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# Drying characteristics and quality attributes of Thunbergia laurifolia leaves using microwave drying

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## Abstract

Fresh and blanched *Thunbergia laurifolia* (*T. laurifolia*) leaves were dried in a microwave dryer (MWD) at 450, 720, and 900 W. The drying data obtained were fitted to four single-layer drying models namely, the Henderson and Pabis, modified Page, modified zero and three-parameter models, to describe the drying behaviors of the leaves. Quality aspects of dried leaves were examined including color, microstructure analysis, total phenolics, and bioactive compounds (caffeic and quercetin). The results showed that the three-parameter model was the most accurate in explaining drying data, due to its resulting in the highest coefficient of determination ($R^2$), as well as the lowest standard error of estimate (SEE) and root mean square error (RMSE). Increasing microwave power from 450 W to 900 W led to 42.82% and 36.51% shorter drying times for fresh and blanched leaves, respectively. The blanched leaves provided better color values in terms of hue angle, browning index, and total color difference than dried leaves without blanching. The fresh leaves that underwent MWD at 900 W had more porous and uniform structures than those subjected to other drying conditions. Blanching and MWD at 900 W was the best treatment for dried *T. laurifolia* leaves, due its resulting in the highest total phenolics, caffeic acid, and quercetin retention.

**Keywords:** *Bioactive compound, drying model, microwave drying, scanning electron microscope, Thunbergia laurifolia,*

## 1. Introduction

*Thunbergia laurifolia* (*T. laurifolia*) is a medicinal plant which belongs to Acanthaceae family. It is called *Rang Chuet* in Thai, and is found throughout Thailand and other Asian countries. *T. luarifolia* leaves are twinning, opposite, and heart-shaped. The leaves are 4–7 cm in width, 8–14 cm in length, and 0.05-0.07 cm thick. The purple flower cultivar has been reported to contain pharmacological properties including antidotal, anti-inflammatory, antipyretic, hepatoprotective, anti-diabetic, and antioxidant properties [1]. Phenolics compounds in *T. laurifolia* can function as an antioxidant as well as a chelating agent, and the phenolic compounds may be useful in cancer chemoprevention [2]. High moisture content can reduce the shelf life of fresh fruits and vegetables. Drying is an ancient food processing technology used to remove water from food in order to preserve its quality. It can also lower the cost of packaging, storage, and transportation of food material by reducing the mass, weight, and volume of the finished product [3]. However, one needs to be concerned about retaining the amount of the bioactive compounds in medicinal plants when drying, as most of these compounds are heat sensitive. Heated-air drying is a conventional drying technique used to produce dried products, but this method requires a long drying time, which both leads to a decrease in the quality of the products and has low energy efficiency. Microwave drying at 915 or 2450 HMz is used to remove water from food materials in atmospheric or in vacuum conditions. Heat transfer occurs through radiation in microwave drying. This is different from direct-convection and contact-conduction in that the foods are generating heat themselves through their own dielectric constant and dielectric loss factor properties. Drying models are usually used to help retain various qualities of foods subjected to the drying process by predicting drying behavior and drying time, improving the design of the dryer, and controlling the drying process. Single-layer drying models can be categorized into three types: theoretical, semi-theoretical, and empirical. These models are used as tools to estimate drying behaviors from the experimental data. The Newton, modified Page, Henderson and Pabis, and three-parameter models have been used in dried leaf production, including that of ivy gourd (3), sweet basil [4], moringa [5], *Centella asiatica* L. urban [6] and *T. laurifolia* [7] leaves. Microwave drying has been used to dry various agricultural products including curry leaves [8], mint leaves [9], and peppermint leaves [10]. Microwave drying has been shown to lead to high lutein retention in curry leaves [8] and high β-carotene retention in curry leaves [8], as well as more porous and uniform microstructure [9] and 85 – 90% shorter drying times in mint leaves compared to heated-air drying [9]. The aims of this study were to determine the effects of blanching and microwaving on drying characteristics and quality aspects including, color values, microstructure changes, total phenolics, and bioactive compounds. In addition, it aims to find the conditions for *T. lauriforia* leaf drying that provide the greatest retention of total phenolics and bioactive compounds.

## 2. Materials and methods

*Thunbergia laurifolia* leaves were harvested from a garden on the Khon Kaen University campus in Khon Kaen, Thailand. Fresh leaves (1$^{st}$ and 2$^{nd}$ pairs from the top of stem) were cleaned using 5 ppm chlorinated water. Steam-microwave blanching was performed for 4 min prior to the drying experiments to inactivate enzymatic browning during drying [7].

