

Drying Kinetics and Changes of Total Phenolic Content, Antioxidant Activity and Color Parameters of Mango and Avocado Pulp in Refractance Window Drying

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Refractance window drying is an innovative technology belonging to the fourth generation of drying technologies that could enhance the quality of the dried product and improve the drying process. In this study, two factors with the type of fruit pulps (avocado and mango) and drying temperature (ranging from 80 to 95°C) were investigated. Results showed that in refractance window drying, the evaporation process rapidly occurred, mainly in the falling-rate period with undetectable constant-rate period. The Weibull was the best fit model among eight investigated mathematical models that could determine the drying behavior. The effective diffusivity was found to be from 4.25×10^{-10} m²/s to 7.24×10^{-10} m²/s for avocado pulp, and from 4.50×10^{-10} m²/s to 10.67×10^{-10} m²/s for mango pulp when the drying temperature was changed from 80 to 95°C. Moreover, the corresponding activation energy was 32.06 and 66.03 kJ/mol for avocado and mango pulp moisture evaporation, respectively, and the highest quality of powders of both dried pulps was obtained after processing at 90°C. The refractance window drying revealed a high potential in the production of fruit powders from avocado and mango due to the high retention of more than 80% of total phenolic content (TPC) and antioxidant activity. TPC could be used as a useful criterion for the evaluation of the drying process in terms of dried product quality.

INTRODUCTION

Drying technology is a traditional unit operation that is most popular and important in food processing and preservation. During the drying process, moisture is removed from the material to enhance the stability of the product, reduce unexpected reactions, extend shelf-life, and produce dried products. Among dried products, powder from fruits and vegetables has been shown to offer exciting benefits as very convenient in developing industrial products such as beverages, baby foods, sauces, confectionery, yogurt, ice cream, nutritional bars, bakery products, and cereals [Ramaswamy & Marcotte, 2005]. Besides, the use of fruit powders entails lower costs of distribution and storage [Zotarelli *et al.*, 2017]. In the literature, some drying methods, such as spray-, drum-, freeze-drying, have been studied in respect of fruit powder production. However, each drying method had still some significant drawbacks related to the quality of powder (spray- and drum drying) or costs of system maintenance and implementation (freeze-drying). Recently, the fourth

generation of drying technologies has been developed to enhance the quality of the dried product and improve the drying process, among which the refractance window (RW) drying is an innovative technology designed to remove moisture from fruit purees to produce powder, dried sheets, or concentrated products [Vega-Mercado *et al.*, 2001]. During the RW drying, the heat conduction from hot water to film interface is dominant and the drying material would absorb energy due to heat conduction from plastic film to force moisture diffusion and evaporation. While heat conduction, convection, and radiation also happen at the hot-water interface and convection occurs at the air-film interface [Raghavi *et al.*, 2018].

In RW drying, the nutritional and sensory values were proved to be preserved effectively, bringing health benefits to consumers [Nindo & Tang, 2007]. In the literature, the RW drying was successfully applied to fruits and vegetables such as carrot, strawberry [Nindo & Tang, 2007], and tomato [Abul-Fadl & Ghanem, 2011]. As a consequence, the nutritional quality (especially vitamin contents) and the sensory values (color, flavor) could be highly retained [Nindo &

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Tang, 2007]. For example, the bright green color of asparagus puree after the RW drying was retained similarly to freeze-drying [Abonyi *et al.*, 2002]. Additionally, thermal efficiency in RW drying was also higher than using convective drying equipment, as illustrated by the reduction of 50–70% in costs and 50% in energy consumption compared to freeze-drying in the same material capacity [Nindo & Tang, 2007].

Among food materials, avocado and mango are fascinating objects of study. Avocado fruits are superfoods rich in nutrients and phytochemicals [Comerford *et al.*, 2016]. Mango possesses high nutritional value [Abbasi *et al.*, 2015; Haytowitz *et al.*, 2018; Shariful *et al.*, 2015]. It belongs to the group of tropical fruits with the top increased consumption with high economic value [Fitzpatrick & Ahrné, 2005; Occena-Po, 2006]. Although both avocado and mango have great nutritional and economic values, they have considerable limitations when it comes to moisture removal. In the literature, some drying methods were applied to dehydrate avocado, such as freeze-drying [Castañeda-Saucedo *et al.*, 2014; Rafidah *et al.*, 2014; Souza *et al.*, 2015], hot-air drying [Temu, 2013], heat-pump drying [Ceylan *et al.*, 2007], or superheated-steam drying [Rafidah *et al.*, 2014]. The most critical drawback in these studies is the long operating time (varying from 3 to more than 20 h), because the higher the temperature or the longer the time of avocado thermal treatment, the more bitter-tasting molecules are produced [Degenhardt & Hofmann, 2010]. However, Degenhardt & Hofmann [2010] found that the thermal processing of avocado within 30 min (at temperatures ranging from 80 to 120°C) or 60 min (at 80°C) only slightly increased bitter taste in comparison with untreated avocado. Thus, the higher quality of dried avocado will be obtained if the temperature and duration of drying are well controlled. In the case of mango, the reported drying methods included freeze- [Caparino *et al.*, 2012], drum- [Caparino *et al.*, 2012; Germer *et al.*, 2018], spray- [Cano-Chauca *et al.*, 2005; Caparino *et al.*, 2012; Zotarelli *et al.*, 2017], spout fluidized bed- [da Cunha *et al.*, 2006], vacuum- [Jaya *et al.*, 2006], hot air- [Yao *et al.*, 2020], infrared- [Yao *et al.*, 2020], foam mat- [Chaux-Gutiérrez *et al.*, 2017], and RW drying [Caparino *et al.*, 2012, 2017; Zotarelli *et al.*, 2015, 2017]. Most of these studies were focused on drying kinetics and physicochemical analysis. A few publications reported about the effect of drying on the quality of dried mango, including the determination of ascorbic acid and β -carotene contents without the analysis of total phenolic content (TPC) and antioxidant activity. Caparino *et al.* [2017] studied mango powder obtained using RW drying, but the results they achieved showed the physical and chemical stability of mango powder during storage [Caparino *et al.*, 2017]. Mango powder obtained using RW drying had a better physical quality than that produced using drum-drying and spray-drying [Caparino *et al.*, 2012; Zotarelli *et al.*, 2017].

