this condition, the difference in moisture content between the samples and the drying air were higher than the later part of the drying process. On average, unpeeled and peeled samples required 19.3 hours and 16 hours, respectively, to complete drying within the experimental drying temperature range (60-80°C). The unpeeled samples have a higher resistance to mass transfer due to the presence of a thin waxy layer (Park 1991).

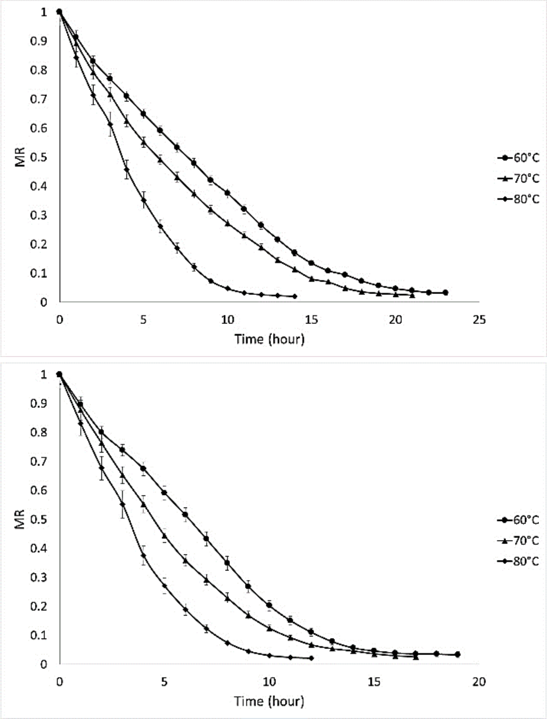

Fig. 3: Drying curves with skin (top) and without skin (bottom)

Fig. 4 shows drying rates curves. The typical falling rates period observed was in agreement with those reported by Ee et al. (2019) and Doymaz (2017) for kedondong and carrot, respectively. Therefore, internal moisture diffusion is the dominant mass transfer mechanism as compared to surface evaporation.

Initial drying rates for peeled samples (-1.21 to -1.91 gH_2O/g dry solid.hr) were higher than unpeeled samples (-1.01 to -1.75 gH_2O/g dry solid.hr). Two falling rates periods were observed. The first and the second falling rate period occured at around 2.2 – 4.3 gH_2O/g dry solid and 4.5 – 6.0 gH_2O/g dry solid for unpeeld and peeles samples, respectively. The earlier transition to the second falling rate period experienced by the peeled samples was due to faster moisture removal in these samples.

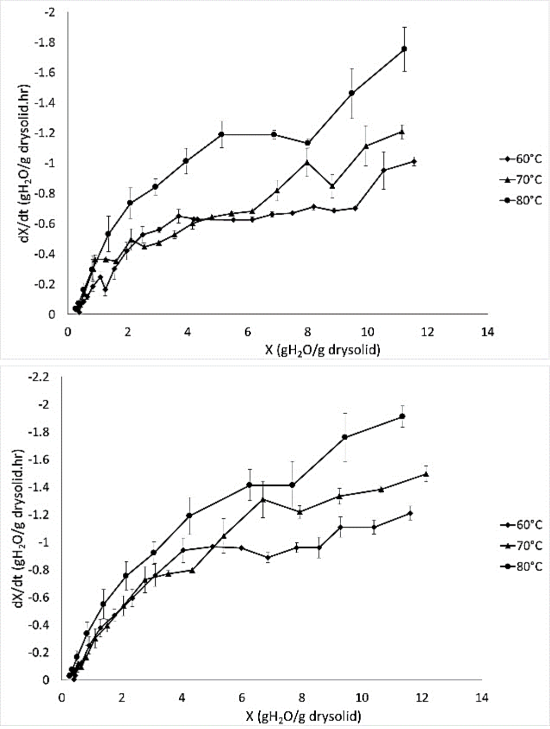

Fig. 4: Drying rates profiles with skin (top) and without skin (bottom)

This result is in agreement with Touil et al. (2014), Daud et al. (2000) and Dhali and Datta (2018). In the first falling rate period, a limited area of the wetted surface was still available, but it diminished once second falling rate period commenced. Subsequently, the surface was completely dry and the plane of evaporation gradually receded from the surface (Dhali and Datta 2018).

Mathematical Modeling

Table 2-7 show results of mathematical modeling. The modified Hii et al.(I) and (II) modelsoutperformed some of the existing models, as shown by the highest R^2, lowest $\chi^2$and lowest *RMSE* values.