### *2.1 Drying process*

The drying process was performed in a microwave oven (Electrolux, model EMS 3067X, Stockholm, Sweden). The technical features of the oven were as follows: 220V, 50 Hz and 1,450W, frequency = 2450 MHz. The size of the oven and rotating glass plate diameter were 520 x 440 x 335 mm and 315 mm, respectively. The experiment to test the effect of microwave power on the drying of *T. laurifolia* leaves was performed at a load of 20 g. The drying was performed at three power levels: 450W (50% setting), 720W (80% setting), and 900W (100% setting). Weight reduction of the sample during drying was recorded at 20-second intervals at each power level using a digital scale with an accuracy of 0.01 g. Drying was finished when the sample moisture content was decreased to about 12% of the baseline [11].
Moisture ratio ($M/M_o$) and drying time were fitted to four single-layer drying models (Henderson and Pabis, modified Page, modified zero, and three-paramete; equations (1)-(4) in Table 1) to obtain a suitable model to explain drying behaviors. Effective moisture diffusivities (equation (5)) and activation energies (equations (6) and (7)) were fitted using a non-linear regression technique with SPSS 19.0 for Windows (SPSS, Inc., Chicago, IL). The coefficient of determination ($R^2$), standard error of estimate (SEE), and root mean square error (RMSE) were used to test the quality of fit of the models. The most suitable model was chosen based on the quality of fit in terms of the highest $R^2$ and lowest SEE and RMSE.

**Table 1.** Mathematical modeling

| Model name | Model | Equations |
|---|---|---|
| Modified Page (MP) | $\frac{M}{M_o} = exp(-Kt)^N$ | (1) |
| Henderson and Pabis (HP) | $\frac{M}{M_o} = A\,exp(-Kt)$ | (2) |
| Modified Zero (MZ) | $\frac{M}{M_o} = exp(-Kt)$ | (3) |
| Three parameter (TP) | $\frac{M}{M_o} = A\,exp[(Kt)^N]$ | (4) |
| Moisture diffusivity ($D_{eff}$) | $\frac{M}{M_o} = \frac{8}{\pi^2} exp\left[-\frac{\pi^2 D_{eff} t}{4L^2}\right]$ | (5) |
| Activation energy | $K = K_0 \exp(-\frac{E_a m}{P})$ | (6) |
| | $D_{eff} = D_0 \exp(-\frac{E_a m}{P})$ | (7) |

### *2.2 Color determination*

Color data of the dried *T. laurifolia* leaves were measured using the Hunter Lab (Ultra Scan Xe U3115, Color Global Co., Virginia, USA). The color data that were measured included L*, a*, and b* values, with L* representing the lightness or darkness of the object, a* representing red (+) or green color (-), and b* representing yellow (+) or blue color (-). H* (hue angle) was also reported in order to evaluate the yellow-green color of the leaves (equation (8)), and C* (chroma) was defined by equation (9).

$$\text{Hue angle} = \tan^{-1}\left(\frac{b^*}{a^*}\right) \tag{8}$$

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \tag{9}$$

Browning-index (BI) was an important color parameter used to evaluate the intensity of brown color in the dried samples [12], and was determined using equations (10)-(11).

$$BI = \left[\frac{100(x - 0.31)}{0.17}\right] \tag{10}$$

where

$$x = \frac{(a + 1.75L)}{(5.645L + a - 3.012b)} \tag{11}$$

Total color difference (ΔE*) was the quality index used to compare the total color difference between the dried leaves and a fresh sample. The ΔE* was calculated using equation (12).

$$\Delta E^* = \sqrt{(L^*{}_2 - L^*{}_1)^2 + (a^*{}_2 - a^*{}_1)^2 + (b^*{}_2 - b^*{}_1)^2} \tag{12}$$

Fresh *T. laurifolia* leaves were used as the standard. A larger ΔE* meant higher color difference from the standard.

*2.3 Microstructure analysis*

The microstructure of dried *T. laurifolia* leaves was studied using scanning electron microscopy (SEM) (S-300N, Hitachi, Tokyo, Japan). Dried samples were cut into 10x10 mm pieces. The pieces of the samples were coated with a gold layer with a thickness of 40–50 nm to inspect the surface and enable cross-section visualization. The microstructure of the dried samples was examined at 15kV and a magnification of 500x [9, 13].

*2.4 Extraction*

About 2 g of *T. laurifolia* was extracted using a modified version of the method proposed by Oonsivilai [14] and Praina *et al.* [15]. The method was modified by the addition of 20 mL portions of boiling water (100 $^oC$) or 1 N of NaOH to be mixed with the powders in the incubator shaker (New Bronswick Scientific, INNOVA 4000, New Jersey, USA) for 30 min. The mixture was centrifuged twice at 10,000 x g (Heraeus Megafuge 8, Thermoscientific, Osterode, Germany) for 5 min between extractions. The supernatant was filtrated using vacuum filtration, and the final volume of the extract was increased to 50 mL using the same extraction solvent. The water extract was used to determine total phenolics, and alkaline extract was used to determine bioactive compounds.

*2.5 Dermination of total phenolics*

The method proposed by Ferruzzi *et al.* [16] was modified by mixing of 0.08 mL of *T. laurifolia* leaf extract, 3.15 mL of double deionized water, and 2 mL of Folin-Ciocalteu. The mixture was blended in a vortex mixer for 15 seconds and incubated for 5 min. After incubation, 2 mL of $NaCO_3$ (7%) was added to the mixture. The solution was blended and kept for 30 min at room temperature for optimal color development. Following incubation, the mixture was placed in a cuvette. A wavelength of 765 nm was used to measure absorbance. A working solution of gallic acid was used to construct a standard curve. The result was reported as mg gallic acid equivalent (GAE)/g dry weight.

