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Characterization of microwave vacuum-dried durian chips

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ABSTRACT

Durian CV. Monthong was subjected to microwave vacuum drying (at 13.33 kPa) to produce durian chips. Various levels of microwave power (3.88 W g^{-1}, 5.49 W g^{-1} and 7.23 W g^{-1}) were used. Prior to the microwave vacuum drying, the sliced durian was either chilled at 4 °C or frozen at −18 °C. Both pretreatments yielded non-significant difference in dissipation factor ($p > 0.05$). Among several thin layer models, the Page model was found to be the best for explaining the drying characteristics of durian chips. An increase in the microwave power intensity produced a clear increase in the drying rate and did not affect lightness and yellowness of the durian chips ($p > 0.05$). The structure and hardness of the dried durian chips were comparable to that of conventionally fried durian chips. In addition, microwave vacuum drying reduced the fat content of the durian chips by at least 90%, compared with conventionally deep fried durian chips.

1. Introduction

Durian (*Durio zibethinus Murr)* is a tropical fruit grown widely in Southeast Asia (Subhadrabandhu and Ketsa, 2001). It is nutritionally rich in carbohydrates, protein, fat, phosphorous, iron and vitamin A. To overcome the problem of oversupply during the harvesting season, various value-added durian products have been developed. Durian chips are one of the most popular durian products, made conventionally by deep frying. Based on health issues, fried durian chips may not be accepted by some consumers (Jamradloedluk et al., 2007).

Drying is one of the alternative methods to produce oil-free snack products. However, conventional hot air drying produces poor quality chips that have problems associated with shrinkage, dark color and hard texture. To improve the quality of the dried products and the process efficiency, microwave vacuum drying could be used (Figiel, 2009). As microwaves can penetrate deep into food material, the entire food product is heated up quickly from the inside to the outside. As a result, rapid water evaporation and the outward flux of escaping vapor are noticeable. Therefore, a possible reduction in the drying time has been suggested (Hu et al., 2006). Giri and Prasad (2007) reported a reduction of 70–90% in the drying time of mushrooms, when hot air drying was replaced with microwave vacuum drying. In addition, Therdthai and Zhou (2009) observed an increase in the drying kinetic rate constant with increased microwave power intensity. Therefore, the drying time of mint leaves was reduced from 2 h in a conventional hot air drier at 60–70 °C to 15 min in a microwave vacuum drier.

Decreasing the pressure during microwave heating reduced the boiling point of water and thereby the drying temperature (Durance et al., 2002). In addition, there was a possible decrease in the number of burning spots (Zhang et al., 2007). Microwave drying should be suitable for drying heat-sensitive materials, such as fruit and vegetables (Hu et al., 2006). Several studies reported that the color of microwave vacuum-dried products was superior to that of hot air-dried products, such as potatoes (Bondaruk et al., 2007), honey (Cui et al., 2008) and mint leaves (Therdthai and Zhou, 2009).

Moreover, microwave vacuum drying can be used to create a desirable, crispy texture for dried foods that can be consumed without the need for rehydration, such as snack foods. The crispy texture was obtained by tissue consisting of air cavities surrounded by a brittle structural phase (Scaman and durance, 2005). Sham et al. (2001) found that a decrease in the chamber pressure during drying increased the puffing and crispness of apple chips. Likewise, Zhang et al. (2007) reported improved puffing and crispness in fish slides, when the pressure was reduced.

A number of authors (Kompany et al., 1993; Arévalo-Pinedo et al., 2004) suggested that prior to drying, physical pretreatments (such as freezing, chilling or blanching) of solid food materials could be used as a method to modify the food structure and thereby affect the drying kinetics. Arévalo-Pinedo and Murr (2006) investigated the kinetics of vacuum drying pumpkin samples that had been pretreated by freezing and blanching. The freezing played a more significant role than the blanching did on the rate of moisture transfer in the samples. However, both pretreatments improved the heat transfer coefficient, compared with untreated samples.

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Chilling is a unit operation, in which the temperature of a material is dropped to between 1 and 8 °C, while freezing is a unit operation, in which the temperature of a material is decreased below its freezing point and the water state is changed to form ice crystals (Fellows, 2000). The formation of ice crystals could reduce the mobility of water molecules in the frozen material and thereby may affect dipole rotation during the microwave heating. In order to determine the effect of a pretreatment before microwave drying on heat generation, the dielectric properties of pretreated samples, including the dielectric constant (representing the capability to absorb microwave energy) and the loss factor (representing the capability to convert absorbed energy into heat) should be taken into account (Lidstrom et al., 2001). The loss tangent is the ratio of the loss factor to the dielectric constant and can be used to describe how well materials can be penetrated by an electrical field and dissipate the energy as heat (Trabelsi et al., 1998).

As above mentioned, microwave vacuum drying has the potential to improve the quality of dried foods. Therefore, the current paper aimed to determine the characteristics of microwave vacuum drying of durian chips which had been pretreated by either freezing or chilling. The texture, color and fat content were compared with conventionally fried durian chips.

2. Material and methods

Durian CV. Monthong was purchased from a local market and sliced by a slicer (OMAS GF 250) to approximately 1.5 mm thickness. The sliced durian was pretreated using three conditions: (1) control (untreated); (2) chilling to 4 °C; and (3) freezing to −18 °C. The control, chilled and frozen durian slices (150 g per batch) were dried using a microwave vacuum drier (previously described in Therdthai and Zhou (2009)). A microwave vacuum oven (MarchCool, Thailand) was operated at three levels of microwave power using the IMPI 2-Liter test (Buffler, 1993). The oven was operated at its rated line voltage with a load of 2000 ± 5 g placed in two 1-L beakers (Pyrex 1000) at an initial water temperature of 20 ± 2 °C. The beakers were placed in the center of the oven. The oven was turned on for 2 min and 2 s. Then, the beakers were removed from the oven. The final temperatures were measured and recorded. The power was calculated from (Eq. (1)) (Buffler, 1991):

$$P(W) = 70 \times \frac{(\Delta T_1 + \Delta T_2)}{2} \quad (1)$$

where $P(W)$ = microwave power. ΔT_1 and ΔT_2 = temperature rise of the water in the first and second beakers, respectively, calculated by subtracting the initial water temperature from the final temperature.

In the current study, the microwave vacuum oven was operated at three levels of microwave power, being 582, 824, 1085 W, which were equal to a microwave intensity of 3.88 W g^{-1} (MV3.88), 5.49 W g^{-1} (MV5.49) and 7.23 W g^{-1} (MV7.23), respectively. The pressure and frequency were controlled at 13.33 kPa and 2450 MHz, respectively.

2.1. Dielectric property measurement

The dielectric constant (ε') and the loss factor (ε'') of durian fruit were measured by an open-ended coaxial probe (Dielectric measurement kit V.2.1.0.; Püschner, Schwanewede, Germany). A network analyzer was used to analyze the signal of the dielectric properties. The measurements were conducted using 6.0 × 4.0 × 2.5 cm^3 durian pieces. All measurements were carried out in duplicate.