In the literature, the RW drying was conducted for mango pulp [Caparino *et al.*, 2012] and low-fat avocado paste [Da Silva & Da Silva, 2018]. However, there is still a limited number of studies on drying kinetics of RW drying of avocado and mango. Only the change of physicochemical properties under the effects of drying conditions was reported. In the field of the drying process, studies on drying kinetics

and the change of quality upon drying are always essential to evaluate the drying process and choose its suitable conditions [Onwude *et al.*, 2016]. The application of innovative drying, such as the RW drying, was expected to produce high-quality dried avocado and mango.

Therefore, this study aimed to investigate the drying kinetics and the changes of TPC, antioxidant activity and color parameters of avocado and mango pulp exposed to RW drying at different drying temperatures. The experimental data was used to determine the drying behavior, the effective diffusivity coefficients, activation energy and quality of dried products. These results would support the identification of suitable conditions of avocado and mango pulp drying.

MATERIALS AND METHODS

Material preparation

Fresh avocado (*Persea americana*) and mango (*Mangifera indica*) were received from a local farm in DakLak and Ben Tre, Vietnam. The fully-ripe avocado and mango without the physical damages were chosen. Then, materials were washed, peeled, and sliced using a fruit knife (Royal VKB, China). Slices were pretreated with steam for 3 min to inactivate enzymes responsible for the browning phenomena, such as polyphenol oxidase and peroxidase. After steaming, slices were cooled promptly in cold water at $5.0 \pm 0.5^\circ\text{C}$. Fruit pulp was then produced using a Berjaya commercial blender (BJY-CB2L60-A, Kuala Lumpur, Malaysia) and passed through 16-mesh sieves to remove large particles and fibers. Before drying, 9% (w/w) maltodextrin was added to pulps to act as a coating material, creating a physical barrier to oxygen and light to protect against chemical and enzymatic degradation [Wang *et al.*, 2009]. Our previous study demonstrated that the addition of maltodextrin (9%, w/w) improved the quality of dried products and facilitated the grinding to produce fruit powder (data not shown).

Refractance window drying apparatus

A custom-built refractance window drying equipment was set up with a similar principle in previous researches [Pariotto *et al.*, 2020; Rajoriya *et al.*, 2019] with some modifications. The drying apparatus was operated in batch laboratory-scale configuration and consisted of a hot water reservoir (0.42 m \times 0.28 m \times 0.10 m) and a thermostatic water bath (DH.WB000106, Daihan-Scientific, Wonju-si, South Korea). A polyester film (Mylar™, Jiangsu, China) with a 0.25-mm thickness was used to conduct heat from hot water to fruit pulp spread into 2-mm-thick layers on the films.

Experimental design and refractance window drying operation

In this study, the experiments were conducted with two factors, including the pulp types (avocado pulp – AP and mango pulp – MP) and 4-level drying temperature (from 80 to 95°C at an interval of 5°C) with three replications.

Each pulp sample was dried using the RW drying system and moisture content was analyzed at 5-min intervals. The drying process was stopped when the moisture content reached of 0.04 g/g on the dry basis (d.b.). The moisture

content was determined by the moisture analyzer with infra-red heating (MB23, Ohaus, Parsippany, NJ, USA). Experiment data was used to determine the mathematical model and kinetic parameters in the RW drying of AP and MP.

To determine the quality of AP and MP after drying, each pulp sample (100 g) was dried to a moisture content of 0.040 ± 0.005 g/g d.b., and dried products were collected. Then, these products were ground to powder for future determination of TPC, antioxidant activity, and color parameters.

Mathematical models for thin-layer drying curves

The moisture ratio (MR) was determined using the following equation [Pala *et al.*, 1996]:

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

where: M_t is moisture content at t drying time (g water/g d.b.) and M_0 is the initial moisture content (g water/g d.b.).

Of the many mathematical models suggested to determine the drying characteristics of food products [Onwude *et al.*, 2016], this study fitted drying curves to the eight semi-theoretical and empirical models including Newton, Page, Modified Page (II), Modified Page (IV), Henderson & Pabis, Logarithmic, Midilli, and Weibull models. Statistical parameters, including the determination coefficient (R^2) and the root mean square error (RMSE), were determined to identify the ability to predict the tested models:

$$R^2 = 1 - \frac{\sum_{i=1}^N (M_{\text{exp},i} - M_{\text{pre},i})^2}{\sum_{i=1}^N (\overline{MR}_{\text{exp}} - MR_{\text{pre},i})^2} \quad (2)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (M_{\text{exp},i} - M_{\text{pre},i})^2} \quad (3)$$

where: $M_{\text{exp},i}$ is the experimental dimensionless moisture ratio, $M_{\text{pre},i}$ is the predicted dimensionless moisture ratio, $\overline{MR}_{\text{exp}}$ is the mean value of the experimental dimensionless moisture ratio, and N is the number of observations.

Determination of the effective diffusivity

Fick's second law of diffusion was chosen to determine moisture movement within the mango and avocado pulp, considered an infinite flat plate. The diffusion equation is as follows:

$$\frac{\partial M}{\partial t} = D_{\text{eff}} \nabla^2 M \quad (4)$$

where: M is the moisture content (g water/g d.b.), D_{eff} is the effective moisture diffusivity (m^2/s), and t is the time (s).

Crank [1975] gave a general analytical solution for thin-layer drying case with some assumptions such as the product

with homogeneous, isotropic sizes, and constant characteristics; negligible shrinkage, negligible external resistance to heat and mass transfer; evaporation only at product surface; uniform initial moisture distribution; constant of the moisture diffusivity. The solution was given as:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(- (2n+1)^2 \pi^2 \frac{D_{\text{eff}}}{L^2} t\right) \quad (5)$$

where: MR is the dimensionless moisture ratio, L is the layer thickness (m), n is the term in series expansion, and t is time (s).