Table 2. Results of mathematical modelling (unpeeled kedondong samples) for 60°C drying

Equation (60°C)		χ^2	RMSE	R^2
Newton	$MR=\exp^{-0.12t}$	0.0040	0.0126	0.9900
Page	$MR=\exp^{-0.05t^{1.40}}$	0.0009	0.0060	0.9962
Henderson & Pabis	$MR=1.06\exp^{-0.12t}$	0.0007	0.0051	0.9971
Midilli & others	$MR=0.94\exp^{-0.03t^{1.49}} + 0.001t$	0.0043	0.0126	0.9900
Logarithmic	$MR=0.99\exp^{-0.11t} + 0.001$	0.0043	0.0126	0.9900
Two-term	$MR=0.17\exp^{-0.12t} +0.83\exp^{-0.12t}$	0.0037	0.0114	0.9909
Verma & others	$MR=0.05\exp^{-0.15t} +0.95\exp^{-0.11t}$	0.0011	0.0063	0.9970
Hii et al.	$MR=0.89\exp^{-0.019t^{1.72}} +0.11\exp^{-53.5t^{1.72}}$	0.0004	0.0038	0.9984
Mod. Hii et al. (I)	$MR=0.89\exp^{-0.02t^{1.72}} +0.11\exp^{-53.5t^{1.72}}$	0.0004	0.0038	0.9984
Mod. Hii et al. (II)	$MR=0.69\exp^{-0.004t^{2.21}} +0.29\exp^{-0.34t^{1.04}} +0.02\exp^{-0.38t^{1.80}}$	*0.0002*	*0.0025*	*0.9992*

In drying experiments at 80°C, both Hii et al. and Modified Hii et al.(I) models showed similar values in the statistical parameters. This similar value was s due to minor difference in the coefficients in these models, coefficients '*b*' and '*1-a*', as there is a possibility that these two values could be similar. The reason for using '*1-a*' in Modified Hii et al.(I) model was to reduce the number of coefficients in the equation that could affect the fitting accuracy in terms of chi-square. Comparison among the moisture ratios profiles as predicted by the various models was shown in Fig. 5-6.

Table 3. Results of mathematical modelling (unpeeled kedondong samples) for 70°C

Equation (70°C)		χ^2	RMSE	R^2
Newton	$MR=\exp^{-0.14t}$	0.0021	0.0095	0.9948
Page	$MR=\exp^{-0.08t^{1.26}}$	0.0006	0.0050	0.9974
Henderson & Pabis	$MR=1.05\exp^{-0.14t}$	0.0005	0.0045	0.9979
Midilli & others	$MR=0.97\exp^{-0.07t^{1.28}} + 0.001t$	0.0023	0.0095	0.9948
Logarithmic	$MR=0.99\exp^{-0.14t} + 0.001$	0.0023	0.0095	0.9948
Two-term	$MR=0.16\exp^{-0.14t} +0.89\exp^{-0.14t}$	0.0020	0.0086	0.9954
Verma & others	$MR=0.05\exp^{-0.15t} +0.95\exp^{-0.13t}$	0.0004	0.0037	0.9991
Hii et al.	$MR=0.89\exp^{-0.04t^{1.49}} +0.11\exp^{-53.5t^{1.49}}$	0.0003	0.0034	0.9988
Mod. Hii et al. (I)	$MR=0.89\exp^{-0.04t^{1.49}} +0.11\exp^{-54t^{1.49}}$	0.0003	0.0034	0.9988
Mod. Hii et al. (II)	$MR=0.86\exp^{-0.04t^{1.46}} +0.12\exp^{-1.07t^{4.3}} +0.02\exp^{-0.001t^{0.98}}$	*4.00×10^{-5}*	*0.0010*	*0.9999*

Typically, the fitting accuracy of the model was also related to the number of terms used. Prediction by a single term model (e.g. Newton model) was usually less accurate than the double terms model (e.g. Verma model, see Fig. 5 and 6). Modified Hii et al.(I) and (II) models have been applied successfully despite the number of terms involved. The coefficients n, n_1, n_2, and n_3 in the models functioned as a correction factor to further fine-tune the accuracy of prediction, which is quite similar to the Page model.

