

## Thin-layer Drying Characteristics of Papaya (*Carica papaya*) Peel using Convection Oven and Microwave Drying

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### ABSTRACT

In this study, papaya (*Carica papaya*) peel was dried using convection oven and microwave drying methods to investigate the drying kinetics and the drying behavior in the attempt to search for a feasible way to utilize waste peel. Three different drying temperatures (45, 55, and 65 °C) and microwave powers (250, 440, and 600 W) were applied to dry the papaya peel, wherein the drying data were fitted into the following seven drying

kinetic models: Lewis, Page, Modified Page, Henderson and Pabis, Logarithmic, Two-Term, and Approximation of Diffusion models. The study outcomes indicated that the Page model emerged as the best fitted model for oven drying of papaya peels with the highest coefficient of determination ( $R^2$ ) value (0.994-0.996) for all the three temperatures. As for microwave drying, the Approximation of Diffusion model exhibited the best fit owing to the highest  $R^2$  value (0.996-0.999) for all the three powers. The effective moisture diffusivity values for convection oven and microwave

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drying methods ranged from  $6.65 \times 10^{-08}$  to  $4.35 \times 10^{-07}$  and from  $2.43 \times 10^{-07}$  to  $6.67 \times 10^{-07}$ , respectively. Additionally, the activation energy values were recorded at 61.301 kJ/mol and 46.621 W/g for oven and microwave drying methods, respectively.

*Keywords:* Activation energy, convection oven drying, drying kinetic models, effective moisture diffusivity, microwave drying, papaya peel.

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## INTRODUCTION

Papaya or paw-paw (*Carica papaya*) belongs to the family of Caricaceae. This tropical fruit is cultivated in many countries, including Australia, Hawaii, Philippines, India, and Malaysia, and is native to Tropical America (Anuar et al., 2008; Yogiraj et al., 2015). The global production of papaya on an area of 441,964 ha recorded up to 130,507,749 tons in 2016 (FAOSTAT, 2016). Its popularity is due to the fruit being low in calorie, as well as rich in antioxidant compounds, minerals, fibers, and vitamins C, B, and E (Prajapati et al., 2017). Hence, papaya has been considered as a nutraceutical fruit. Due to its large consumption, papaya results in significant amount of wastes, in terms of peels and seeds.

The by-products constitute 20-25% of papaya fruit weight, which consist of 12% peels and 8.5% seeds (Pavithra et al., 2017b; Medina et al., 2003). Apart from being rich in protein ( $11.67 \pm 0.04\%$ ), total fiber ( $32.51 \pm 0.03\%$ ), carbohydrates ( $47.33 \pm 0.08\%$ ), ash ( $5.98 \pm 0.03\%$ ), fat ( $2.51 \pm 0.13\%$ ), and several minerals, such as potassium ( $516.33 \pm 0.82$  mg/100 g) and phosphorus ( $221.54 \pm 0.85$  mg/100 g) (Martial-didier et al., 2017), papaya peels also contain high phenolic content, hence making them a natural antioxidant (Ang et al., 2012; Jamal et al., 2017). Papaya peels constitute total, soluble, and insoluble dietary fibers with  $59.8 \pm 0.5$ ,  $19.93 \pm 0.01$ , and  $39.9 \pm 0.5$  (g/100), respectively (Calvache et al., 2016). Previous studies have highlighted the use of papaya peel in several food products, including cookies, chapathis, thelpa, and whole wheat bread (Bokaria & Ray, 2016; Pavithra et al., 2017a; Santos et al., 2018; Waghmare & Arya, 2012).

Vast amount of waste is generated due to disposal of fruit peels and seeds without being subjected to further treatment. Besides being hazardous to the environment, the waste has high potential to be used and converted after performing biological treatments into value-added products, raw material for other industries or even as animal feed/fodder. Hence, there is a need to develop such bio-production and recovery processes of these waste that would not only be economical to the agriculture sector, but also exert a positive impact on the environment (Laufenberg et al., 2003). The nutritional components in these by-products can be applied to fortify processed food, which yields a variety of new products, namely jams, jellies, pies, and pastries. As a result, such products are not only nutritionally enriched, but are also packed with more nutrients (Storck et al., 2013).

Preservation of food by cost effective means and hygienic ways can be of importance, especially with the global shortage of food supply (Yaldiz et al., 2001). Drying refers to a method that preserves food, which has been in use since ancient times. This process involves removal of moisture from a product by reducing water activity, and hence, making it preservable over a longer period of time (Omolola et al., 2015). Several benefits of drying process include decrease in water activity leading to retardation of microbial growth and deteriorative reactions, as well as lesser costs of storage and transportation owing to reduced volume and weight occupied by the commodity (Caccavale et al., 2016; Castro et al., 2018). In fact, a substantial number of studies have analyzed papaya peels by focusing on drying using the convection method (Altaf et al., 2015; Koubala et al., 2014; Martialdidier et al., 2017; Santos et al., 2014). However, the influence of temperature upon the drying behavior of the peels is nowhere to be found in the literature.