*2.6 Determination of bioactive compounds (caffeic acid quercetin)*

The *T. laurifolia* leaf extract was analyzed to measure the amount of caffeic acid and quercetin content using a Waters$^{TM}$ (Alliance HPLC, Waters Corporation, Milford, MA, USA). The HPLC method detailed by Oonsivilia [14] was performed to characterize the extracts. An HPLC system that consisted of a Waters 717 plus autosampler 43 (Waters$^{TM}$, USA), Waters in-line degasser (Waters$^{TM}$, USA), Waters 486 tunable absorbance detector (Waters$^{TM}$, USA), and a reversed-phase C18 (3.8 mm inside diameter × 150 mm) column (Milford, MA) with a guard column packed with C18 Waters NovaPak was employed for chromatography. A gradient elution with the mobile phase composed of water/acetic acid (98:2, v/v) was in reservoir A and acetonitrile was in reservoir B. An initial solvent ratio of 99:1 A/B with a linear gradient to 70:30 A/B over 20 min was used, followed by a 5 min linear gradient back to 99:1 A/B and 5 min equilibration at the initial condition for a total chromatographic run time of 30 min. The flow rate (1 mL/min) was applied at 35°C. A volume of 15 µL of each extract was injected, and the detection wavelength was $\lambda$ = 270 nm. Calibration curves were constructed from the authentic standard injection of quercetin and caffeic acid.

*2.7 Statistical treatment*

A completely randomized 2x3 factorial design was used to investigate the main characteristics of the fresh and blanched *T. laurifolia* leaves at each of the microwave power levels (450 W, 720 W and 900 W) and their interaction. Three replication tests were used to examine each drying treatment. Analysis of variance (ANOVA) was calculated using SPSS 19.0 for Windows (SPSS, Inc., Chicago, IL). Duncan’s multiple range tests were used to compare the significance of treatment at a 95% confidence interval.

## 3. Results and discussion

*3.1 Drying experiment*

*3.1.1 Modeling of drying behaviors of T. laurifolia leaves*

The drying of the fresh and blanched *T. laurifolia* leaves was conducted in a microwave dryer (MWD) at 450, 720, and 900 W. The moisture ratio ($M/M_0$) and drying time were fitted to four single-layer drying models (Henderson and Pabis, modified Page, modified Zero and three-parameter) to ascertain the model that best explained drying behaviors. Effective moisture diffusivities ($D_{eff}$) and activation energy (Ea) were also reported.

The drying model constants of *T. laurifolia* leaves are summarized in Table 2. It was found that the three-parameter model was the single-layer drying model that best described the behavior of *T. laurifolia* leaves during drying, as the model provided the highest $R^2$ and the lowest SEE and RMSE. This is consistent with research conducted by Phoungchandang and Kongpim [4] and Potisate *et al.* [5], who found that the three-parameter model was the best drying model to explain the drying behaviors of sweet basil [4] and moringa leaves [5]. A three-parameter model was applied in order to predict the drying curves. The exponent ($N$) was put at the drying constant and drying time of the Modified Zero model to maximize the influence of drying temperature and relative humidity of the drying air for both fresh and blanched leaf drying. Moreover, the constant (A) was put to an exponential term in the modified zero model to explain the effect of moisture diffusion on the samples [5] .

Typical drying curves of fresh and blanched *T. laurifolia* leaves are shown in Figures 1 and 2, respectively. The curves show the moisture ratio and drying time of the fresh and blanched leaves predicted from the three-parameter model compared with the experimental drying data. A constant drying period was not found, and drying occurred in the falling rate drying period (Figure 1 and 2), as drying rates were entirely decreased during the drying processes (Figure 3 and 4). During the falling rate drying period, the rate of water movement from the inside of the leaf to the surface was lower than the rate at which water evaporates into the surrounding air. The surface, therefore, dried out [6]. Increasing the microwave power from 450 W to 900 W led to 42.82% and 36.51% shorter drying times for the fresh and blanched leaves, respectively (Table 3). These results were consistant with those of a report by Torki-Harchegani *et al.* [10], which examined microwave drying of peppermint leaves.

Drying constants (K, $min^{-1}$) are also shown in Table 2. The drying constants of the dried fresh and blanched *T. laurifolia* leaves were within the ranges of 0.4024 to 0.7222 $min^{-1}$ and 0.5403 to 0.7828 $min^{-1}$, respectively. The results showed that the drying constants increased when the microwave power was increased and with blanching treatment. Blanching positively affected the drying constant because the leaf structure was softened due to heat treatment, allowing for faster moisture removal in these leaves than from fresh leaves [3]. Increases in microwave power substantially increased the drying rate, which revealed that mass transfer within these samples was faster than in those dried using slow microwave power. This is because the higher power generated rapid heating within the samples providing a large vapor pressure gradient between the center and the surface of the product due to the characteristics of microwave volumetric heating [18].

Effective moisture diffusivities ($D_{eff}$) of the leaves are presented in Table 3. As shown, $D_{eff}$ values increased when microwave power was increased and with blanching treatment. The values were within the range of 1.346E-8 to 2.610E-8 $m^2/s$ under applied drying conditions. A similar observation was made in a study conducted by Evin in 2011 [17]. Evin’s study found that the elevation of microwave power led to an increase in the heating of the product followed by an increase in the vapor pressure inside of the product, which led, in turn, to a higher diffusion of moisture inside the product [17].