Table 4. Results of mathematical modelling (unpeeled kedondong samples) for 80°C

Equation (80°C)		χ^2	RMSE	R^2
Newton	$MR=\exp^{-0.23t}$	0.0034	0.0145	0.9924
Page	$MR=\exp^{-0.12t^{1.41}}$	0.0004	0.0052	0.9983
Henderson & Pabis	$MR=1.05\exp^{-0.23t}$	0.0004	0.0047	0.9986
Midilli & others	$MR=0.98\exp^{-0.11t^{1.4}} + 0.001t$	0.0040	0.0145	0.9924
Logarithmic	$MR=1.06\exp^{-0.23t} + 0.001$	0.0040	0.0145	0.9924
Two-term	$MR=0.13\exp^{-0.23t} +0.9\exp^{-0.23t}$	0.0031	0.0124	0.9948
Verma & others	$MR=0.05\exp^{-0.15t} +0.95\exp^{-0.22t}$	0.0017	0.0095	0.9963
Hii et al.	$MR=0.88\exp^{-0.06t^{1.72}} +0.12\exp^{-53.5t^{1.72}}$	*0.0001*	*0.0022*	*0.9997*
Mod. Hii et al. (I)	$MR=0.88\exp^{-0.06t^{1.72}} +0.12\exp^{-53.5t^{1.72}}$	*0.0001*	*0.0022*	*0.9997*
Mod. Hii et al. (II)	$MR=0.23\exp^{-0.001t^{3.61}} +0.75\exp^{-0.19t^{1.25}} +0.01\exp^{-0.38t^{0.88}}$	0.0003	0.0027	0.9995

Table 5. Results of mathematical modelling (peeled kedondong samples) 60°C

Equation (60°C)		χ^2	*RMSE*	R^2
Newton	$MR=\exp^{-0.15t}$	0.0058	0.0166	0.9862
Page	$MR=\exp^{-0.05t^{1.54}}$	0.0011	0.0069	0.9962
Henderson & Pabis	$MR=1.01\exp^{-0.14t}$	0.0007	0.0056	0.9973
Midilli & others	$MR=0.95\exp^{-0.04t^{1.6}} + 0.001t$	0.0065	0.0166	0.9862
Logarithmic	$MR=0.99\exp^{-0.14t} + 0.001$	0.0065	0.0166	0.9862
Two-term	$MR=0.09\exp^{-0.15t} +0.91\exp^{-0.15t}$	0.0055	0.0148	0.9882
Verma & others	$MR=0.1\exp^{-0.16t} +0.9\exp^{-0.14t}$	0.0028	0.0108	0.9934
Hii et al.	$MR=0.89\exp^{-0.23t^{1.83}} +0.11\exp^{-53.8t^{1.83}}$	0.0002	0.0030	0.9992
Mod. Hii et al. (I)	$MR=0.89\exp^{-0.23t^{1.8}} +0.11\exp^{-54^{1.8}}$	0.0002	0.0030	0.9992
Mod. Hii et al. (II)	$MR=0.45\exp^{-0.001t^{3.05}} +0.54\exp^{-0.22t^{0.88}} +0.01\exp^{-0.39t^{1.04}}$	*2x10⁻⁵*	*0.0008*	*0.9999*

Table 6. Results of mathematical modelling (peeled kedondong samples) 70°C

Equation (70°C)		χ^2	*RMSE*	R^2
Newton	$MR=\exp^{-0.19t}$	0.0025	0.0115	0.9948
Page	$MR=\exp^{-0.09t^{1.35}}$	0.0002	0.0034	0.9991
Henderson & Pabis	$MR=1.06\exp^{-0.19t}$	0.0002	0.0030	0.9993
Midilli & others	$MR=0.98\exp^{-0.09t^{1.32}} + 0.001t$	0.0028	0.0115	0.9948
Logarithmic	$MR=0.99\exp^{-0.17t} + 0.001$	0.0028	0.0115	0.9948
Two-term	$MR=0.09\exp^{-0.19t} +0.91\exp^{-0.19t}$	0.0021	0.0095	0.9965
Verma & others	$MR=0.02\exp^{-0.16t} +0.98\exp^{-0.18t}$	0.0010	0.0067	0.9979
Hii et al.	$MR=0.92\exp^{-0.06t^{1.53}} +0.08\exp^{-53.5t^{1.53}}$	7×10^{-5}	0.0017	0.9998
Mod. Hii et al. (I)	$MR=0.92\exp^{-0.06t^{1.53}} +0.08\exp^{-53.5t^{1.53}}$	6×10^{-5}	0.0017	0.9998
Mod. Hii et al. (II)	$MR=0.27\exp^{-0.002t^{2.78}} +0.72\exp^{-0.17t^{1.19}} +0.01\exp^{-0.41t^{0.79}}$	4×10^{-5}	*0.0010*	*0.9999*