The most basic principle involved in oven drying method is the transfer of heat energy by convection from the hot air to the product surface (Castro et al., 2018). However, conventional thermal treatments operate at a higher temperature during the falling rate period and have prolonged drying time. This subsequently leads to thermally degraded end-products that are undesirable (Demiray et al., 2017). Due to such reasons, microwave drying method offers an advantage. In microwave, the heat is generated as a result of alternating microwave field affecting the alignment of dipolar water molecules present in materials, and thus generating heat energy (Darvishi, 2012). As a comparison to oven drying, microwave successfully lowers the drying time, as well as provide uniform energy distribution on the material and high final-product characteristics in terms of aroma, color and overall product acceptability (Darvishi et al., 2014; Feng et al., 2012). Another benefit in microwave drying is that the temperature and moisture gradient follow similar directions as opposed to oven drying where the moisture leaves the product against temperature gradient. Thus, the energy absorbed by water molecules is rapid and it evaporates at a quicker rate leading to a shortening of drying time (Doymaz et al., 2015). With that, this present study compared oven and microwave drying method to investigate the drying behavior of papaya peels.

Since there are many challenges when it comes to drying in terms of fruit structure, composition complexity, and biological variability; mathematical modelling serves as a useful tool to overcome such issues. This is especially beneficial for stimulation of temperature, moisture, and velocity distribution, including those variables that possess high temporal and spatial resolution (Abera et al., 2016; Castro et al., 2018; Defraeye, 2014). Heat transfer, mass transfer, thermal conductivity, and specific heat are some of the essential properties that are useful in designing an ideal dryer (Tahmasebi et al., 2011). The common kinetic models applied in this study were Lewis, Page, Modified Page, Henderson and Pabis, Logarithmic, Two-Term, and Approximation of Diffusion models, which have

been used in many past studies that assessed banana peels (Khawas et al., 2014), lemon slices (Torki-Harchegani et al., 2016), pineapples (Ravula et al., 2017), as well as dika nuts and kernels (Aregbesola et al., 2015). Such studies have paved the way for developing various drying models. These equations are crucial to estimate and to obtain both drying times and drying curves (Menges & Ertekin, 2006), which in turn, are essential for food safety, sensory, and nutritional quality (Castro et al., 2018).

Keeping these in mind, this study probed into the drying kinetics of papaya peel using oven and microwave methods. Next, the drying data obtained were compared with the predicted values by using the seven thin-layer drying models. The main objective of this study is focused on selecting the best fit model to accurately describe the effect of thin-layer drying of papaya peels at three various conditions for each drying method. In addition to this, both aspects of effective moisture diffusivity and activation energy were investigated. Lastly, the comparison between the two techniques determined the best method for drying papaya peels.

## **Materials and Methods**

### **Materials**

In this experiment, papayas (*Carica papaya*) were bought from a wet market located in Seri Kembangan, Selangor, Malaysia. A fully ripened fruit of the *Sekaki* variety with an average weight of 1.707 kg was selected for this study. The fruit was washed thoroughly using tap water to remove any surface dirt particles. It was then cut manually using a stainless-steel knife to separate pulp, peel, and seeds. The peels were divided into small portions of 2x2 cm<sup>2</sup> with an average thickness of 3.45 mm. They were rinsed with running water to remove remaining mucilage. Before proceeding with the tests, the initial moisture content was measured with a convection oven (Memmert, Schwabach, Germany) at 105 °C for 24 hours until constant weight was achieved (AOAC, 1995). For each drying process, approximately 10 g of papaya peel sample was used. The experiments were run thrice for each temperature and power intensity.

### **Drying Procedure**

As for the oven drying method, the papaya peels were distributed uniformly on petri plates and placed on a stainless-steel tray (40 x 28 cm). They were loaded into a pre-heated oven (Memmert, Schwabach, Germany) at 45, 55, and 65 °C. Moisture loss of the sample was measured by using a digital balance with ±0.001 g accuracy placed nearby. Weight loss was recorded at every 30 min interval up to 4 h, later at every 1 h interval for the next 5 h, and finally, 5 h intervals until constant weight was achieved. In order to avoid interference with the drying procedure, the sample weight was recorded quickly.

As for the microwave drying method, the papaya peel sample was placed in a petri plate, and then on a turntable fitted inside the microwave cavity (Panasonic microwave model NN-C2003S, Malaysia). The most ideal microwave performance can be obtained with the presence of turntable, which also helps in reducing the amount of microwaves reflected onto the magnetron. The microwave used in the experiment had 242 x 412 x 426 mm cavity dimensions. The microwave was operated at three different power intensities of 250, 440, and 600 W. Moisture loss of the sample was recorded as weight difference for every 1 min interval using a digital balance. The drying process was carried out until no difference was observed between the successive weighing sessions. The weighing of sample was performed rapidly to prevent any disturbance during the drying procedure.