Activation energy ($E_a$) is the smallest amount of energy required to commence moisture diffusion from a product. The Arrhenius model was modified for MWD using (m/P) due to presence of pertinent independent variables [18]. The $E_a$ values of dried *T. laurifolia* leaves under MWD conditions are presented in Table 4. The $E_a$

values were within the range of 23.97 to 43.39 W/g. This range coincided with the reported values for MWD in olive pomace (20.98 W/g) [19] and mango ginger (21.6 W/g) [20]. The result revealed that the blanched dried leaves provided a lower $E_a$ than leaves that were dried without blanching. This is because the blanching treatment helped decrease the leaf wax and increase permeability of the cell wall [17], which led to the evaporation in the blanched leaves requiring lower energy than that in the fresh leaves.

**Table 2** Results of statistical analysis of the drying models for microwave dried *T. laurifolia* leaves

| Models | | Microwave power (W) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Fresh | | | Blanched | | |
| | | 450 | 720 | 900 | 450 | 720 | 900 |
| Modified Page | K ($min^{-1}$) | 0.4159 | 0.6667 | 0.7355 | 0.5726 | 0.7484 | 0.8094 |
| | $R^2$ | 0.9939 | 0.9956 | 0.9944 | 0.9842 | 0.9912 | 0.9868 |
| | SEE | 0.0270 | 0.0230 | 0.0257 | 0.0421 | 0.0322 | 0.0396 |
| | RMSE | 0.0261 | 0.0220 | 0.0243 | 0.0403 | 0.0304 | 0.0371 |
| Henderson and Pabis | K ($min^{-1}$) | 0.4751 | 0.7422 | 0.8028 | 0.6280 | 0.8118 | 0.8698 |
| | $R^2$ | 0.9390 | 0.9645 | 0.9644 | 0.9539 | 0.9633 | 0.9561 |
| | SEE | 0.0852 | 0.0653 | 0.0651 | 0.0719 | 0.0657 | 0.0724 |
| | RMSE | 0.0823 | 0.0623 | 0.0614 | 0.0689 | 0.0619 | 0.0677 |
| Modified Zero | K ($min^{-1}$) | 0.4236 | 0.6913 | 0.7550 | 0.5916 | 0.7659 | 0.8239 |
| | $R^2$ | 0.9198 | 0.9564 | 0.9567 | 0.9483 | 0.9576 | 0.9520 |
| | SEE | 0.0977 | 0.0724 | 0.0719 | 0.0762 | 0.0706 | 0.0757 |
| | RMSE | 0.0944 | 0.0690 | 0.0677 | 0.0729 | 0.0666 | 0.0708 |
| Three parameter | K ($min^{-1}$) | 0.4024 | 0.6494 | 0.7222 | 0.5403 | 0.7269 | 0.7828 |
| | $R^2$ | 0.9959 | 0.9964 | 0.9950 | 0.9882 | 0.9923 | 0.9884 |
| | SEE | 0.0220 | 0.0207 | 0.0245 | 0.0372 | 0.0300 | 0.0364 |
| | RMSE | 0.0213 | 0.0198 | 0.0231 | 0.0349 | 0.0283 | 0.0348 |

**Table 3** Effective moisture diffusivity ($D_{eff}$, $m^2/s$) of dried *T. laurifolia* leaves

| Blanching methods | MW (W) | $D_{eff}$ ($m^2/s$) | Drying time (min) | $R^2$ | SEE ($m^2/s$) | RMSE ($m^2/s$) |
|---|---|---|---|---|---|---|
| Fresh | 450 | 1.346E-8 | 4.67 | 0.804 | 0.153 | 0.148 |
| | 720 | 2.233E-8 | 3.33 | 0.862 | 0.129 | 0.123 |
| | 900 | 2.384E-8 | 2.67 | 0.851 | 0.133 | 0.126 |
| Blanched | 450 | 1.894E-8 | 3.67 | 0.857 | 0.127 | 0.121 |
| | 720 | 2.440E-8 | 2.67 | 0.858 | 0.129 | 0.122 |
| | 900 | 2.610E-8 | 2.33 | 0.847 | 0.135 | 0.126 |

MW: Microwave power

**Table 4** Activation energy (W/g) predicted from drying constant (K) and effective moisture diffusivity ($D_{eff}$) of dried *T. laurifolia* leaves

| Blanching methods | $K_o$ ($min^{-1}$) | Ea (W/g) | $R^2$ | SEE ($min^{-1}$) | RMSE ($min^{-1}$) | $D_o$ ($m^2/s$) | Ea (W/g) | $R^2$ | SEE ($m^2/s$) | RMSE ($m^2/s$) |
|---|---|---|---|---|---|---|---|---|---|---|
| Fresh | 1.314 | 43.388$^a$ | 0.993 | 0.014 | 0.012 | 4.339E-8 | 42.391$^a$ | 0.972 | 9.395E-10 | 1.747E-10 |
| Blanched | 1.145 | 27.718$^a$ | 0.996 | 0.008 | 0.006 | 3.622E-8 | 23.972$^a$ | 0.998 | 7.671E-10 | 1.427E-10 |