For long drying times, the first term in the above series expansion ($n=0$) was considered as an approximate solution:

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

The effective diffusivity (D_{eff}) was found on the basis of Eq. 6 by the non-linear least square method using the Levenberg-Marquardt algorithm [Marquardt, 1963].

Determination of activation energy

The activation energy (E_a) of moisture removal was estimated from an Arrhenius equation, and it was given as:

$$D_{\text{eff}} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (7)$$

where: E_a is the activation energy (kJ/mol), R is the ideal gas constant (8.3143 kJ/mol), T is the absolute temperature (K), and D_0 is the pre-exponential factor (m^2/s).

Preparation of extracts

The preparation of extracts from avocado and mango pulps was performed according to Wang *et al.* [2010] and Bloor [2001] procedures, respectively, with some modifications. The AP (0.2 g) was mixed with 10 mL of the solvent (7 mL acetone + 0.03 mL glacial acetic acid + 2.97 mL water), and the MP (0.5 g) was mixed with 10 mL of the solvent (6 mL methanol + 4 mL water). The suspensions were vortexed for 30 s at 2,000 rpm using the VELP ZX4 advanced IR vortex mixer (VELP Scientifica, Milan, Italy). Then, after sonication (40 KHz, 240 W, 5 min) in the Pro 100 ultrasonic cleaner (Asonic, Ljubljana, Slovenia), the samples were again vortexed for 10 s and cooled for 20 min at 10°C . The cooled samples were then sonicated for a second time at the previous conditions and centrifuged in the PLC-05 centrifuge (Gemmy Industrial Corp., Taipei, Taiwan) at $1,220 \times g$ for 10 min. The supernatant was collected and diluted to 25 mL to analyze TPC and DPPH radical scavenging activity.

Determination of total phenolic content

The total phenolic content of the extract was determined according to ISO 14502-1:2005 [2005] method. Briefly, 0.6 mL of the extract was mixed with 1.5 mL of the Folin-Ciocalteu reagent (10-fold dilution) and allowed to stand for

5 min at room temperature. Then, 1.2 mL of 7.5% Na₂CO₃ solution was added, and the mixture was incubated for 1 h in the dark. Finally, the absorbance of the mixture was measured at 765 nm using the UV-9000 spectrometer (Metash, Shanghai, China). TPC was determined through the gallic acid standard curve and expressed as mg gallic acid equivalent per g of pulp on the dried basis (mg GAE/g d.b.). For the dried powders, the retention percentage of TPC was calculated on the basis of the ratio of TPC of powdered pulp to TPC of pulp before drying.

Determination of antioxidant activity

The 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity of the extract was determined according to Brand-Williams *et al.* [1995] with minor changes. To prepare the radical stock solution, 24 mg of solid DPPH[•] were dissolved in 100 mL of methanol and stored at 4°C in the dark for 24 h. The DPPH[•] working solution was prepared by diluting the DPPH[•] stock solution to the absorbance of 1.1 units at 515 nm using methanol. Then, 150 mL of the extract was reacted with 2850 mL of DPPH[•] working solution for 30 min under dark conditions. Finally, the absorbance of the mixture was measured at 515 nm over methanol blank. In parallel, the standard curve for Trolox was prepared and DPPH radical scavenging activity was expressed as mg Trolox equivalent per g of pulp on the dried basis (mg TE/g d.b.). For the dried powders, the retention percentage of antioxidant activity was calculated on the basis of the ratio of DPPH[•] scavenging activity of powdered pulp to DPPH[•] scavenging activity of pulp before drying.

Determination of color attributes

The values of *L*^{*}, *a*^{*}, and *b*^{*} color parameters were measured with the NR110 precision colorimeter (Shenzhen 3nh Technology Co., Guangdong, China) using the Hunter CIELAB color system. *L*^{*} indicates lightness, with a scale ranging from 0 (black) to 100 (white). Positives and negatives in *a*^{*} represent red and green, whereas positives and negatives in *b*^{*} represent yellow and blue, respectively.

Statistical analysis

All experiments were conducted in triplicate. The mean and standard deviation were calculated in WPS Spreadsheets software (Microsoft Inc., Redmond, WA, USA). The coefficients of mathematical models were found by the non-linear least square method based on the Levenberg-Marquardt algorithm. One-way analysis of variance (ANOVA) was used to determine the differences between samples, and Tukey's multiple range test was applied to determine significant differences between mean values at the significance level of 5%. Pearson correlation was also calculated to determine the coefficients between TPC, antioxidant activity and color parameters of avocado and mango powders.

RESULTS AND DISCUSSION

Quality of avocado and mango pulp

Before performing the drying experiments, the materials were standardized and analyzed for the physicochemical properties. Table 1 shows the chemical composition of fresh

TABLE 1. The physicochemical properties of avocado and mango pulp.

Properties	Avocado pulp	Mango pulp
Moisture (g/100 g fresh pulp)	82.4±0.5	90.03±0.68
Total phenolic content (mg GAE/g d.b.)	5.33±0.06	23.18±0.45
Antioxidant activity (mg TE/g d.b.)	1.60±0.05	6.31±0.66
	<i>L</i> [*]	61.05±1.02
Color parameters	<i>a</i> [*]	-23.77±1.17
	<i>b</i> [*]	55.05±1.09

GAE – gallic acid equivalents; TE – Trolox equivalents; d.b. – dry basis.

avocado and mango pulp. The moisture content in avocado pulp (82.4±0.5 g/100 g) and mango pulp (90.03±0.68 g/100 g) were significantly different from those shown in previous studies for avocado [Kassim *et al.*, 2013; Lye *et al.*, 2020] and mango [Jaya & Das, 2003; Pu & Sun, 2017]. Differences in variety, culture, soil properties, ripeness stage, harvest time, and post-harvest handling could all contribute to this variation. Table 1 shows that the mango pulp had a higher content of total phenolics and antioxidant activity than avocado pulp.