### Drying Kinetics Model

The calculation of moisture ratio (MR) of papaya peels was carried out by converting the experimental drying data obtained (Erdem et al., 2014):

$$\text{MR} = \frac{M_t - M_e}{M_i - M_e} \quad [1]$$

$M_t$ ,  $M_i$ , and  $M_e$  refer to moisture content at time  $t$ , initial moisture content, and moisture content at equilibrium, respectively.

Theoretically, equilibrium state can be reached after an infinite drying time. Hence,  $M_e$  can be neglected for long drying periods as its value is small when compared to  $M_i$  and  $M_t$ . Also, such low values present with complications in microwave heating as the smaller amount of moisture content results in lower dielectric loss and the determination of moisture loss rate becomes difficult (Cui et al., 2004; Darvishi et al., 2014; Holeček & Kohout, 2016). The dimensionless quantity of MR can be, hence, simplified to Equation [2]:

$$\text{MR} = \frac{M_t}{M_i} \quad [2]$$

In order to determine the most appropriate drying equation, the drying data of papaya peels were fitted into seven different thin-layer drying equations (Table 1). SPSS software was applied to perform non-linear regression analysis of the experimental data. Based on the highest coefficient of determination ( $R^2$ ), the best fit mathematical models to the drying data was selected (Fikry & Al-Awaadh, 2016; Rayaguru & Routray, 2012).

### Effective Moisture Diffusivity

Effective moisture diffusivity ( $D_{\text{eff}}$ ) can be estimated from drying curves by applying Fick's second law of diffusion. The equation for one-dimensional slab geometry is given as (Srikiatden & Roberts, 2007):

$$\frac{\partial M}{\partial t} = D_{eff} \left( \frac{\partial^2 M}{\partial^2} + \frac{\eta}{r} \frac{\partial M}{\partial r} \right) \quad [3]$$

Where,  $\eta$  is a constant and is 0 for planar geometry. The initial and boundary conditions are taken as  $M(r,0) = M$ , at  $t = 0$

In this equation, it is assumed that the initial moisture distribution is uniform, moisture migration is by diffusion, while shrinkage, temperature and external resistance is inconsiderable throughout the drying process (Crank, 1975). The peel samples were considered as infinite slab geometry. Therefore, Fick's diffusion equation is as given below:

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

Equation 4 can be expanded as follows for the first three series:

$$MR = \frac{8}{\pi^2} \left( \exp^{-\left(\frac{\pi}{2}\right)^2 N_{Fi}} + \frac{1}{9} \exp^{-9\left(\frac{\pi}{2}\right)^2 N_{Fi}} + \frac{1}{25} \exp^{-25\left(\frac{\pi}{2}\right)^2 N_{Fi}} \right) \quad [5]$$

Where  $N_{Fi}$  denotes Fourier number,  $\frac{D_{eff} \times t}{4L^2}$  and  $L$  represents half thickness of the material. For long drying times, the Fourier number is greater than 0.1 and the unaccomplished moisture ratio is  $< 0.6$ . Therefore, the first term of the series will dominate and the equation can be simplified to Equation 6 (Darvishi, 2012; Darvishi et al., 2014; Srikiatden & Roberts, 2007):

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad [6]$$

Where,  $D_{eff}$  stands for effective moisture diffusivity ( $m^2/s$ ),  $L$  reflects sample thickness (m), and  $t$  is drying time (s).

The above equation can be evaluated for Fourier number (denoted as  $F_o$ ) with numerical value equal to  $\frac{D_{eff} \times t}{4L^2}$ . Equation 6 can be written as (Darvishi et al., 2014; Sharma & Prasad, 2004):

$$MR = \frac{8}{\pi^2} \exp(-\pi^2 F_o) \quad [7]$$

Therefore,

$$F_o = -0.101 \ln(MR) - 0.0213 \quad [8]$$

Effective moisture diffusivity can be determined as follows:

$$D_{eff} = \frac{F_o}{\frac{t}{4L^2}} \quad [9]$$

As an alternative to Equation 9, slope method can also be used to determine  $D_{eff}$  by

a plot of drying data in the form of  $\ln(\text{MR})$  against drying time,  $t$ . This plot results in a straight line and the slope is as follows (Thorat et al., 2012):

$$\text{Slope} = \frac{\pi^2 D_{eff}}{4L^2} \quad [10]$$

### Activation Energy

As for convection oven drying, activation energy ( $E_a$ ) was calculated by using Arrhenius equation, as portrayed in Equation 11, which relates effective moisture diffusivity ( $D_{eff}$ ) with temperature (Mirzaee et al., 2009).

$$D_{eff} = D_o \exp\left(-\frac{E_a}{R(T + 273.15)}\right) \quad [11]$$

Where,  $D_o$  is defined as Arrhenius or pre-exponential factor ( $\text{m}^2/\text{s}$ ),  $E_a$  refers to activation energy ( $\text{kJ/g mol}$ ),  $R$  stands for universal gas constant ( $8.314 \text{ kJ/kg}$ ), and  $T$  reflects drying temperature. The equation was rearranged as follows:

$$\ln(D_{eff}) = \ln(D_o) \left(-\frac{E_a}{R(T + 273.15)}\right) \quad [12]$$

For convection oven drying,  $E_a$  can be obtained from the slope of  $\ln(D_{eff})$  vs  $1/T$  plot (Ravula et al., 2017).