The dielectric constant describes the ability of a material to store electrical potential energy under the influence of an electric field, while the loss factor quantifies the efficiency with which the absorbed energy is converted into heat (Sosa-Morales et al., 2010). The ratio of the loss factor to the dielectric constant is defined as the dissipation factor or loss tangent (tan δ) as presented in (Eq. (2)):

$$tan\delta = \frac{\varepsilon''}{\varepsilon'} \quad (2)$$

This allows a comparison of the power lost to the power stored and can be used to describe the material loss (Al-Muhtaseb et al., 2010)

The penetration depth, D_p, the distance at which the microwave power drops to $1/e$ (e = 2.718) or 36.8% of the transmitted value of its surface value, is an important parameter in characterizing microwave heating. It is generally related to temperature distribution in microwave heating (Ahmed et al., 2007). D_p can be calculated using (Eq. (3)) (Sosa-Morales et al., 2010):

$$D_p = \frac{\lambda_0\sqrt{\varepsilon'}}{2\pi\varepsilon''} \quad (3)$$

where λ_0 = the free space microwave wavelength (for 2.45 GHz. λ_0 = 12.2 cm.)

2.2. Drying characterization

For each drying condition, 14 bulks of durian slices (150 g per bulk) were prepared to dry in the microwave vacuum dryer. The first bulk of slices were brought to determine initial moisture content of durian slices. The second bulk was dried for 1 min to represent the change of moisture content after drying for 1 min. The third bulk was dried for 2 min continuously to represent change of moisture content after drying for 2 min. Similarly, others bulks would be dried continuously for 3, 4, 5,..., 12 min to represent change of moisture content after drying for 3, 4, 5,..., 12 min, respectively. Finally, the last bulk was dried continuously for 13 min to represent change of moisture after whole drying process. The moisture content of the microwave vacuum-dried durian chips was analyzed using the AOAC method (AOAC, 2000). The change in moisture during drying was expressed as a moisture ratio defined by (Eq. (4)):

$$\text{Moisture ratio} = \frac{X_i - X_e}{X_0 - X_e} \quad (4)$$

where X_0 and X_i = the moisture content (kg water kg dry solid^{-1}) at initial time 0 and time I, X_e = the equilibrium moisture content (kg water kg dry solid^{-1}).

The kinetics of the moisture ratio during microwave vacuum drying was simulated using thin layer models are follows:

Lewis model (Ayensu, 1997):

$$MR = \exp(-kt) \quad (5)$$

Page model (Karathanos and Belessiotis, 1999):

$$MR = \exp(-kt^n) \quad (6)$$

Henderson and Pabis (Henderson and Pabis, 1961):

$$MR = a\exp(-kt) \quad (7)$$

Modified. Henderson and Pabis (Karathanos, 1999):

$$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht) \quad (8)$$

Logarithmic (Yaldiz et al., 2001):

$$MR = a\exp(-kt) + c \quad (9)$$

Two-Term model (Togrul and Pehlivan, 2002):

$$MR = a\exp(-kt) + c\exp(-gt) \quad (10)$$

Wang and Singh (Wang and Singh, 1987):

$$MR = 1 + at + bt^2 \quad (11)$$

where: k, n, a, b, c, g and h = the model constants, t = the drying time (min).The goodness of the correlation coefficient (r), root mean square error (RMSE) and chi-square ($\chi 2$) between the modeled moisture ratio and the experimental data were used to determine each model's performance. In addition, residual plots were also provided.

Table 1
Dielectric property (mean ± standard error) of durian samples.

Pretreatment	Dielectric constant	Dielectric loss factor	Loss tangent	Penetration depth (cm)
Control	23.96[b] ± 0.24	7.83[b] ± 0.04	0.33[a] ± 0.00	1.21[b] ± 0.01
Chilling	26.49[a] ± 0.54	8.83[a] ± 0.05	0.33[a] ± 0.01	1.13[b] ± 0.01
Freezing	11.53[c] ± 0.40	3.62[c] ± 0.18	0.31[a] ± 0.00	1.82[a] ± 0.06

[a–c] = significant ($p \leqslant 0.05$) difference within the same column.

2.3. Effective moisture diffusivity of durian slices

The effective diffusivity, D_{eff} was determined using the analytical solution of Fick's second law (Coulson et al., 1987). Based on Fick's law and the assumptions of: (1) symmetric mass transfer with respect to the centre; (2) a constant diffusion coefficient; and (3) no shrinkage, the effective moisture diffusivity of water in the durian chips was estimated from the change in the moisture ratio and the drying time using the modified Crank's equation shown in (Eq. (12)) (Singh and Heldman, 2001; Therdthai and Zhou, 2009)

$$\frac{X_i X_e}{X_0 - X_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left(-\frac{(2n-1)^2\pi^2 D_{\text{eff}}}{4L^2}.t\right) \quad (12)$$

where D_{eff} = the effective moisture diffusivity (m^2 s^{-1}), L = the half thickness of the durian chips (0.75×10^{-3} m), t = drying time (s), X_i = the moisture content (kg water kg dry solid^{-1}) at time i, X_e = the equilibrium moisture content (kg water kg dry solid^{-1}).

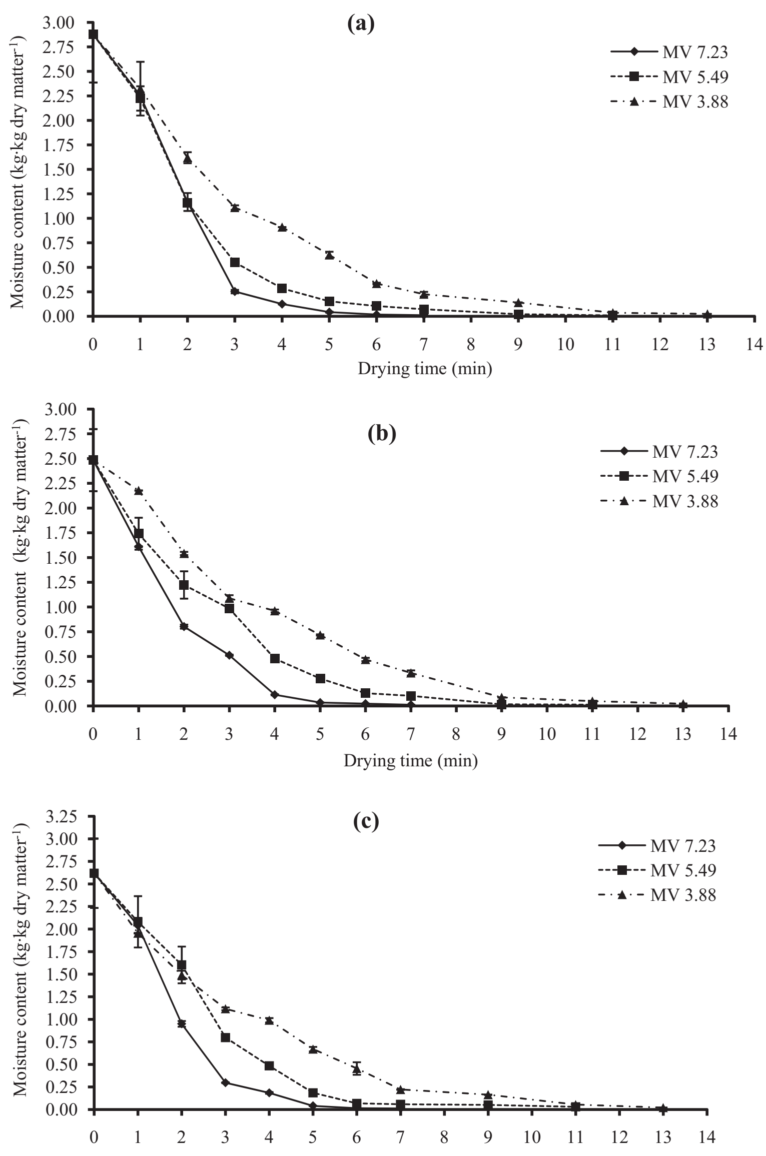

Fig. 1. Change of moisture content during microwave vacuum drying with pretreatment prior to drying by: (a) control; (b) chilling; and (c) freezing.