Drying curves and drying rate

The changes of moisture content during RW drying of AP and MP at different drying temperatures are shown in Figure 1 and Figure 2, respectively. The results revealed that the higher the RW temperature was, the shorter was the drying time. Specifically, when the temperature increased from 80 to 95°C, it would consume from 70 to 40 min for AP and from 85 to 45 min for MP to remove moisture from the initial moisture content to 0.040 g/g d.b., respectively. Figure 1b and Figure 2b present the drying rate *versus* moisture content during RW drying of AP and MP at different temperatures. The results showed that the higher the RW drying temperature was, the higher was the drying rate. It was clear that the higher RW drying temperature could increase the absorbed heat energy transferred from hot water to materials [Raghavi *et al.*, 2018]. Then, the more considerable heat rising in the material was, the faster was internal and external moisture diffusion. Therefore, the higher RW drying temperature would increase the drying rate and significantly reduce drying time.

For RW drying of AP, it was observed that the drying process only happened in the falling-rate period with the undetectable constant-rate period (Figure 1b). Meanwhile, there are two periods, including (i) the pre-heating period in the first 5 min of the drying process, and (ii) the falling-rate period for RW drying of MP (Figure 2b). Therefore, the RW drying of AP and MP mainly occurred in the falling-rate period. This phenomenon is because the conditions required for constant rate drying are seldom met [Berk, 2018], leading to all of the practical dryings of biological products taking place in the falling-rate period [Madamba *et al.*, 1996]. Also, most of the studies on drying have supported this conclusion [Onwude *et al.*, 2016]. Besides, the evaporation process happened rapidly in drying, causing the drying to occur only in the falling-rate period. In this study, the material grinding could release free

water from the vacuole and the xylem, so it was easy to evaporate when the pulp was spread into thin layers and quickly heated. That caused the moisture removal in RW drying of AP and MP to happen very fast. Similar observations were reported in the literature for RW drying of tomato [Abul-Fadl & Ghanem, 2011], murta berry leather [Gómez-Pérez *et al.*, 2020], and mango slices [Ochoa-Martínez *et al.*, 2012].

The drying rates were found to be positively correlated with moisture content. At the beginning of the drying process, it was observed that all samples had a higher drying rate (Figure 1 and Figure 2). Continuing the drying process, the drying rate decreased during moisture removal. Initially, the moisture content in the material was high; the heat energy from hot water transferred to materials would force water evaporation faster. Subsequently, the driving force of moisture removal was reduced. Because of the rubbery-glassy phase transition of the material, the critical phenomenon during drying would change the material from soft and rubbery to hard and glassy [Gulati & Datta, 2015]. Plus, when most of the free water escaped, heat energy was mainly responsible for breaking the water bonding, then diffusing moisture to evaporate. Therefore, the smaller moisture content was, the slower was the drying rate in the RW drying of AP and MP.

Mathematical model for RW drying of AP and MP

Changes in moisture ratio during RW drying of AP and MP were used to evaluate the fitting of mathematical models, and then to figure out the best model describing the behavior of RW drying of AP and MP. The selection was based on statistical parameters, including the coefficient of determination (R^2) and root-mean-square error (RMSE) (Table 2).

The thin-layer model, which has the highest R^2 value and smallest RMSE, was the best in this study. The average R^2 and RMSE were calculated to be convenient to compare the predicted power of mathematical models. The results showed that the higher the R^2 value was, the smaller was the RMSE. Among eight investigated models, the order of decreasing the average value of R^2 was as follows: (i) for RW drying of AP: Weibull > Midilli > Logarithmic > Modified Page (IV), Modified Page (II) and Page > Henderson & Pabis > Newton, and (ii) for RW drying of MP: Weibull > Midilli > Modified Page (IV) > Modified Page (II) and Page > Logarithmic > Henderson & Pabis > Newton.

The Newton model is the simplest model for determining the behavior of the drying process and the Henderson & Pabis model was developed from the first term in the numerical solution of Fick's second law of diffusion equation [Onwude

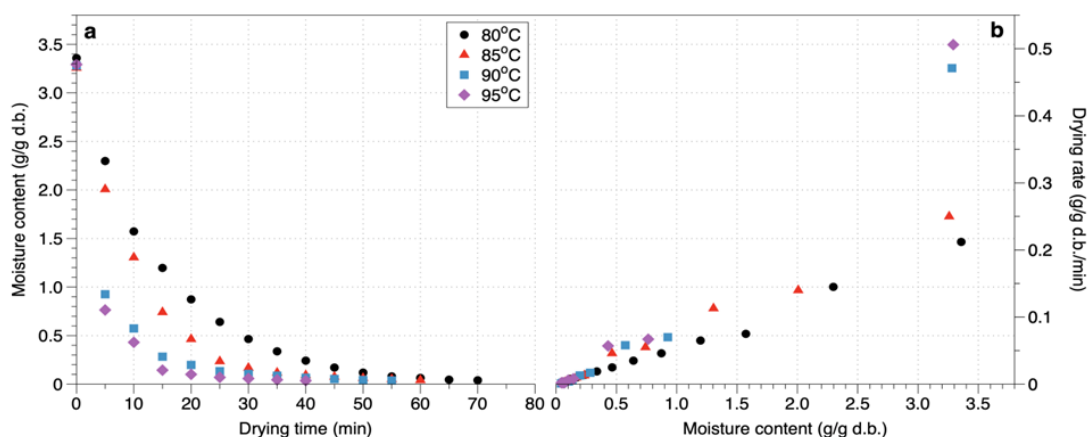


FIGURE 1. The changes of moisture content (a) and the drying rate curves (b) in refractance window drying of avocado pulp at different temperatures.