Temperature cannot be precisely applied as a measurable quantity within the drier of a microwave oven. In such cases, the activation energy can be determined by using the modified version of Arrhenius equation (Dadali et al., 2007). With this modified equation,  $E_a$  was assumed to be linked with  $D_{eff}$  and  $m/P$ , which refer to effective moisture diffusivity and ratio of microwave output power to sample mass, respectively, as opposed to the drying temperature in the original equation.

$$D_{eff} = D_o \exp\left(-E_a \frac{m}{P}\right) \quad [13]$$

Where,  $D_o$  is Arrhenius or pre-exponential factor ( $\text{m}^2/\text{s}$ ),  $E_a$  represents activation energy ( $\text{W/g}$ ),  $m$  stands for sample mass ( $\text{g}$ ), and  $P$  refers to microwave output power ( $\text{W}$ ). Equation 13 can be written as follows:

$$\ln(D_{eff}) = \ln(D_o) \left(-E_a \frac{m}{P}\right) \quad [14]$$

As for microwave drying,  $E_a$  was obtained from the slope of  $\ln(D_{eff})$  vs  $m/P$  plot (Bagheri & Kashaninejad, 2018).

## RESULTS AND DISCUSSION

### Drying of Papaya Peels

The plots of MR against the drying time of papaya peels at varied temperature and power values are illustrated in Figure 1a and 1b. The preliminary study showed that microwave



drying at 1000W was not applicable as the papaya peel was burnt and further testing was discontinued. The peels comprised 11-13% of total fruit weight, which is comparable to the composition previously reported (Medina et al., 2003). The initial moisture content of the peels of 91.7% (w.b.) was obtained. Figure 1a and 1b portray that the drying time required to reach the final moisture content in oven was longer, when compared to that obtained from microwave drying. 9.33-9.47% (d.b.) was reached within 8-48 h for oven drying while microwave drying achieved 9.15-9.48 (d.b.) between 8 and 17 min. Microwave drying, thus, resulted in a 98.33-99.40% reduction in drying time to reach the final moisture content. This variance in drying time is very large and highlights the advantage of using the microwave drying method. Prolonged drying by oven may result in undesirable changes in the product. As per previous studies, microwave leads to shortening of drying time when compared to conventional oven and infrared methods (Darvishi et al., 2014).

The results reveal that microwave drying had superior mass transfer efficiency than oven drying. This was especially seen during higher microwave power which generated larger heat inside the sample leading to a creation of huge difference in vapour pressure between the product centre and surface due to volumetric heating in microwave (Darvishi et al., 2013). The main dielectric component in food materials is water which makes them respond well to microwaves. Thus, the absorption of microwave power is faster and more efficient provided that there is residual moisture (Arslan & Özcan, 2010). The initial moisture content of the peels was high during the primary stages of drying process; thus, a higher microwave absorption was seen resulting in a higher drying rate as a result of high moisture diffusion. As the moisture was lost during the process, the microwave absorption was also reduced and the drying occurred in the falling rate period. (Darvishi et al., 2014).

In the case of oven drying, the drying time reduced as the temperature was raised. Drying of agricultural products relies on several essential factors, such as indigenous properties, initial and final moisture contents, as well as drying methods and conditions. With increment in drying temperature, the heat transfer rate also increased between the heating air and the sample. This led to rapid evaporation of moisture and thus, reduction in the duration of drying (Torki-Harchegani et al., 2016). A similar effect was reported for pineapple (Olanipekun et al., 2014) and date fruits (Al-Awaadh et al., 2015).

As for microwave drying, the figure vividly shows that increment in power sped the drying process. In precise, increase in microwave power resulted in considerable reduction in MR. This is attributable to increased drier oven chamber temperature and microwave intensity, which eventually increase microwave power and hence, rapid loss of moisture at higher power rates (Minaei et al., 2012). Similar results for microwave drying effect on drying time were reported for apple pomace (Wang et al., 2006) and onion slices (Arslan & Özcan, 2010).