2.4. Color of durian chips

The color of the durian chips was determined using a spectrophotometer (Minolta CM-3500d; Konica Minolta Holdings Inc., Tokyo, Japan). By reflectance, the CIELAB parameters (L^*, a^* and b^*) were obtained using a D65 illuminant at 10° observation.

2.5. Structural characteristics of durian chips

The structures of commercially fried durian chips and the microwave vacuum dried durian chips prepared using various pretreatment methods and drying conditions were investigated by scanning electron microscope (SEM). The cross-section of the samples was sputter-coated with gold and determined with a scanning electron microscope (JEOL, JSM 5600LV, Tokyo, Japan). Magnification was adjusted to 100×.

2.6. Hardness of durian chips

The hardness of the dried durian chips and of commercially fried durian chips was measured using a texture analyzer (TA500; Lloyd Instruments Ltd., Hampshire, UK) with two replications. Each chip was placed on a hollow planar base. A ball probe (0.5 mm diameter) was used with a speed of 5 mm s^{-1}. The compression force was recorded.

2.7. Fat content of durian chips

Approximately 2 g of microwave vacuum dried samples and commercially fried samples were weighted into thimbles for solvent extraction (using petroleum ether). Fat extraction was carried out using a Soxtec System (Foss Soxtec System Model 2050; Foss Analytical AB, Hoganas, Sweden).

2.8. Statistical analysis

Experimental data were analyzed using analysis of variance (ANOVA) in the statistical package SPSS® version 12.0 (SPSS (Thailand) Co., Ltd., Bangkok, Thailand). Duncan's multiple range tests was used to establish the multiple comparisons of mean values. Mean values were considered significantly different at the 95% confidence level ($p \leqslant 0.05$).

3. Results and discussion

3.1. Dielectric properties of durian

In microwave heating, the dielectric constant describes the ability of a material to store electrical potential energy under the influence of an electric field, while the loss factor quantifies the efficiency with which the absorbed energy is converted into heat (Sosa-Morales et al., 2010). Table 1 presents the dielectric properties of samples of untreated durian and pretreated durian (chilled and frozen durian). The dielectric constant and the loss factor decreased when the samples were frozen, because of the confined ice crystal structure in the material. Therefore, the mobility of the water molecules in the frozen material was reduced, compared with fresh and chilled material. The tightly bound water molecules affected dipole rotation, and as a result, there was decreased ability of the material to absorb microwave energy and convert it into heat (Yam et al., 2004). Compared to the control, chilling caused a rise in the dielectric constant from 23.96 to 26.49. The loss factor increased also, from 7.83 to 8.83, because at low temperature more energy was required to overcome the intermolecular bond (Sahin and Sumnu, 2006). Similar trends have been observed in other foodstuffs, such as garlic (Sharma et al., 2002), salmon fillets (Wang et al., 2008) and potato puree (Seyhun et al., 2009).

When the microwaves penetrated the material, their power was weakened, because some of the energy was absorbed by the material. The penetration depth (D_p) is the distance required to decrease the energy to 36.8% of its energy at the surface. Therefore, it can describe how well a material absorbs microwaves. Normally, a reduced penetration depth indicates an increase in the ability of a material to absorb microwave energy (Yam et al., 2004). In the current study, freezing significantly ($p \leqslant 0.05$) increased the penetration depth in the durian chips, compared with the control and chilling. This was possibly because ice in frozen material was less effective in absorbing microwaves than the water in unfrozen material. The results coincided with those reported by Yam et al. (2004). The loss tangent of untreated and pretreated durian samples was not significantly ($p > 0.05$) different, indicating that the

Table 2
Model parameters and performance of the thin layer models of durian slices without pretreatment. (r = the goodness of the correlation coefficient, RMSE = root mean square error and χ^2 = chi-square).

Drying condition	Model	Parameter	RMSE	r	χ^2
MV 3.88	Lewis	$k = 0.4032$	0.0721	0.9884	0.0057
	Page	$k = 0.2214$, $n = 1.2733$	0.0192	0.9983	0.0005
	Henderson and Pabis	$k = 0.4587$, $a = 1.4856$	0.1551	0.9793	0.0294
	Mod. Henderson and Pabis	$k = 0.1539$, $a = 4.3774$, $b = -4.4251$, $c = 1.0649$, $g = 0.0979$, $h = 0.0376$	0.0198	0.9981	0.0009
	Logarithmic	$k = 0.2923$, $a = 1.0723$, $c = -0.0434$	0.0239	0.9972	0.0008
	Two-Term model	$k = 0.2117$, $a = 5.0569$, $c = -4.0319$, $g = 0.1909$	0.0219	0.9977	0.0008
	Wang and Singh	$a = -0.2114$, $b = 0.0107$	0.0449	0.9917	0.0025
MV 5.49	Lewis	$k = 0.5779$	0.072	0.9841	0.0058
	Page	$k = 0.3213$, $n = 1.3401$	0.0294	0.9966	0.0011
	Henderson and Pabis	$k = 0.6086$, $a = 1.2017$	0.0753	0.9812	0.0071
	Mod. Henderson and Pabis	$k = 0.2282$, $a = 5.3790$, $b = -6.3817$, $c = 2.0454$, $g = 0.1516$, $h = 0.0869$	0.0410	0.9926	0.0042
	Logarithmic	$k = 0.4574$, $a = 1.0866$, $c = -0.0344$	0.0484	0.9897	0.0033
	Two-Term model	$k = 0.3194$, $a = 6.5771$, $c = -5.5278$, $g = 0.2947$	0.0448	0.9912	0.0034
	Wang and Singh	$a = -0.2817$, $b = 0.0181$	0.0804	0.9741	0.0081
MV 7.23	Lewis	$k = 0.8966$	0.1564	0.9340	0.0278
	Page	$k = 0.2672$, $n = 1.7966$	0.0228	0.9983	0.0007
	Henderson and Pabis	$k = 1.0412$, $a = 1.8711$	0.3167	0.9122	0.1337
	Mod. Henderson and Pabis	$k = 0.0837$, $a = 8.5593$, $b = -14.2696$, $c = 6.7563$, $g = -0.0045$, $h = -0.0558$	0.0565	0.9884	0.0128
	Logarithmic	$k = 0.4395$, $a = 1.1694$, $c = -0.1087$	0.0742	0.9798	0.0088
	Two-Term model	$k = 0.2957$, $a = 6.7611$, $c = -5.6993$, $g = 0.2633$	0.0706	0.9819	0.0099
	Wang and Singh	$a = -0.3690$, $b = 0.0328$	0.0591	0.9883	0.0046

inherent dissipation of electromagnetic energy was not affected by the pretreatment prior to the drying.