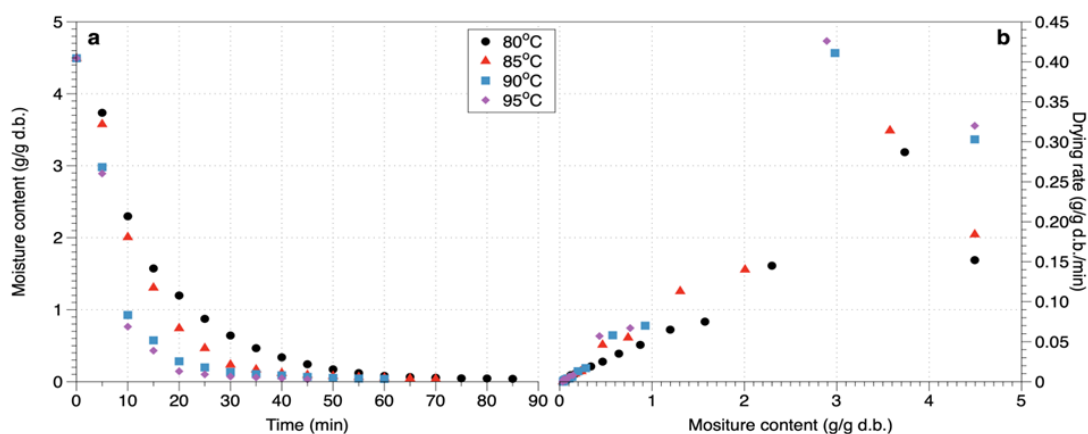


FIGURE 2. The changes of moisture content (a) and the drying rate curves (b) in refractance window drying of mango pulp at different temperatures.

TABLE 2. Equation parameters of drying models and statistical parameters of non-linear regression analysis for refractance window drying of avocado pulp and mango pulp at different temperatures.

Model and equation	Temperature (°C)	Avocado pulp			Mango pulp		
		Equation parameters	R ²	RMSE	Equation parameters	R ²	RMSE
Newton model MR = exp(-kt)	80	k=0.0639	0.9952	0.02147	k=0.0643	0.9915	0.02720
	85	k=0.0962	0.9988	0.01025	k=0.0839	0.9962	0.01840
	90	k=0.1525	0.9966	0.01725	k=0.1345	0.9934	0.02390
	95	k=0.2196	0.9976	0.01576	k=0.1568	0.9966	0.01879
		Average	0.9971	0.01618	Average	0.9944	0.02207
Page MR = exp(-kt ⁿ)	80	k=0.0451; n=1.119	0.9978	0.01516	k=0.0469; n=1.108	0.9935	0.02459
	85	k=0.0926; n=1.015	0.9989	0.01055	k=0.0557; n=1.153	0.9994	0.00793
	90	k=0.1516; n=1.003	0.9966	0.01809	k=0.1007; n=1.132	0.9946	0.02263
	95	k=0.2798; n=0.872	0.9982	0.01459	k=0.1158; n=1.145	0.9979	0.01566
		Average	0.9979	0.01460	Average	0.9964	0.01770
Modified Page (II) MR = exp(-(kt) ⁿ)	80	k=0.0627; n=1.119	0.9978	0.01516	k=0.0614; n=1.108	0.9935	0.02459
	85	k=0.0959; n=1.015	0.9989	0.01055	k=0.0816; n=1.153	0.9994	0.00793
	90	k=0.1524; n=1.003	0.9966	0.01809	k=0.1316; n=1.132	0.9946	0.02263
	95	k=0.2321; n=0.872	0.9982	0.01459	k=0.1521; n=1.145	0.9979	0.01566
		Average	0.9979	0.01460	Average	0.9964	0.01770
Modified Page (IV) MR = a exp(-kt ⁿ)	80	a=1.0100; k=0.0472; n=1.107	0.9978	0.01516	a=1.021; k=0.0513; n=1.085	0.9938	0.02474
	85	a=0.9997; k=0.0925; n=1.015	0.9989	0.01055	a=1.002; k=0.0561; n=1.150	0.9994	0.00824
	90	a=1.0020; k=0.1525; n=1.001	0.9966	0.01809	a=1.004; k=0.1021; n=1.128	0.9946	0.02369
	95	a=1.0010; k=0.2801; n=0.872	0.9982	0.01459	a=1.002; k=0.1163; n=1.143	0.9979	0.01673
		Average	0.9979	0.01460	Average	0.9964	0.01835
Henderson & Pabis MR = a exp(-kt)	80	a=1.0310; k=0.0658	0.9962	0.01985	a=1.037; k=0.0665	0.9928	0.02588
	85	a=1.0020; k=0.0964	0.9988	0.01069	a=1.024; k=0.0857	0.9968	0.01760
	90	a=1.0020; k=0.1528	0.9966	0.01808	a=1.012; k=0.1359	0.9935	0.02469
	95	a=0.9985; k=0.2194	0.9977	0.01683	a=1.008; k=0.1578	0.9967	0.01972
		Average	0.9973	0.01636	Average	0.9950	0.02197
Logarithmic MR = a exp(-kt) + c	80	a=1.0350; k=0.0646; c=-0.0062	0.9963	0.02037	a=1.037; k=0.0668; c=0.0016	0.9928	0.02671
	85	a=0.9976; k=0.0984; c=-0.0063	0.9990	0.01030	a=1.027; k=0.0845; c=-0.0046	0.9969	0.01804
	90	a=0.9894; k=0.1610; c=-0.0162	0.9984	0.01295	a=1.004; k=0.1401; c=-0.0099	0.9942	0.02454
	95	a=0.9830; k=0.2327; c=-0.0175	0.9995	0.00841	a=1.006; k=0.1592; c=-0.0029	0.9967	0.02095
		Average	0.9983	0.01301	Average	0.9952	0.02256
Midilli MR = a exp(-kt) + bt	80	a=1.0070; k=0.0430; n=1.146; b=-2.1E-04	0.9983	0.01446	a=1.019; k=0.0473; n=1.118; b=1.7E-04	0.9943	0.02445
	85	a=0.9981; k=0.0861; n=1.049; b=-2.2E-04	0.9994	0.00885	a=1.000; k=0.0529; n=1.177; b=1.7E-04	0.9980	0.00512
	90	a=1.0010; k=0.1343; n=1.071; b=-4.3E-04	0.9986	0.01289	a=1.004; k=0.0926; n=1.181; b=3.5E-04	0.9963	0.02077
	95	a=1.0000; k=0.2423; n=0.958; b=-4.8E-04	0.9992	0.01139	a=1.001; k=0.1080; n=1.184; b=3.3E-04	0.9986	0.01475
		Average	0.9989	0.01190	Average	0.9968	0.01627
Weibull MR = a - b exp(-kt ⁿ)	80	a=0.0162; b=-0.9903; k=0.0417; n=1.164	0.9984	0.01391	a=0.0151; b=-1.0030; k=0.0455; n=1.14	0.9946	0.02392
	85	a=0.0117; b=-0.9862; k=0.0854; n=1.059	0.9993	0.00909	a=0.0992; b=-0.9898; k=0.0521; n=1.189	0.9998	0.00501
	90	a=0.0218; b=-0.9789; k=0.1227; n=1.137	0.9992	0.00950	a=0.0201; b=-0.9826; k=0.0836; n=1.249	0.9971	0.01836
	95	a=0.0186; b=-0.9816; k=0.2212; n=1.029	0.9995	0.00906	a=0.0141; b=-0.9869; k=0.1032; n=1.222	0.9988	0.01358
		Average	0.9991	0.01039	Average	0.9976	0.01522