Drying Kinetics of Papaya Peel

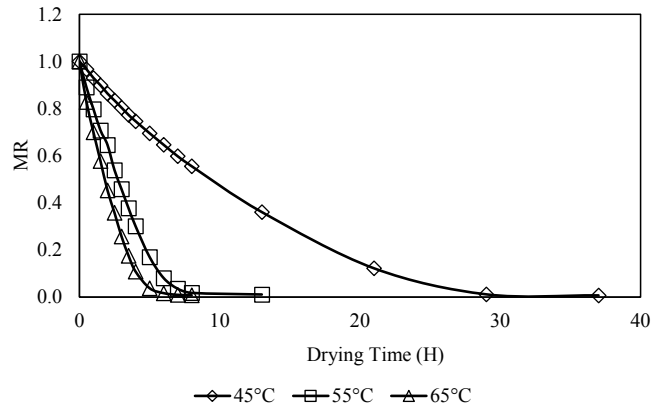


Figure 1a. Plot of moisture ratio (MR) versus drying time (hour) of papaya peel under oven drying

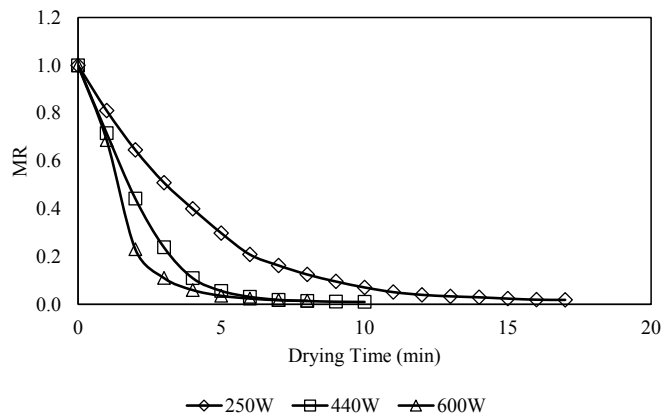


Figure 1b. Plot of moisture ratio (MR) versus drying time (min) of papaya peel under microwave drying

Table 1

*Thin-layer drying models used for drying of papaya peel*

Model	Mathematical Equation	References
Lewis	$MR = \exp(-kt)$	Doymaz (2005)
Page	$MR = \exp(-kt^n)$	Page (1949)
Modified Page	$MR = \exp(-kt)^n$	Yaldiz et al. (2001)
Henderson and Pabis	$MR = a \exp(-kt)$	Doymaz (2004)
Logarithmic	$MR = a \exp(-kt) + c$	Togrul and Pehlivan (2002)
Two-Term Model	$MR = a \exp(-k_0t) + b \exp(-k_1t)$	Rahman et al. (1998)
Approximation of Diffusion	$MR = a \exp(-kt) + (1-a) \exp(-kat)$	Lahsasni et al. (2004)

Table 2  
 Values of model constants for thin-layer drying of papaya peels

Model Name	Coefficients					
	45°C	55°C	65°C	250W	440W	600W
<b>Lewis/ Newton</b>	<i>k</i> 0.081(0.018) 0.988	0.294(0.046) 0.966	0.444(0.031) 0.981	0.244(0.011) 0.996	0.460(0.030) 0.955	0.607(0.027) 0.972
<b>Page</b>	<i>k</i> <b>0.053(0.014)</b> <b>1.198(0.012)</b> <b>0.995</b>	<b>0.181(0.06)</b> <b>1.315(1.42)</b> <b>0.994</b>	<b>0.337(0.017)</b> <b>1.298(0.039)</b> <b>0.996</b>	0.203(0.028) 1.118(0.055) 0.998	0.326(0.034) 1.358(0.124) 0.999	0.414(0.023) 1.633(0.082) 0.993
<b>Modified Page</b>	<i>k</i> 0.567(0.427) 0.38(0.47) 0.988	0.448(0.072) 0.661(0.082) 0.965	0.466(0.014) 0.952(0.041) 0.981	0.338(0.034) 0.724(0.040) 0.996	0.819(0.279) 0.601(0.185) 0.985	1.342(0.892) 0.841(0.878) 0.972
<b>Henderson and Pabis</b>	<i>k</i> 0.086(0.02) 1.053(0.044) 0.990	0.316(0.044) 1.068(0.016) 0.972	0.487(0.008) 1.053(0.002) 0.983	0.250(0.007) 1.028(0.019) 0.997	0.475(0.033) 1.042(0.011) 0.987	0.627(0.026) 1.041(0.003) 0.974
<b>Logarithmic</b>	<i>k</i> 0.075(0.025) 1.092(0.029) -0.075(0.041) 0.994	0.256(0.051) 1.166(0.055) -0.118(0.042) 0.982	0.383(0.037) 1.116(0.004) -0.329(0.408) 0.992	0.240(0.009) 1.036(0.020) -0.014(0.003) 0.997	0.437(0.034) 1.065(0.016) -0.031(0.007) 0.990	0.600(0.024) 1.055(0.003) -0.016(0.001) 0.975
<b>Two-Term</b>	<i>k0</i> 0.086(0.02) 0.086(0.02) 0.494(0.032) 0.538(0.038) 0.990	0.316(0.044) 0.316(0.044) 0.533(0.009) 0.535(0.009) 0.972	0.465(0.035) 0.465(0.035) 0.637(0.1) 0.412(0.094) 0.984	0.244(0.018) 0.224(0.018) 0.512(0.010) 0.516(0.015) 0.997	0.475(0.033) 0.475(0.033) 0.520(0.007) 0.521(0.005) 0.987	0.627(0.026) 0.627(0.026) 0.524(0.004) 0.518(0.007) 0.974
<b>Approximation of Diffusion</b>	<i>k</i> 0.127(0.037) 1.736(0.021) 0.993	0.448(0.047) 1.896(0.074) 0.991	0.632(0.054) 1.817(0.036) 0.995	<b>0.307(0.008)</b> <b>1.616(0.119)</b> <b>0.999</b>	<b>0.676(0.080)</b> <b>1.916(0.134)</b> <b>0.999</b>	<b>1.082(0.060)</b> <b>2.326(0.076)</b> <b>0.996</b>