3.2. Drying characteristics during microwave vacuum drying

Changes in the moisture content of the durian slices during microwave vacuum drying are presented in Fig. 1. At the beginning of drying, the moisture content of the durian chips reduced quickly. The drying kinetics of the durian slices was similar, regardless of the pretreatment method prior to drying. This was due to the non-significant difference in the loss tangent of the samples ($p > 0.05$). Thus, the efficiency for converting the microwave energy into thermal energy was similar, so the drying rate for the durian slices was not different. However, increasing the microwave power intensity from 3.88 to 7.23 W g^{-1} enhanced the moisture reduction. This agreed with other studies, including those on mushrooms (Giri and Prasad, 2007), apple pomace (Wang et al., 2007), spinach (Ozkan et al., 2007) and beetroot (Figiel, 2010). Therefore, the drying times required to reduce the moisture content to less than 0.1 kg water kg dry solid^{-1} were 7, 9 and 11 min for microwave vacuum drying with microwave power levels of 7.23 W g^{-1}, 5.49 W g^{-1} and 3.88 W g^{-1}, respectively.

When the durian slices were exposed initially to the microwave heating, an increased drying rate was observed, possibly due to a fast rise in the sample's temperature to reach water boiling point. This was due to rapid heating by the microwaves. A similar effect with microwave heating under vacuum conditions on the rate of moisture change was found in the drying of mushroom slices (Giri and Prasad, 2007) and mint leaves (Therdthai and Zhou, 2009). The change in the moisture content slowed down later, when the moisture content had decreased, because the dielectric constant of food samples tends to decrease as the moisture content decreases (Scaman and durance, 2005). When the moisture content of the durian samples was reduced to 0.75 kg water kg dry solid^{-1}, the rates of moisture change in the durian slices from the various pretreatments and microwave power levels were similar. This

Table 3
Model parameters and performance of the thin layer models of durian slices pretreated by chilling. (r = the goodness of the correlation coefficient, RMSE = root mean square error and χ^2 = chi-square).

Drying condition	Model	Parameter	RMSE	r	χ^2
MV 3.88	Lewis	k = 0.3533	0.0906	0.9829	0.0090
	Page	k = 0.1508, n = 1.3992	0.0324	0.9955	0.0013
	Henderson and Pabis	k = 0.4587, a = 1.4856	0.1635	0.9592	0.0327
	Mod. Henderson and Pabis	k = 0.1137, a = 4.7221, b = −3.8664, c = 0.1692, g = 0.0767, h = −0.0562	0.0280	0.9964	0.0017
	Logarithmic	k = 0.2342, a = 1.1178, c = −0.0791	0.0314	0.9955	0.0014
	Two-Term model	k = 0.1654, a = 4.8133, c = −3.7782, g = 0.1439	0.0299	0.9959	0.0014
	Wang and Singh	a = −0.1898, b = 0.0089	0.0345	0.9946	0.0015
MV 5.49	Lewis	k = 0.5614	0.0980	0.9747	0.0107
	Page	k = 0.2972, n = 1.2864	0.0349	0.9948	0.0015
	Henderson and Pabis	k = 0.6693, a = 1.9056	0.3035	0.9564	0.1151
	Mod. Henderson and Pabis	k = 0.1527, a = 5.6234, b = −5.2312, c = 0.6013, g = 0.1041, h = −0.0031	0.0227	0.9976	0.0013
	Logarithmic	k = 0.3412, a = 1.0647, c = −0.0556	0.0292	0.9959	0.0012
	Two-Term model	k = 0.2373, a = 5.9349, c = −4.9301, g = 0.2154	0.0266	0.9966	0.0012
	Wang and Singh	a = −0.2520, b = 0.0151	0.0447	0.9929	0.0025
MV 7.23	Lewis	k = 0.8311	0.0973	0.9736	0.0108
	Page	k = 0.4143, n = 1.4339	0.0248	0.9975	0.0008
	Henderson and Pabis	k = 0.9468, a = 1.6510	0.2346	0.9607	0.0734
	Mod. Henderson and Pabis	k = 0.2090, a = 6.3460, b = −5.5257, c = 0.1864, g = 0.1542, h = −0.1146	0.0205	0.9982	0.0017
	Logarithmic	k = 0.4891, a = 1.0829, c = −0.0649	0.0296	0.9962	0.0014
	Two-Term model	k = 0.3384, a = 6.4455, c = −5.4297, g = 0.3081	0.0267	0.9969	0.0014
	Wang and Singh	a = −0.3743, b = 0.0339	0.0333	0.9957	0.0015

Table 4
Model parameters and performance of the thin layer models of durian slices pretreated by freezing. (r = the goodness of the correlation coefficient, RMSE = root mean square error and χ^2 = chi-square).

Drying condition	Model	Parameter	RMSE	r	χ^2
MV 3.88	Lewis	k = 0.344	0.0532	0.9914	0.0031
	Page	k = 0.2619, n = 1.1054	0.0289	0.9959	0.0010
	Henderson and Pabis	k = 0.3784, a = 1.2773	0.0994	0.9834	0.0121
	Mod. Henderson and Pabis	k = 0.1973, a = 1.8131, b = −0.8263, c = 0.0001, g = 0.1261, h = −0.4403	0.0211	0.9977	0.0010
	Logarithmic	k = 0.2573, a = 1.043, c = −0.0495	0.0218	0.9975	0.0007
	Two-Term model	k = 0.2038, a = 2.0081, c = −1.0184, g = 0.1473	0.0214	0.9976	0.0007
	Wang and Singh	a = −0.2001, b = 0.0098	0.0449	0.9929	0.0025
MV 5.49	Lewis	k = 0.572	0.1245	0.9593	0.0172
	Page	k = 0.2174, n = 1.5261	0.0259	0.9974	0.0008
	Henderson and Pabis	k = 0.6363, a = 1.4684	0.1638	0.9466	0.0335
	Mod. Henderson and Pabis	k = 0.1044, a = 7.3556, b = −8.9763, c = 2.6610, g = 0.0471, h = −0.0121	0.0415	0.9930	0.0043
	Logarithmic	k = 0.3391, a = 1.1429, c = −0.0826	0.0581	0.9863	0.0048
	Two-Term model	k = 0.2236, a = 9.0374, c = −7.9792, g = 0.2069	0.0534	0.9885	0.0047
	Wang and Singh	a = −0.2577, b = 0.0156	0.0478	0.9908	0.0029
MV 7.23	Lewis	k = 0.9244	0.1541	0.9369	0.0271
	Page	k = 0.2699, n = 1.7847	0.0209	0.9984	0.0005
	Henderson and Pabis	k = 1.1102, a = 2.2376	0.4401	0.9099	0.2582
	Mod. Henderson and Pabis	k = 0.1243, a = 6.0042, b = −7.0928, c = 2.1313, g = 0.0261, h = −0.0673	0.0519	0.9899	0.0108
	Logarithmic	k = 0.4481, a = 1.1531, c = −0.0975	0.0661	0.9836	0.0069
	Two-Term model	k = 0.3019, a = 7.2396, c = −6.1838, g = 0.2727	0.0627	0.9852	0.0079
	Wang and Singh	a = −0.3675, b = 0.0327	0.0543	0.9895	0.0039