**Table 5** Color parameters of dried *T. laurifolia* leaves

| Blanching Methods | Microwave powers (P) | L* | a* | b* | Chroma | Hue angle (degree) | BI | ΔE* |
|---|---|---|---|---|---|---|---|---|
| | 450 | 23.80 ± 0.41$^a$ | 6.33 ± 0.33$^e$ | 36.55 ± 0.75$^c$ | 37.09 ± 0.73$^c$ | 80.16 ± 0.58$^a$ | 926.10 ± 75.25$^d$ | 36.11 ± 0.23$^e$ |
| Fresh | 720 | 24.81 ± 0.39$^b$ | 5.46 ± 0.37$^d$ | 34.47 ± 0.72$^b$ | 34.90 ± 0.70$^b$ | 80.99 ± 0.65$^b$ | 690.62 ± 41.26$^c$ | 35.24 ± 0.25$^d$ |
| | 900 | 31.22 ± 0.77$^c$ | -1.65 ± 0.33$^c$ | 32.56 ± 0.67$^a$ | 32.60 ± 0.67$^a$ | 92.89 ± 0.58$^c$ | 406.25 ± 15.12$^b$ | 29.98 ± 0.20$^c$ |
| | 450 | 45.33 ± 0.39$^d$ | -13.51 ± 0.33$^b$ | 36.80 ± 0.95$^{cd}$ | 39.20 ± 0.93$^d$ | 110.16 ± 0.58$^d$ | 292.66 ± 6.23$^a$ | 27.59 ± 0.08$^a$ |
| Blanched | 720 | 45.70 ± 0.41$^e$ | -13.61 ± 0.34$^b$ | 37.33 ± 0.70$^{de}$ | 39.74 ± 0.69$^{de}$ | 110.04 ± 0.51$^d$ | 294.14 ± 4.49$^a$ | 27.68 ± 0.09$^a$ |
| | 900 | 46.53 ± 0.40$^f$ | -13.90 ± 0.37$^a$ | 37.60 ± 0.77$^e$ | 40.09 ± 0.75$^e$ | 110.30 ± 0.58$^d$ | 291.41 ± 4.86$^a$ | 27.90 ± 0.10$^b$ |

Mean values in the same column with different superscripts are significantly different, at $p \leq 0.05$ according to Duncan's Multiple Range Test.

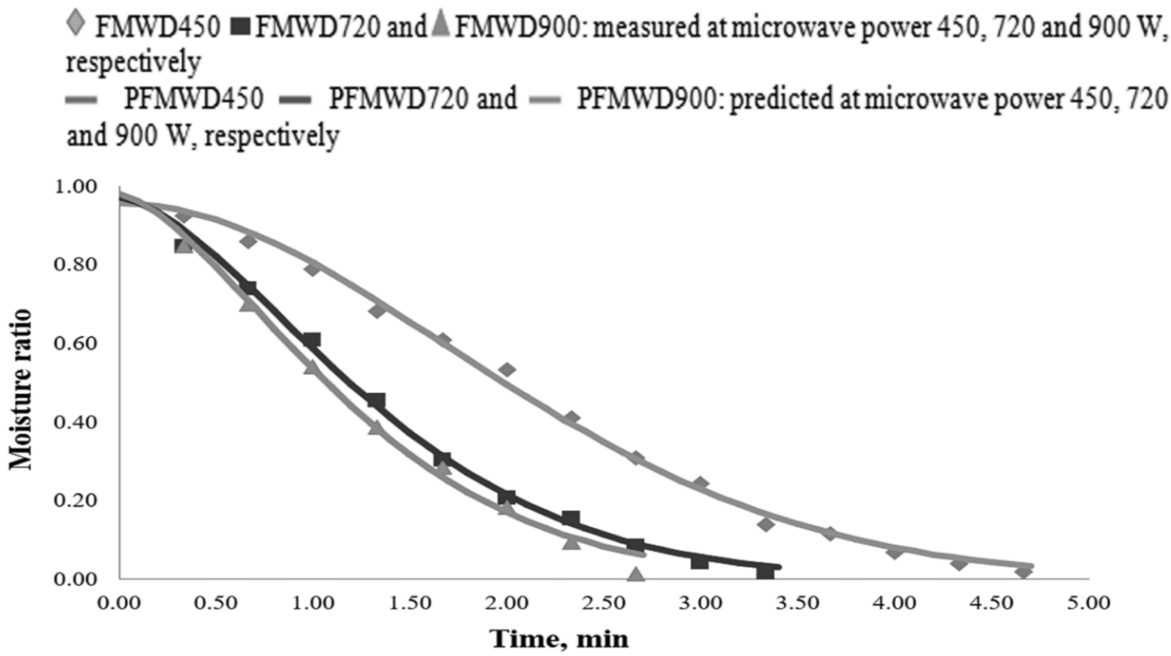


**Figure 1** Moisture ratio of fresh *T. laurifolia* leaves predicted from the three-parameter model compared with the observed experimental data from MWD