### Mathematical Modelling

The MRs calculated from oven and microwave drying methods for papaya peels were fitted into seven thin-layer drying models, as displayed in Table 1. The resulting statistical regression of the models, along with the drying model constants and the coefficient of determination ( $R^2$ ) that assessed the goodness of fit, is shown in Table 2. The proposed model for all oven temperatures and microwave powers resulted in average values of  $R^2$  ranging from 0.965 to 0.996 and from 0.955 to 0.999, respectively. The Page model emerged as the best fit for the oven drying method due to the highest value of coefficient of regression (0.996) (Figure 2a). Meanwhile, the Approximation of Diffusion revealed to be the best fit with 0.999 regression coefficient for the microwave drying method (Figure 2b). These results are comparable with those obtained from drying of green beans ( $R^2 = 0.9992\text{--}0.9994$ ) reported by Doymaz (2005) and Quercus fruit ( $R^2 = 0.9807\text{--}0.9995$ ) by Tahmasebi et al. (2011).

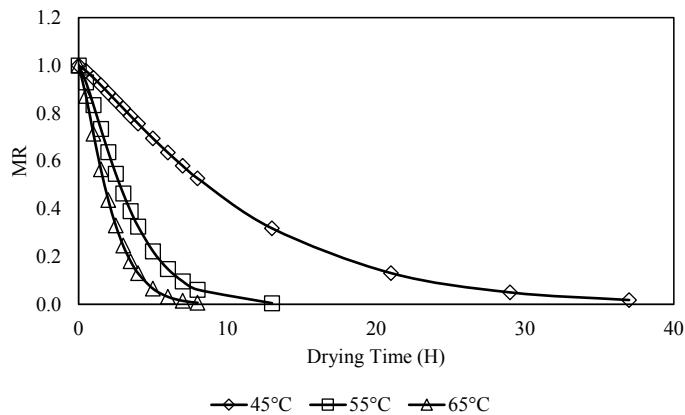


Figure 2a. Plot of moisture ratio (MR) versus drying time (hour) in Page Model under oven drying

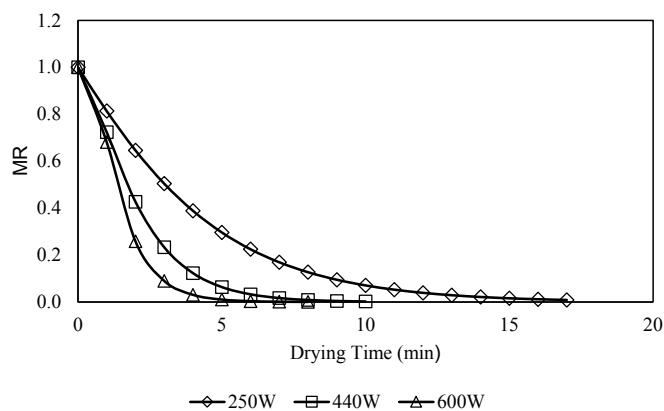


Figure 2b. Plot of moisture ratio (MR) versus drying time (min) in Approximation of Diffusion Model under microwave drying

### Effective Moisture Diffusivity

The effective moisture diffusivity ( $D_{eff}$ ) is illustrated in Figure 3a and 3b in a plot of  $\ln(MR)$  against drying time. The resulting values of  $D_{eff}$  given in Table 3 are within the range of  $10^{-11}$  until  $10^{-6}$  for agricultural products, as reported in prior studies on lemon slices (Torki-Harchegani et al., 2016) and garlics slices (Madamba et al., 1996). The effect of  $D_{eff}$  for the two drying methods is projected in terms of intensity graph (Figure 4). Each drying method was studied at three intensity levels: low, medium, and high, as represented by 1, 2, and 3, respectively. The low levels are denoted by 45°C and 250 W, medium levels by 55°C and 440 W, and high levels by 65°C and 600 W. This figure shows that the  $D_{eff}$  for microwave was higher at all intensity levels, when compared to that of oven drying. This high effective moisture diffusivity indicates that the movement of moisture within the sample was faster, which in turn, resulted in shorter drying time to hit the final moisture content. This subsequently reduced drying time and can save energy and minimize processing costs. Thus, microwave drying at 600 W can be considered as an appropriate drying technique. Similar results were obtained for oven and microwave drying methods comparison with Ahmad et al. (2017), Arslan and Özcan (2010) and Demiray et al. (2017).