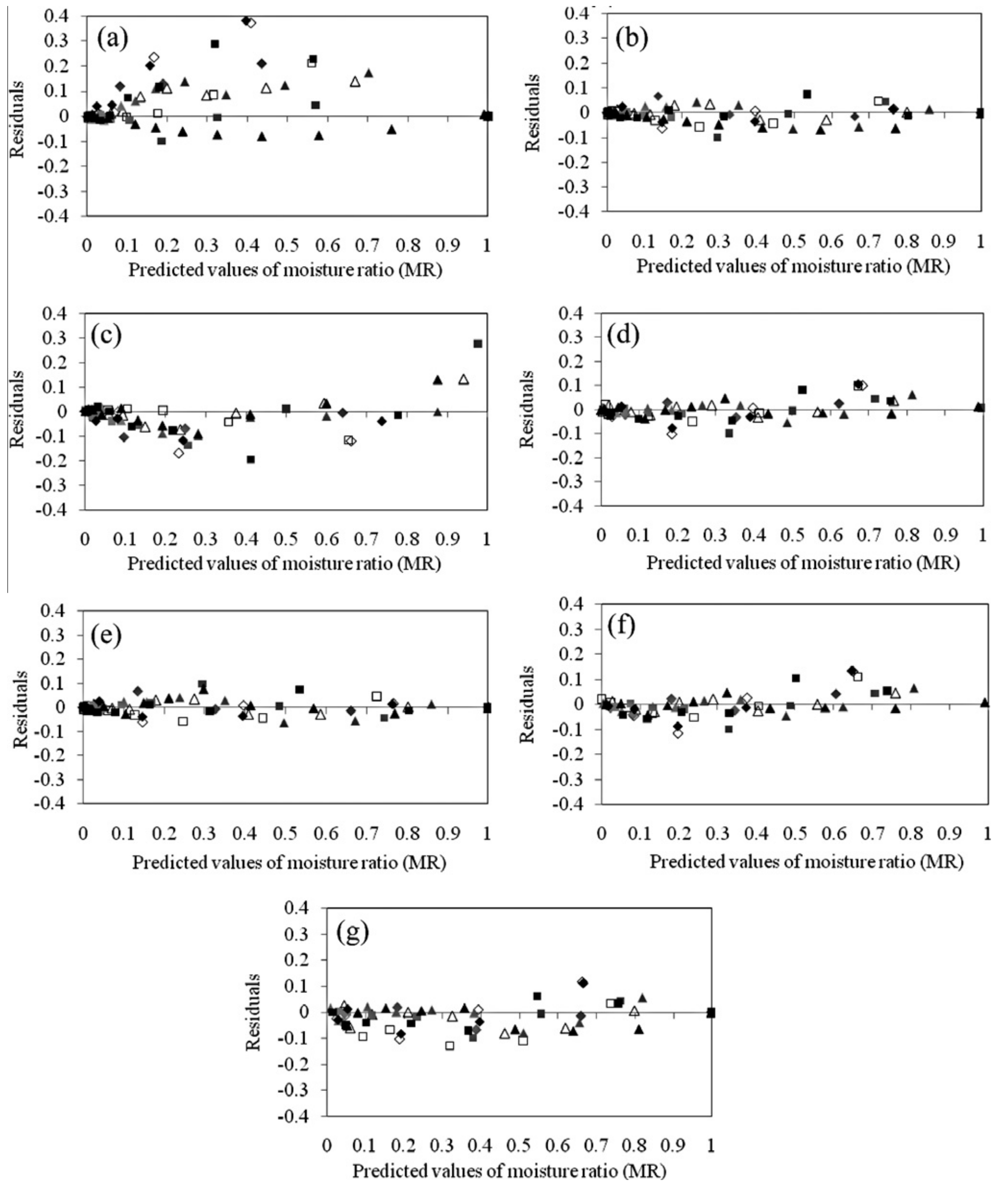

Fig. 2. Residual plots of thin layer models: (a) Lewis, (b) Page, (c) Henderson and Pabis, (d) Mod. Henderson and Pabis, (e) Logarithmic, (f) Two-term model and (g) Wang and Singh. ◇ MV 7.23 □ MV 5.49 △ MV 3.88 represented drying condition. White, gray and black represented pretreatment methods including control, chilling and freezing, respectively.

indicated the significance of internal resistance to mass transfer at low moisture content in the materials (Giri and Prasad, 2007).

The experimental data of moisture change during drying was fitted with thin layer models. The models' performance and parameters are shown in Tables 2–4. The Page model was superior to the other models, having the lowest RMSE, ranging from 0.0192 to 0.0349, the lowest χ^2 ranging from 0.0005 to 0.0015 and the highest correlation coefficient (r), and ranging from 0.9948 to 0.9984. Moreover, the residual plot of the Page model was not systematic and very close to x-axis (Fig. 2).

Table 5
Effective moisture diffusivity of durian slices during the microwave vacuum drying.

Condition		D_{eff}	RMSE	r	χ^2
Control	MV3.88	0.8510×10^{-7}	0.1230	0.9220	0.0167
	MV5.49	1.2360×10^{-7}	0.1198	0.9867	0.0159
	MV7.23	1.9314×10^{-7}	0.1904	0.9412	0.0414
Chilling	MV3.88	0.7373×10^{-7}	0.1415	0.9879	0.0220
	MV5.49	1.1984×10^{-7}	0.1376	0.9800	0.0210
	MV7.23	1.7822×10^{-7}	0.1372	0.9786	0.0215
Freezing	MV3.88	0.7161×10^{-7}	0.1037	0.9947	0.0118
	MV5.49	1.2225×10^{-7}	0.1650	0.9657	0.0302
	MV7.23	1.9948×10^{-7}	0.1879	0.9439	0.0403

Table 6
CIELAB color values (mean ± standard error) of microwave vacuum-dried durian chips.

Pretreatment	Drying condition	L^*	a^*	b^*
Control	MV3.88	$84.25^a \pm 0.23$	$-0.31^d \pm 0.03$	$26.45^a \pm 0.67$
	MV5.49	$83.90^a \pm 0.33$	$0.48^c \pm 0.01$	$25.56^a \pm 0.54$
	MV7.23	$83.57^a \pm 1.92$	$1.39^b \pm 0.06$	$23.05^a \pm 2.18$
Chilling	MV3.88	$82.52^a \pm 0.20$	$-0.30^d \pm 0.00$	$23.58^a \pm 2.26$
	MV5.49	$83.18^a \pm 2.04$	$-0.41^d \pm 0.04$	$22.58^a \pm 0.30$
	MV7.23	$80.69^a \pm 2.70$	$2.05^a \pm 0.02$	$23.30^a \pm 2.62$
Freezing	MV3.88	$83.40^a \pm 0.12$	$0.53^c \pm 0.06$	$26.64^a \pm 0.12$
	MV5.49	$82.46^a \pm 0.02$	$0.40^c \pm 0.07$	$24.60^a \pm 0.82$
	MV7.23	$82.13^a \pm 0.22$	$1.58^b \pm 0.56$	$24.27^a \pm 1.10$

$^{a-d}$ = significant ($p \leqslant 0.05$) difference within the same column.