Table 7. Results of mathematical modelling (peeled kedondong samples) 80°C

Equation (80°C)		χ^2	*RMSE*	R^2
Newton	$MR=\exp^{-0.27t}$	0.0033	0.0153	0.9928
Page	$MR=\exp^{-0.14t^{1.41}}$	0.0003	0.0047	0.9988
Henderson & Pabis	$MR=1.06\exp^{-0.27t}$	0.0003	0.0044	0.9989
Midilli & others	$MR=0.99\exp^{-0.14t^{1.38}} + 0.001t$	0.0040	0.0153	0.9928
Logarithmic	$MR=0.99\exp^{-0.27t} + 0.001$	0.0040	0.0153	0.9928
Two-term	$MR=0.08\exp^{-0.27t} +0.92\exp^{-0.27t}$	0.0030	0.0126	0.9959
Verma & others	$MR=0.02\exp^{-0.16t} +0.98\exp^{-0.26t}$	0.0016	0.0098	0.9966
Hii et al.	$MR=0.9\exp^{-0.1t^{1.5}} +0.1\exp^{-54.2t^{1.5}}$	*0.0001*	*0.0024*	*0.9997*
Mod. Hii et al. (I)	$MR=0.9\exp^{-0.1t^{1.52}} +0.1\exp^{-54.2t^{1.52}}$	*0.0001*	*0.0024*	*0.9997*
Mod. Hii et al. (II)	$MR=0.13\exp^{-0.002t^{3.89}} +0.85\exp^{-0.19t^{1.21}} +0.01\exp^{-0.39t^{1.04}}$	0.0002	0.0024	0.9997

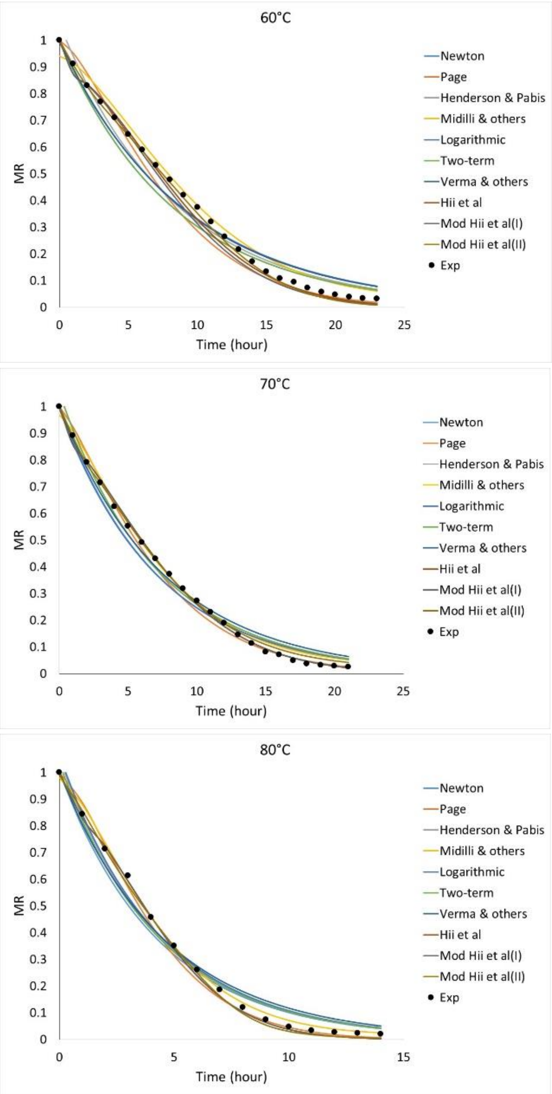

Fig. 5: Comparison between experimental and predicted moisture ratios at 60°C (top), 70°C (middle), and 80°C (bottom) for unpeeled samples

Effective Diffusivity

Table 8 shows effective diffusivities determined from the drying data. Diffusion occurred faster in peeled samples as shown by the higher effective diffusivities (2.36×10^{-11} - 4.01×10^{-11} m^2/s) than peeled samples (1.82×10^{-11} – 3.53×10^{-11} m^2/s). Further comparison with those reported in the literature showed that current studies showed a lower diffusivity value (10^{-11} m^2/s) than what have been reported in the literature (10^{-7} – 10^{-10} m^2/s) (Ee at al. 2019, Yaacob et al. 2019).