The highest diffusivity value obtained from oven drying was recorded at 65°C, while the lowest was at 45°C. In precise, moisture diffusivity increased as the temperature of drying air was hiked. This may be due to the more prominent absorption of moisture, which increased the moisture gradient between the sample and the surrounding air conditions (Mirzaee et al., 2009). Hence, it can be concluded that the aspect of effective moisture diffusivity increased as the drying air temperature increased, as similarly reported for berberis fruit (Aghbashlo et al., 2008) and kachkal banana peels (Khawas et al., 2014).

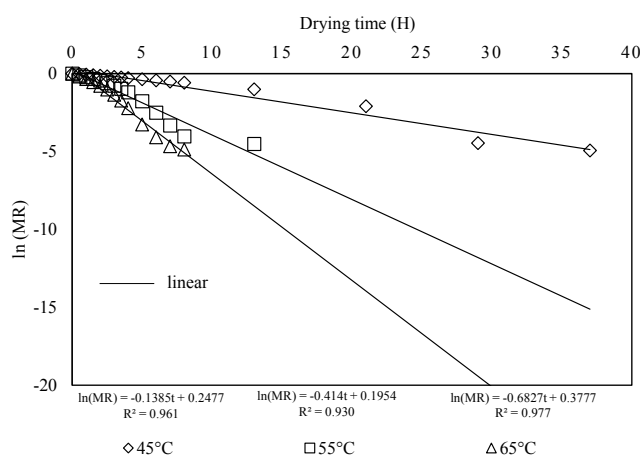


Figure 3a. Plot of  $\ln(MR)$  versus drying time at various drying temperatures

Drying Kinetics of Papaya Peel

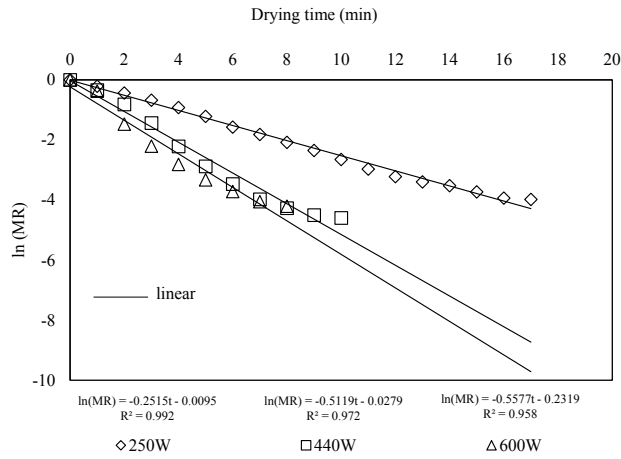


Figure 3b. Plot of ln(MR) versus drying time at various microwave powers

Table 3

Effective moisture diffusivity of papaya peels

Temp(°C)/Power (W)	$D_{eff}$ (m <sup>2</sup> /s)
45	$6.65 \times 10^{-08}$
55	$2.75 \times 10^{-07}$
65	$4.35 \times 10^{-07}$
250	$2.43 \times 10^{-07}$
440	$4.67 \times 10^{-07}$
600	$6.67 \times 10^{-07}$

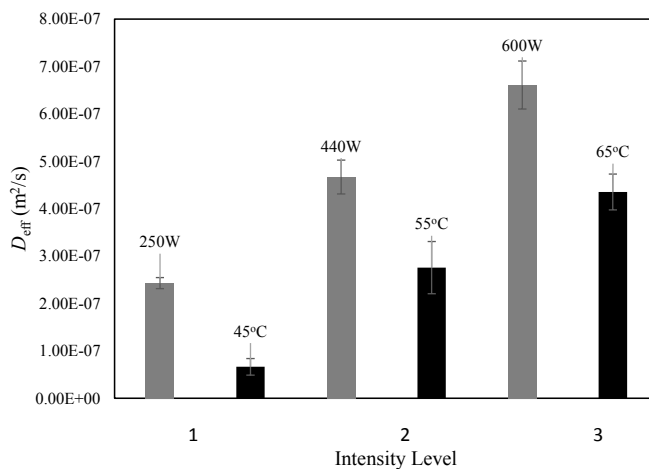


Figure 4. Effect of drying methods on effective moisture diffusivity at three level of intensity 1, 2 and 3; low, medium and high intensity, respectively

In microwave drying, the highest diffusivity value was obtained at 600 W, while the lowest was at 250 W. This increase in moisture diffusivity with the rise in microwave power can be justified by the increased heating energy. Higher heating energy subsequently increased water molecule activity, which led to greater moisture diffusivity as the samples were dried at higher microwave power (Demiray et al., 2017). Similar trend was also reported for drying of pineapple (Olanipekun et al., 2014) and apple pomace (Wang et al., 2006).