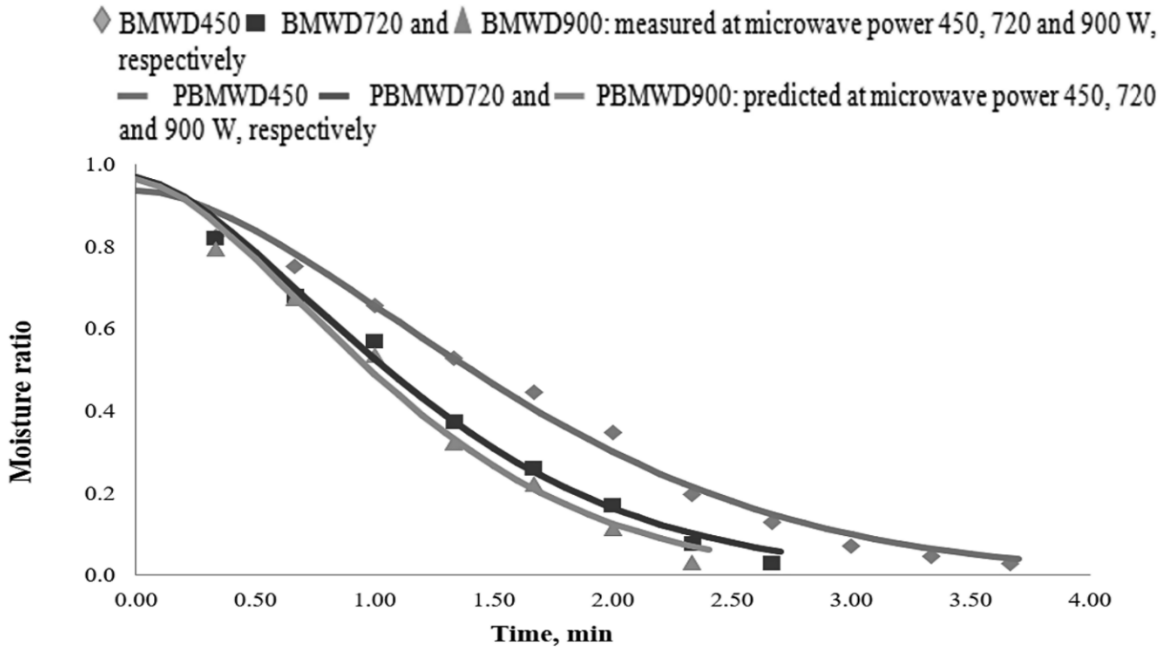


**Figure 2** Moisture ratio of blanched *T. laurifolia* leaves predicted from the three-parameter model compared with the observed experimental data from MWD