R² – determination coefficient; RMSE – root mean square error; MR – moisture ratio; k – drying constant; n, a, b, c, α – empirical parameters.

et al., 2016]. Both the Newton and Henderson & Pabis models had the lowest power of prediction in the change of moisture ratio during RW drying of AP and MP (Table 2). From Newton and Henderson & Pabis model, the Logarithmic, Page, Modified Page (II), Modified Page (IV) were developed by either addition of the constant “c” or a dimensionless empirical constant “n”. The experimental data from this study showed the ability in prediction was higher in developed models (higher R² and lower RMSE values) (Table 2). Midilli and Weibull models were inserted both a dimensionless empirical constant “n” or linear term “bt” and the constant “a”, respectively. That was the reason why Midilli and Weibull models had the highest power of prediction.

In the literature review, Onwude et al. [2016] pointed to many studies in which it was concluded that the Midilli model was the most suitable in determining the thin-layer drying characteristics of fruits and vegetables. However, these studies were carried out without analyzing the Weibull model. Only a few publications conducted evaluations of both the Midilli and Weibull models. They confirmed that both of them were suitable to represent the behavior of the thin-layer drying of persimmon slices [Doymaz, 2012] and lemongrass [Nguyen et al., 2019]. However, in our study, the Weibull model was the best fit model among the investigated models with the highest value of R² and lowest RMSE values. Some previous studies showed that the Weibull model could characterize the drying behavior of mango slices [Corzo et al., 2010], pepino fruit [Uribe et al., 2011], quince slices [Tzempelikos et al., 2015] and yam slices [Ju et al., 2018].

Effective diffusivity and activation energy

During the drying process, the mechanism of moisture transport is not known precisely. Therefore, numerous studies used effective diffusivity as a valid value to determine the ability of moisture removal from different materials using different drying methods. In this study, the effective diffusivity (with R² values) for RW drying of AP and MP was found and presented in Table 3, which also shows the activation energy for moisture removal (with R² values) for AP and MP in RW drying.

The result revealed that when the RW drying temperature was increased from 80 to 95°C, D_{eff} would increase from 4.25 × 10⁻¹⁰ m²/s to 7.24 × 10⁻¹⁰ m²/s for AP, and from 4.50 × 10⁻¹⁰ m²/s to 10.67 × 10⁻¹⁰ m²/s for MP. The range of these D_{eff} values was from 10⁻¹¹ to 10⁻⁸ m²/s when dealing with thin-layer food drying [Onwude et al., 2016]. It seems that the increase in D_{eff} with the temperature was mainly due to a higher hot water temperature in which a more significant amount of thermal energy was transferred into materials leading to faster movement of the water molecules from inside to the surface to evaporate. Some studies in RW drying showed similar results [Rajoriya et al., 2019, 2021]. In the literature, the D_{eff} values in drying of AP are still limited. For mango, Corzo et al. [2008] obtained values of D_{eff} changing from 1.74 × 10⁻¹⁰ to 3.15 × 10⁻¹⁰ m²/s and from 2.30 × 10⁻¹⁰ to 3.28 × 10⁻¹⁰ m²/s for green and half-ripe mango, respectively, when the air-drying temperature varied from 50 to 80°C [Corzo et al., 2008].

The activation energy for AP and MP moisture evaporation was 32.06 and 66.03 kJ/mol in RW drying, respectively.

TABLE 3. The effective diffusivity (D_{eff}) and the activation energy (E_a) in refractance window drying of avocado pulp and mango pulp

Material	Temperature (°C)	D _{eff} (m ² /s)	R ²	E _a (kJ/mol)	R ²
Avocado pulp	80	4.45 × 10 ⁻¹⁰	0.9978	32.06	0.8363
	85	5.02 × 10 ⁻¹⁰	0.9610		
	90	5.15 × 10 ⁻¹⁰	0.9083		
	95	7.24 × 10 ⁻¹⁰	0.9138		
Mango pulp	80	4.50 × 10 ⁻¹⁰	0.9928	66.03	0.9678
	85	5.79 × 10 ⁻¹⁰	0.9968		
	90	9.19 × 10 ⁻¹⁰	0.9935		
	95	10.67 × 10 ⁻¹⁰	0.9967		

R² – coefficient of determination.