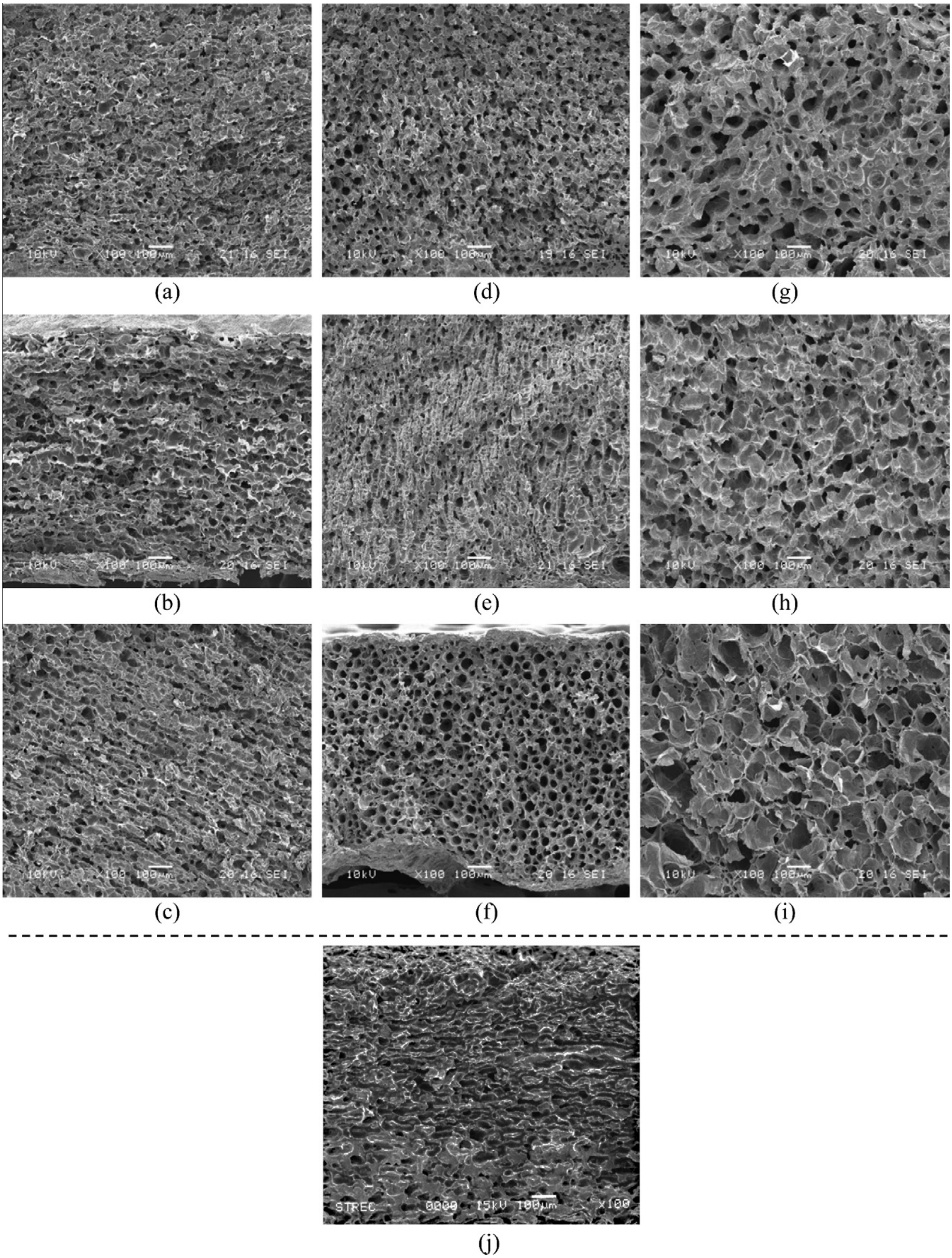

Fig. 3. Scanning electron micrograph of durian chips. Left: Control at: (a) MV3.88; (b) MV5.49; and (c) MV7.23, Middle: Chilling prior to drying at: (d) MV3.88; (e) MV5.49; and (f) MV7.23, Right: Freezing prior to drying at: (g) MV3.88; (h) MV5.49; and (i) MV7.23, Bottom: Commercial fried durian chip (j).

3.3. Effective moisture diffusivity of durian slices

The effective moisture diffusivity (D_{eff}) of the durian slices at various microwave power levels and under various pretreatments was obtained using (Eq. (12)). According to Table 5, there was an increase in the power intensity (D_{eff}) from 0.8510×10^{-7} to 1.9314×10^{-7} m^2.s^{-1} for untreated durian, from 0.7376×10^{-7} to 1.7822×10^{-7} m^2.s^{-1} for chilled durian and from 0.7162×10^{-7} to 1.9948×10^{-7} for frozen durian. The effective moisture diffusivity of the durian slices could be improved by using microwave vacuum drying, compared with hot air drying ($D_{eff} = 1.49 - 2.15 \times 10^{-8}$ m^2 s^{-1}) and superheated-steam drying ($D_{eff} = 0.97 - 1.44 \times 10^{-8}$ m^2 s^{-1}) from a previous study (Jamradloedluk et al., 2007).

3.4. Color of durian chips

Chilling and freezing prior to microwave vacuum drying and using different levels of microwave power had no significant effect ($p > 0.05$) on the lightness (L^*-value) and yellowness (b^*-value) of the microwave vacuum-dried durian chips (Table 6). However, redness (positive a^*-value) of dried durian chips was clearly observed when the levels of microwave powers was increased. The L^*, a^* and b^* of fresh durian were 85.22 ± 2.33, −1.89 ± 0.89 and 18.84 ± 3.61, respectively. After the microwave vacuum drying, lightness was slightly decreased whereas redness and yellowness were increased. The durian chips became cream in color with L^*, a^* and b^* values of 80.69–84.25, −0.31–2.05 and 22.58–26.64, respectively. Compared to the dried durian chips from superheated-steam drying at 140 °C (L^*-value = 70.0, a^* = 6.0 and b^* = 32.5; Jamradloedluk et al. (2007)), the color of microwave vacuum-dried durian chips was lighter. Charoensiri et al. (2009) found 41.4 µg/100 g beta-carotene in the durian samples. Degradation of beta-carotene could be the cause of color change in the durian samples. The color pigment may be auto-oxidized by the reaction with atmospheric oxygen. The reaction rates depend on the intensity of oxygen, light and heat. Therefore, the vacuum conditions could retain the natural color of materials. This improvement was also observed in many agricultural products, including, carrots and Chinese chive leaves (Cui et al., 2004), edamames (Hu et al., 2006) and parsley (Bohm et al., 2002).