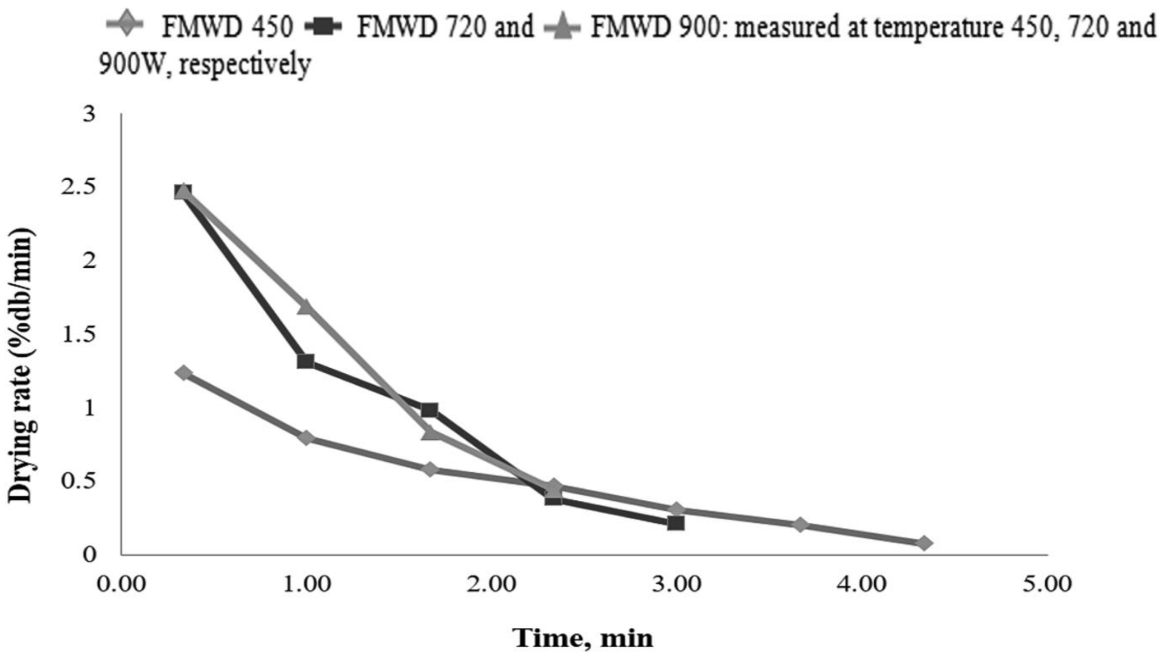


**Figure 3** Drying rate of fresh *T. laurifolia* leaves using MWD at 450, 720, and 900 W

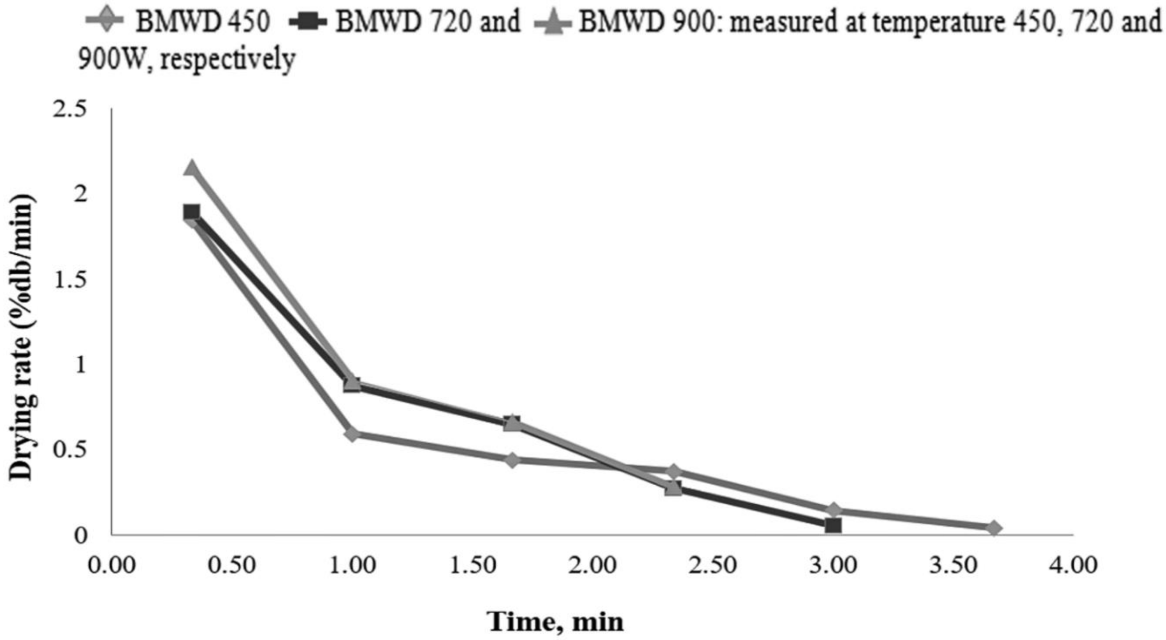


**Figure 4** Drying rate of blanched *T. laurifolia* leaves using MWD at 450, 720, and 900 W

*3.1.2 Color determination*

The influence of microwave power level and blanching treatment on the color parameters of dried *T. laurifolia* leaves is presented in Table 5. The color values were reported in terms of L*, a*, b*, hue angles, chroma, browning index (BI), and total color difference (ΔE*) of the dried *T. laurifolia* leaves compared with fresh leaves. The L* values of both fresh and blanched dried leaves increased with greater microwave power. The L* values of dried blanched leaves were higher than those of dried fresh leaves at the same level of microwave power. These results were similar to those from a 2007 a report by Vadivambal and Jayas [21]. As microwave power was increased, the a* values decreased in dried fresh leaves and slightly decreased dried blanched leaves. The a* values of dried blanched leaves were lower than those of the dried fresh samples at the same microwave power. This means that the dried blanched samples exhibited a greener color than the dried fresh samples. These results are consistent with those of a 2010 study by Porntewabancha and Siriwongwilaichat [22]. As microwave power was increased, the b* and chroma values of the dried fresh leaves decreased, whereas those of the dried blanched leaves increased. The b* and chroma values of dried blanched leaves were higher than those of the dried fresh leaves. The hue angles of the dried fresh leaves increased with increasing microwave power, while the hue angles of dried blanched leaves were not significantly affected by microwave power ($p > 0.05$). The hue angles of the dried blanched leaves were higher than those of the dried fresh leaves. The BIs of the dried fresh leaves decreased with increasing microwave power while those of dried blanched leaves were not significantly different ($p > 0.05$). The BIs of dried blanched leaves were lower than those of dried fresh leaves. This means that blanching treatment inhibited the enzymatic browning reaction [4]. As microwave power was increased, the total color difference ($\Delta E^*$) of dried fresh leaves decreased and that of the dried blanched leaves were slightly lower. Dried blanched leaves provided lower $\Delta E^*$ values than dried fresh leaves. In a 2010 study, Porntewabancha and Siriwongwilaichat [22] reported that pre-treated dried lettuce leaves were greener in color than untreated dried lettuce leaves. Blanching inactivates enzymes involved in chlorophyll degradation, resulting in the retention of green color in dried leaves. The highest Hue angles and the lowest BIs were found in blanched samples dried at 450 to 900 W, whereas the lowest $\Delta E^*$ was found in blanched samples dried at 450 to 720 W. This shows that blanching and microwave power level significantly affected the color parameters of *T. laurifolia* leaves ($p \leq 0.05$).

*3.1.3 Scanning electron micrograph*

Microscopy is a useful technique for studying the influence of processing parameters and ingredients on the microstructure of foods [23]. Scanning electron microscopy (SEM) is an extremely useful tool in visualizing the microstructure of foods because it combines many of the best features of light microscopy (LM) and transmission electron microscopy (TEM) [24]. This was used to measure the structure of dried *T. laurifolia* leaves (Figure 5). Drying fresh leaves at 900 W (Figure 5c) led to the least cell damage, tissue shrinkage, and collapse among the MWD conditions tested. A previous study showed that the cell structure of microwave-dried moringa leaves was more porous and that these leaves had a more open cell structure than heated-air-dried leaves. In addition, elevation of microwave power tended to increase the evaporation rate, resulting in less shrinkage and case hardening [5].