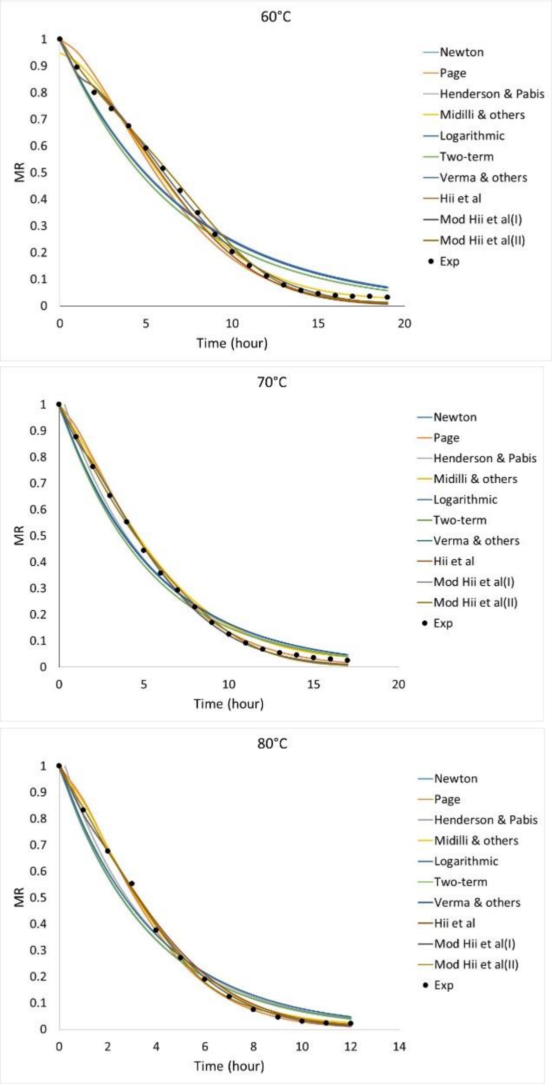

Fig. 6: Comparison between experimental and predicated moisture ratios at 60°C (top), 70°C (middle), and 80°C (bottom) for peeled samples

The difference between the reported value in the literature and in the recent study can be associated with the different origins of the samples and different initial moisture content. Also, the treatments and drying conditions in the literature (e.g. pre-treatment with an osmotic solution and slab geometry) were different from this study.

Nevertheless, the range of effective diffusivities determined falls within the order of magnitudes reported for most food products (10^{-6} – 10^{-12} m^2/s) (Zogzas et al. 1996).

Table 8. Effective diffusivities (D_e) of kedondong fruit samples

	D_e (m^2/s)	
Temperature (°C)	With skin	Without skin
60	1.82×10^{-11}	2.36×10^{-11}
70	2.07×10^{-11}	2.63×10^{-11}
80	3.53×10^{-11}	4.01×10^{-11}
60-80	4.20×10^{-7} - 9.87×10^{-9} (Ee at al. 2019)	
25-70	1.58×10^{-10} - 1.84×10^{-10} (Yaacob et al. 2019)	

Eq. (12) and (13) show temperature dependency of the Arrhenius equations. It shows that the activation energy of the drying of peeled kedondong samples was lower (25.8 kJ/mol) than unpeeled samples (32.1 kJ/mol).

$$D_e(with\ skin) = 1.87 \times 10^{-6} exp^{\frac{-32.1}{RT}} \quad (12)$$

$$D_e(without\ skin) = 8.9 \times 10^{-4} exp^{\frac{-25.8}{RT}} \quad (13)$$

The unpeeled samples formed an additional layer of mass transfer resistance and required a higher activation energy to release moisture.

CONCLUSIONS

Drying kinetics of the hot air drying of unpeeled and peeles kedondong fruit were investigated. Drying kinetics showed that only falling rate periods were observed. Mathematical modeling showed that Modified Hii et al. (I) and (II) models gave an excellent fitting with R^2, $\chi 2$ and RMSE within the range of 0.9992 - 0.9999, 4.0 × 10-5 - 0.0002 and 0.0008 - 0.0025, respectively. Effective diffusivities was observed to be between 1.82×10^{-11} - 4.01×10^{-11} m^2/s, which fell within the range reported in literatures. The activation energy was found to be higher in unpeeled samples (32.1 kJ/mol) due to additional mass transfer resistance that impeded moisture diffusion. Results from this study could provide knowledge and information in optimizing the drying process of kedondong fruit or other food with same properties as kedondong in food processing industry

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