3.5. Microstructure of durian chips

The microstructure of the cross section of the durian chips was examined to explore the effect of pretreatment methods and microwave power levels on the samples (Fig. 3). From the scanning electron micrographs, the microwave-dried chips had both uniform pore size and pore distribution, because during the microwave vacuum drying there was rapid and extensive vaporization. As a result, vapor could increase the pressure inside the chips, as well as enhancing the porosity (Therdthai and Zhou, 2009). When the durian slices were pretreated by freezing prior to microwave vacuum drying, the dried durian chips had a large porous sponge-like structure, (Fig. 3g–i). This was possible because water could be evaporated rapidly from the ice-crystal state under vacuum conditions (Shyu and Hwang, 2001). Furthermore, the microwave vacuum dried durian chips contained a comparable structural characteristic to the commercial fried durian chips (Fig. 3j).

3.6. Texture of durian chips

The hardness of the microwave vacuum-durian chips was in the range 3.67–5.88 N (Fig. 4), which was in the same range as that of conventionally fried durian chips (5.0–7.0 N). This indicated that the durian chip texture obtained was comparable to that of fried durian chips, possibly due to the vacuum conditions and the rapid heating by the microwaves. During microwave heating, microwave energy was absorbed by the water. Then, the water was vaporized within the durian chips and transferred to the surface, which created a vapor pressure differential between the core of the chip and the chip surface. Therefore, by reducing the chamber pressure, the pressure differential was possibly increased and thereby the outward force was increased. This could have produced the puffing characteristics and crispness of the chips. This finding coincided with the results reported by Sham et al. (2001), who found that puffing apple chips with decreased density were obtained when the chamber pressure used in microwave drying was reduced.

An increase in the microwave power level from 3.88 to 5.49 W g^{-1} tended to reduce the hardness of the durian chips. Similarly, Zhang et al. (2007) found that increased microwave power could increase the expansion ratio and crispness of fish slices. However, a further increase to 7.23 W g^{-1} was found likely to create a hot spot and thereby an increase in the breaking resistance.

As a pretreatment prior to drying, freezing tended to reduce the hardness of the dried chips, due to the larger porous structure than in either untreated or chilled durian chips (Fig. 3). Likewise, Shyu and Hwang (2001) reported an improvement in the crispness of fried apple samples when freezing was applied as a pretreatment.

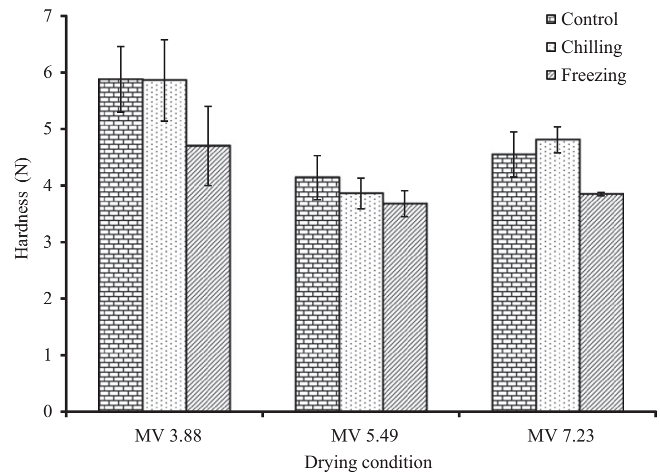

Fig. 4. Hardness of microwave vacuum-dried durian samples. The bars show the standard error of the mean.

3.7. Fat content of durian chips

The microwave vacuumed durian chips contained 2.07–3.01% fat content (Table 7). There was no significant ($p > 0.05$) impact of pretreatment and drying condition on fat content of the dried durian chips. Compared with commercially fried durian chips

Table 7
Fat content (mean ± standard error) of microwave vacuum-dried durian chips.

Pretreatment	Microwave power intensity (W g^{-1})	Fat content^{ns} (% dry basis)
Control	3.88	2.07 ± 0.02
	5.49	2.10 ± 0.04
	7.23	2.18 ± 0.04
Chilling	3.88	2.36 ± 0.23
	5.49	2.34 ± 0.44
	7.23	2.42 ± 0.51
Freezing	3.88	2.71 ± 0.82
	5.49	2.77 ± 0.43
	7.23	3.01 ± 0.34

ns = non-significant ($p > 0.05$) difference within the same column.

(32.19–36.54% fat content), the microwave vacuum drying process reduced the fat content of the durian chips by at least 90%. With the additional benefits of retaining natural color and having a porous structure and comparable texture, microwave vacuum drying, therefore, could be considered as an alternative process to produce low-fat durian chips.

4. Conclusions

The thin layer models were used to describe the drying kinetics of the durian slices. The Page model provided the best fit. By increasing the microwave power intensity, the effective moisture diffusivity and drying rate were increased. Therefore, drying time could be reduced. Pretreatment by chilling and freezing did not affect the drying kinetics. However, freezing prior to the microwave vacuum drying could reduce hardness due to the modification of the microstructure of the durian samples. Therefore, fresh durian could be better preserved by freezing until processing. The structure and texture of the microwave vacuum-dried durian chips were comparable to those of conventionally fried durian chips. Their color was closed to the natural color of raw materials. Moreover, the fat content of the durian chips was reduced by at least 90%, which should be beneficial to their shelf-life and also to human health. To evaluate consumer acceptance, a further study is underway into the variation in flavor due to the replacement of the frying process with drying alternatives.