### Activation Energy

Activation energy ( $E_a$ ) can be defined as the minimum quantity of energy required to initiate diffusion of moisture from the internal areas of a product. It cannot be used to compare the two drying methods as  $E_a$  is associated to temperature in case of oven drying and to ratio of power output to sample mass for microwave drying. This could be due to the various mechanisms adhered by each drying technique. Hence, it is an unsuitable parameter to identify the appropriate drying method for papaya peels. Nevertheless, it can still be used to compare within similar drying method.

The plot of logarithmic for  $\ln(D_{eff})$  versus  $1/T$  was drawn to obtain activation energy ( $E_a$ ), as portrayed in Figure 5a. Based on the outcomes, a linear relationship was derived from the Arrhenius-type equation with the value of  $E_a$  being 61.301 kJ/mol. This value falls within the range between 12.7 and 110 kJ/mol for most food materials (Zogzas et al., 1996). The results appear to be similar with the reported values found in the literature, such as 60.08 kJ/mol for lemon slices (Torki-Harchegani et al., 2016), as well as 52.275 and 52.859 kJ/mol for sweet and sour pomegranate arils, respectively (Minaei et al., 2012). The activation energy obtained, however, seemed lower than that recorded for berberis fruit with 110.837-130.61 kJ/mol (Aghbashlo et al., 2008).

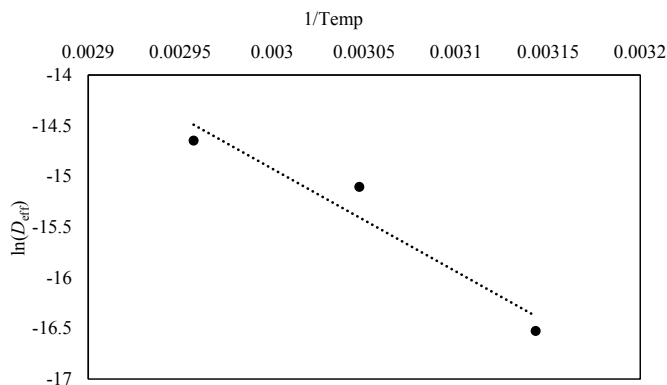


Figure 5a. Plot of  $\ln(D_{eff})$  versus reciprocal of temperature

$E_a$  obtained from the plot for logarithmic of moisture diffusivity vs sample weight/power level ( $m/P$ ) is illustrated in Figure 5b. The outputs signify a linear relationship owing to the modified Arrhenius-type exponential equation dependence. The observed  $E_a$  value in this study was 46.621 W/g. The results obtained are comparable with 45.05 W/g for rambutan seed (Ahmad et al., 2017) and lower than 21.6 W/g for mango ginger (Murthy & Manohar, 2012).

In both the drying methods, the resulting higher activation energy reflected that more energy was required to break the moisture bonds, which retarded moisture velocity and extended drying process (Ahmad et al., 2017).

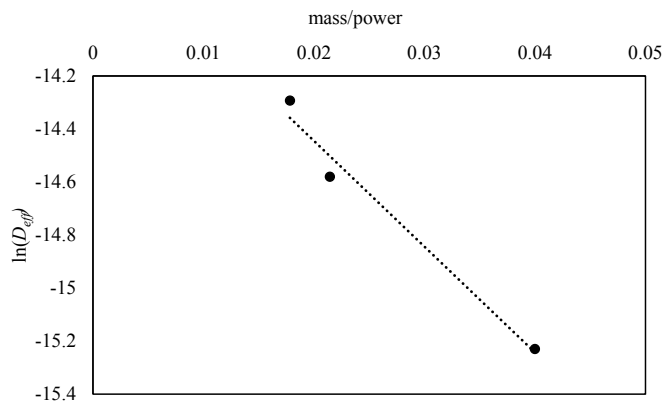


Figure 5b. Plot of  $\ln(D_{\text{eff}})$  versus mass/power

## CONCLUSION

Convection oven drying of papaya peels at 45, 55, and 65 °C and microwave drying at 250, 440, and 600 W was performed to analyze the thin-layer drying characteristics. Seven drying models were applied to describe the drying kinetics of the papaya peel. Among the models examined, the Page model exhibited the best results with the highest  $R^2$  value of 0.996 for oven drying. The highest effective moisture diffusivity was  $4.35 \times 10^{-7}$  at 65 °C, while the lowest was  $6.65 \times 10^{-8}$  at 45 °C. Activation energy was recorded at 61.301 kJ/mol for this method. In the microwave drying technique, the Approximation of Diffusion model resulted in the highest  $R^2$  value (0.999). The effective moisture diffusivity observed at 600 W ( $6.67 \times 10^{-7}$ ) was the highest, whereas 250 W ( $2.43 \times 10^{-7}$ ) was the lowest. Activation energy of 46.621 W/g was also obtained for the microwave method. By comparing the drying times and the effective moisture diffusivity of papaya peels using the two drying methods, the microwave drying technique at 600 W emerged as the most appropriate technique.



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