In the literature review of Onwude et al. [2016], most publications found E_a values for thin-layer drying of fruits and vegetables ranging from 14.42 to 43.26 kJ/mol; however, few reports obtained E_a values varying from 78.93 to 130.61 kJ/mol. The results clearly showed that MP required more energy for removing moisture than AP. It showed that the drying material's composition, type, and characteristics would directly affect the activation energy values.

Changes of polyphenol content, antioxidant activity and color in RW drying of AP and MP

Figure 3 shows the percentage retention of TPC and antioxidant activity in dried AP and MP at different RW drying conditions. For AP, the retention of TPC decreased when the drying temperature was increased from 80 to 85°C (*p* < 0.05) but the TPC tended to reach highest retention at the drying temperature of 90°C (85.4%). For MP, when drying temperature varied from 80 to 95°C, the TPC retention increased gradually to get highest values at 90°C (85.6%) (*p* < 0.05) and then insignificantly dropped at 95°C (*p* ≥ 0.05). The changes of antioxidant activity were similar to the trend of TPC retention (Figure 3).

Figure 3 also indicated that, generally, the loss of TPC and antioxidant activity occurred in the drying process. During drying, the degradation of TPC was mainly due to the action of enzymes, such as polyphenol oxidases (PPOs) and peroxidase (POD) [McSweeney & Seetharaman, 2015]. The activities of PPOs and POD were previously reported in avocado and mango [Korbel et al., 2013]. The PPOs in avocado pulp were more heat-resistant than those in other fruits and vegetables [Zhou et al., 2016]. However, under heat inactivation at 84°C for 15 min, only around 0.2% of the relative activity of PPOs was maintained in avocado flesh [Gómez-López, 2002]. Vanini et al. [2010] found that fruit maturation, as well as changes in temperature and time, can reduce POD activity. For mango fruit, PPO and POD were most active at temperatures of 50–60°C [Korbel et al., 2013] and could be inactivated at high temperatures of 70–90°C [Queiroz et al., 2008]. Thus, the PPO and POD could have a significant impact on the degradation of phenolics in avocado and mango. In this study, the results indicated that high temperature (90–95°C)

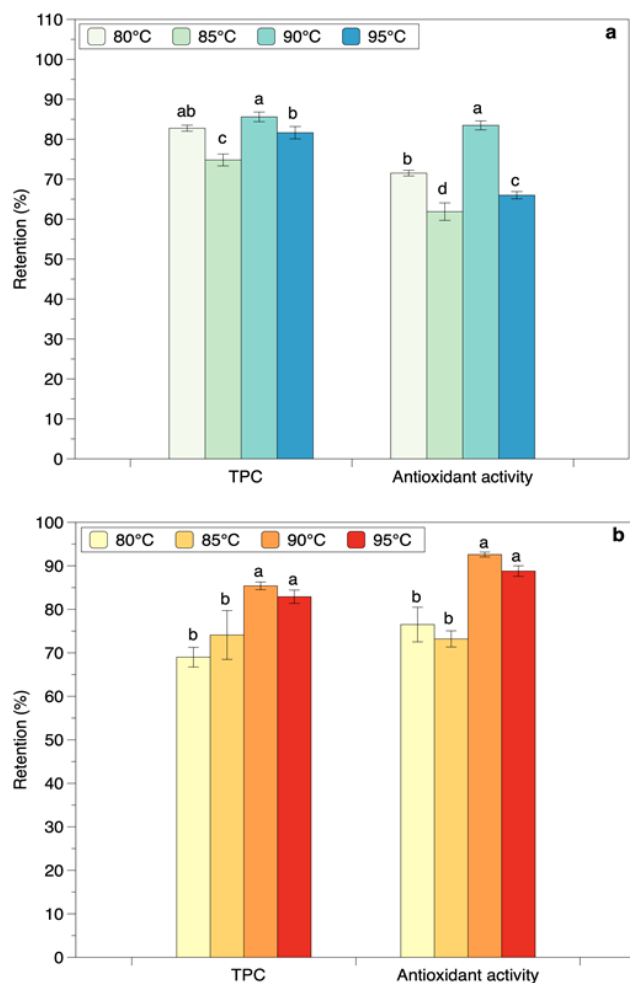


FIGURE 3. The total phenolic content (TPC) and antioxidant activity of powders of avocado pulp (a) and mango pulp (b) obtained by refractance window drying at different temperatures. The same letters above bars within a group indicated that the values are not significantly different ($p \geq 0.05$).

represented the good control of enzyme activity leading to the highest retention of TPC. Besides, drying at lower temperatures (80–85°C) consumed more time to complete operation, which could increase the levels of phenolic degradation. In the drying process, the change of moisture content also contributed to the enzyme activity because of the positive correlation between moisture content and water activity [Chen, 2019]. Therefore, in the initial drying process, the high amount of water could accelerate enzymatic reactions, thereby enhancing degradation of phenolics. The higher temperature resulted in higher rate of reactions, causing more loss at drying temperature of 95°C than 90°C. As a consequence, the drying of AP and MP by the RW technique at 90°C allowed retaining the highest TPC.

Phenolics and phytopigments, such as carotenoids, could act as antioxidants [Huyut *et al.*, 2017; Lanfer-Marquez *et al.*, 2005] based on their structure ideal for acting as free radical scavengers, reducing agents or inhibitors of the formation of free radicals under the catalysis of transition metals. As expected, in this study, the correlations between the antioxidant activity and TPC were very strong, with correlation coefficients of 0.825 and 0.881 for avocado and mango powders,