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References

AOAC, 2000. Official Methods of Analysis, 17th ed. The Association of Official Analytical Chemists, Maryland, USA.
Ahmed, J., Ramaswamy, H.S., Raghavan, V.G.S., 2007. Dielectric properties of butter in the MW frequency range as affected by salt and temperature. Journal of Food Engineering 82 (3), 351–358.
Al-Muhtaseb, A.H., Hararah, M.A., Megahey, E.K., McMinn, W.A.M., Magee, T.R.A., 2010. Dielectric properties of microwave-baked cake and its constituents over a frequency range of 0915–2.450 GHz. Journal of Food Engineering 98 (1), 84–92.
Arévalo-Pinedo, A., Murr, F.E.X., Giraldo-Zuñiga, A.D., Arévalo, Z.D.S., 2004. Vacuum drying of carrot (*Daucus carota*): effects of pretreatments and parameters process. In: Proceedings of the 14th International Drying Symposium, São Paulo, Brazil, pp. 2021–2062.
Arévalo-Pinedo, A., Murr, F.E.X., (, 2006. Kinetics of vacuum drying of pumpkin (*Cucurbita maxima*): modeling with shrinkage. Journal of Food Engineering 76 (4), 562–567.
Ayensu, A., 1997. Dehydration of food crops using a solar dryer with convective heat flow. Solar Energy 59, 121–126.
Bohm, M., Bade, M., Kunz, B., 2002. Quality stabilization of fresh herbs using a combined vacuum-microwave drying process. Advances in Food Science 24 (2), 55–61.
Bondaruk, J., Markowski, M., Blaszczak, W., 2007. Effect of drying conditions on the quality of vacuum-microwave dried potato cubes. Journal of Food Engineering 81 (2), 306–312.
Buffler, C.R., 1991. A guideline for power output measurement of consumer microwave ovens. Microwave World, 10(5), 15. In: Buffler, C.R. (Ed.) (1993), Microwave Cooking and Processing: Engineering Fundamentals for the Food Scientist, Van Nostrand Reinhold, New York, USA, pp. 169.
Buffler, C.R., 1993. Microwave cooking and processing: engineering fundamentals for the food scientist. Van Nostrand Reinhold, New York, USA. pp. 169.
Charoensiri, R., Kongkachuichai, R., Suknicom, S., Sungpuag, P., 2009. Beta-carotene, lycopene, and alpha-tocopherol contents of selected Thai fruits. Food Chemistry 113 (1), 202–207.
Coulson, J.M., Richardson, J.F., Backhurst, J.R., Harker, J.H., 1987. In: Chemical Engineering, Unit Operation, 3rd ed. Pergamon Press Ltd., UK, pp. 717–718.
Cui, Z-W., Sun, L-J., Chen, W., Sun, D-W., 2008. Preparation of dry honey by microwave-vacuum drying. Journal of Food Engineering 84 (4), 582–590.
Cui, Z-W., S-Y., Xu, Sun, D-W., 2004. Effect of microwave-vacuum drying on the carotenoids retention of carrot slices and chlorophyll retention of Chinese chive leaves. Drying Technology 22 (3), 563–575.
Durance, T.D., Wang, J.H., 2002. Energy consumption, density, and rehydration rate of vacuum microwave- and hot-air convection- dehydrated tomatoes. Journal of Food Science 67 (6), 2212–2216.
Fellows, P., 2000. In: Food processing technology: principles and practice, 2nd ed. Woodhead Publishing Ltd., Cambridge, p. 575.
Figiel, A., 2009. Drying kinetics and quality of vacuum-microwave dehydrated garlic cloves and slices. Journal of Food Engineering 94 (1), 98–104.
Figiel, A., 2010. Drying kinetics and quality of beetroots dehydrated by combination of convective and vacuum-microwave methods. Journal of Food Engineering 98 (4), 461–470.
Giri, S.K., Prasad, S., 2007. Drying kinetics and rehydration characteristics of microwave-vacuum and convective hot-air dried mushrooms. Journal of Food Engineering 78 (2), 512–521.
Henderson, S.M., Pabis, S., 1961. Grain drying theory I: temperature effect on drying coefficient. Journal of Agricultural Research Engineering 6, 169–174.
Hu, Q., Zhang, M., Mujumdar, A.S., Xiao, G., Sun, J., 2006. Drying of edamames by hot air and vacuum microwave combination. Journal of Food Engineering 77 (4), 977–982.
Jamradloedluk, J., Nathakaranakule, A., Soponronnarit, S., Prachayawarakorn, S., 2007. Influences of drying medium and temperature on drying kinetics and quality attributes of durian chip. Journal of Food Engineering 78 (1), 199–205.
Karathanos, V.T., 1999. Determination of water content of dried fruits by drying kinetic. Journal of Food Engineering 39 (4), 337–344.
Karathanos, V.T., Belessiotis, V.G., 1999. Application of a thin layer equation to drying data of fresh and semi-dried fruits. Journal of Agricultural Engineering Research 74 (4), 335–361.
Kompany, E., Benchimol, J., Allaf, K., Ainseba, B., Bouvier, J.M., 1993. Carrot dehydration for instant rehydration: dehydration kinetics and modeling. Drying Technology 11 (3), 451–470.
Lidstrom, P., Tierney, J., Wathey, B., J., Westman, 2001. Microwave assisted organic synthesis – A review. Tetrahedron 75 (45), 9225–9283.
Ozkan, I.A., Akbudak, B., Akbudak, N., 2007. Microwave drying characteristics of spinach. Journal of Food Engineering 78 (2), 577–583.
Sahin, S., Sumnu, S.G., 2006. Physical Properties of Food. Springer, New York.
Scaman, C.H., Durance, T.D., 2005. Emerging Technologies for Food Processing. Elsevier Academic Press, London. pp. 768.
Seyhun, N., Ramaswamy, H., Sumnu, G., Sahin, S., Ahmed, J., 2009. Comparison and modeling of microwave tempering and infrared assisted microwave tempering of frozen potato puree. Journal of Food Engineering 92 (3), 339–344.
Sham, P.W.Y., Scaman, C.H., Durance, T.D., 2001. Texture of vacuum microwave dehydrated apple chips as affected by calcium pretreatment, vacuum level and apple variety. Journal of Food Science 66 (9), 1341–1347.
Sharma, G.P., Prasad, S., 2002. Dielectric properties of garlic (*Allium sativum* L) at 2450 MHz as function of temperature and moisture content. Journal of Food Engineering 52 (4), 343–348.
Shyu, S.L., Hwang, L.S., 2001. Effects of processing conditions on the quality of vacuum fried apple chips. Food Research International 34 (2-3), 133–142.
Singh, R.P., Heldman, D.R., 2001. In: Introduction to Food Engineering, 3rd ed. Academic Press, USA, p. 356.
Sosa-Morales, M.E., Valerio-Junco, L., López-Malo, A., Garćia, H.S., 2010. Dielectric properties of foods: reported data in the 21st century and their potential applications. LWT – Food Science and Technology 43 (4), 1169–1179.
Subhadrabandhu, S., Ketsa, S., 001. In: Durian King of Tropical Fruit. Daphne Brasell Associates Ltd., New York, p. 178.
Therdthai, N., Zhou, W., 2009. Characterization of microwave vacuum drying and hot air drying of mint leaves (*Mentha cordifolia Opiz ex Fresen*). Journal of Food Engineering 91 (3), 482–489.
Togrul, I.T., Pehlivan, D., 2002. Mathematical modeling of solar drying of apricots in thin layers. Journal of Food Engineering 55 (3), 209–216.
Trabelsi, S., Kraszewski, A.W., Nelson, S.O., 1998. A microwave method for on-line determination of bulk density and moisture content of particulate materials. IEEE Transactions on Instrumentation and Measurement 47 (1), 127–132.
Wang, C.Y., Singh, R.P., 1987. A single layer drying equation for rough rice. ASAE. Paper No. 3001.
Wang, Y., Tang, J., Rasco, B., Kong, F., Wang, S., 2008. Dielectric properties of salmon fillets as a function of temperature and composition. Journal of Food Engineering 87 (2), 236–246.
Wang, Z., Sun, J., Chen, F., Liao, X., Hu, X., 2007. Mathematical modeling on thin layer microwave drying of apple pomace with and without hot air pre-drying. Journal of Food Engineering 80 (2), 536–544.
Yaldiz, O., Ertekin, C., Uzun, H.B., 2001. Mathematical modeling of thin layer solar drying of sultana grapes. Energy 26 (5), 457–465.
Yam, K.L., Lai, C.C. (Eds.), 2004. Microwavable frozen food or mealsMarrell, K.D., Hui, Y.H., Nip, W-K., Lim, M.H., Legarreta, I.G., Cornillon, P. (Eds.). Handbook of Frozen Foods. CRC Press, USA, pp. 581–593.
Zhang, J., Zhang, M., Shan, L., Fang, Z., 2007. Microwave-vacuum heating parameters for processing savory crisp bighead carp (*Hypophthalmichthys nobilis*) slices. Journal of Food Engineering 79 (3), 885–891.