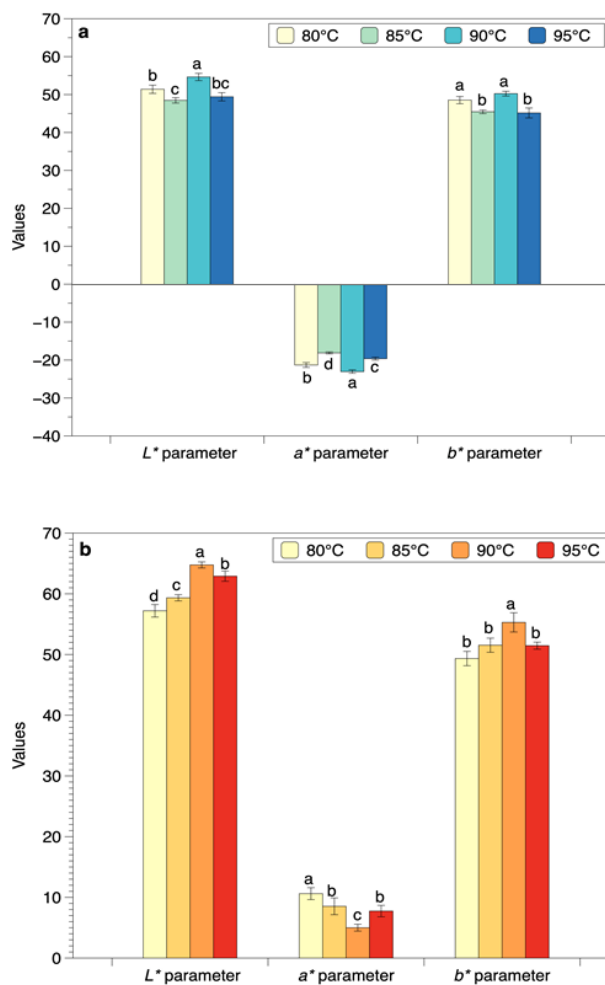


FIGURE 4. The color parameters of powders avocado pulp (a) and mango pulp (b) obtained by refractance window drying at different temperatures. The same letters above bars within a group indicated that the values are not significantly different ($p \geq 0.05$).

respectively, obtained by RW drying at different temperatures (Table 4 and Table 5). The correlation between TPC and antioxidant activity measured as DPPH^{*} scavenging activity was also found for dried Thai red curry powder [Inchuen *et al.*, 2010] and dried fruits, such as apples, mulberries, apricots, and black mulberries [Bushra Sultana, 2012]. It was noted that beyond TPC, other antioxidants found in avocado and mango also contributed to the antioxidant activity, such as vitamins, natural pigments, *etc.* [Lye *et al.*, 2020; Schieber *et al.*, 2000]. However, the high correlation coefficients between TPC and antioxidant activity (more than 0.8) indicated that the phenolics played an important role in the total antioxidant activity.

Figure 4 shows values of the color parameters L^* , a^* and b^* of AP and MP dried using RW at different temperatures. Compared to pulp before drying, the L^* and b^* values of the color of the powders were lower and a^* values was higher. It is implied that, in this study, the color of the dried samples became darker (decrease in L^* value), less green (increase in a^* value), and more yellow (increase of b^* value). Besides, the color parameters (L^* and a^*) had strong correlations with TPC (Table 4 and Table 5).

TABLE 4. Coefficients of Pearson correlation between total phenolic content (TPC), antioxidant activity, and color parameters (L^* , a^* , and b^*) of avocado powders obtained by refractance window drying at different temperatures.

	TPC	Antioxidant activity	L^*	a^*
Antioxidant activity	0.825 (0.001)	1		
L^*	0.815 (0.001)	0.926 (0.000)	1	
a^*	-0.893 (0.000)	-0.957 (0.000)	-0.889 (0.000)	1
b^*	0.760 (0.004)	0.879 (0.000)	0.937 (0.000)	-0.867 (0.000)

The p values are shown in parentheses. Correlations are considered statistically significant at $p < 0.05$ (in bold).

During thermal processing, the discoloration of the product happened, related to pigment destruction and oxidation, enzymatic and non-enzymatic browning, and phenolic polymerization [Bahloul *et al.*, 2009]. For the green-pigmented foods, such as avocado, the less green color was mainly due to the biotransformation of chlorophylls to pheophytins by replacing magnesium ion with hydrogen ions in the center of the porphyrin ring [Rudra *et al.*, 2008]. For foods with the high sugar content, like mango, the browning phenomena were associated with Maillard reaction and caramelization [Potter & Hotchkiss, 1995]. For fruits containing phenolics, it was reported that the browning phenomena were linked to the enzymatic breakdown of these compounds, producing brown pigments [Dorantes-Alvarez *et al.*, 1998; Hershkovitz *et al.*, 2005]. That explained why the correlation was very strong between TPC and color parameters (L^* value and a^* value).

CONCLUSIONS

This study aimed to determine the RW drying behavior of AP and MP. It was found that the drying process mainly occurred in the falling-rate period. Among the investigated mathematical models, the Weibull model showed the best-predicted power of moisture ratio change during RW drying of AP and MP. The effective diffusivity and activation energy for moisture removal in RW drying of AP and MP were in previously reported ranges of thin-layer drying of food. The RW drying had significant effects on the quality of dried avocado and mango and drying at 90°C could retain the highest quality of dried products. It was observed that the RW drying had a high potential in the production of fruit powder from avocado and mango due to the ability to retain more than 80% of TPC and antioxidant activity. This study found that TPC could be used as a useful criterion for evaluating drying process in terms of dried product quality because TPC was strongly correlated with the antioxidant activity and color parameters.

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TABLE 5. Coefficients of Pearson correlation between total phenolic content (TPC), antioxidant activity, and color parameters (L^* , a^* , and b^*) of mango powders obtained by refractance window drying at different temperatures.

	TPC	Antioxidant activity	L^*	a^*
Antioxidant activity	0.881 (0.000)	1		
L^*	0.905 (0.000)	0.888 (0.000)	1	
a^*	-0.748 (0.005)	-0.672 (0.017)	-0.883 (0.000)	1
b^*	0.514 (0.087)	0.529 (0.077)	0.705 (0.010)	-0.805 (0.002)

The p values are shown in parentheses. Correlations are considered statistically significant at $p < 0.05$ (in bold).

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CONFLICT OF INTERESTS

The authors declare no conflict of interest.

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