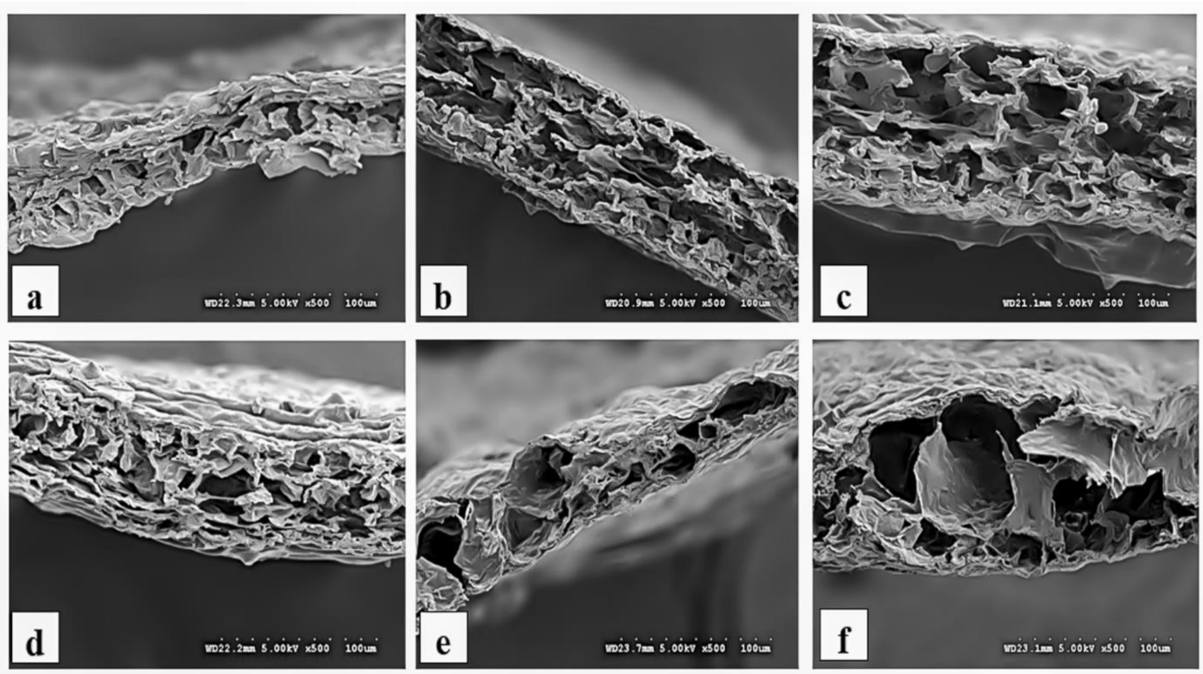


**Figure 5** SEM photographs (500×) of MWD dried *T. laurifolia* leaves (a – c) fresh dried *T. laurifolia* leaves at 450, 720 and 900 W, respectively; (d – f) blanched dried *T. laurifolia* leaves at 450, 720 and 900 W, respectively

*3.1.4 Total phenolics*

Phenolics are universal secondary metabolites in plants. They are composed of a large group of bioactive compounds. A number of phenol subunits have been categorized into two basic groups: simple phenols and polyphenols. The simple phenols group contains the so-called phenolic acids or phenols with carboxyl group underlying the specificity of their function [25]. Phenolics or polyphenols have received considerable attention because of their antioxidant, antimutagenic, and antitumor activities [26]. The total phenolic content of the leaves tested in this study is presented in Table 6. The blanched and dried leaves had higher total phenolic content than leaves that were dried without blanching at the same microwave power. The blanched *T. laurifolia* leaves that were dried at 900W contained the highest content of total phenolics. The short drying time obtained from MWD was able to increase the phenolic content of MWD dried samples [27] and total phenolics declined with lower power and longer drying times.

*3.1.5 Bioactive compounds*

Many bioactive compounds in food function as antioxidants. Previous studies have looked at the relationship between antioxidants and risk of disease [28]. Epidemiological studies have shown a strong and consistent protective effect of vegetable consumption against the risk of several age-related diseases such as cancer, cardiovascular disease, cataract, and macular degeneration [29].

Bioactive compounds, including caffeic acid and quercetin content, are presented in Table 6. According to Table 6, the blanched *T. laurifolia* leaves that underwent MWD at 900 W retained the highest caffeic acid and quercetin content. These results are in accordance with those of a study by Wojdylo *et al.* [30], which revealed that high microwave power provided the best quality of dried product and that the drying process had a positive effect on quercetin and keampferol content. In addition, blanching treatment and MWD at 900 W led to the retention of 45.83% of caffeic acid and 27.03% of quercetin in the dried leaves. Drying at high power has been shown to lead to shorter drying times [27], while drying at low microwave power has been shown to lead to longer drying times, resulting in a decrease in the quality of the dried product [5].

**Table 6** Total phenolics and bioactive compounds of dried *T. laurifolia* leaves

| Blanching methods | Microwave power (W) | Total phenolics (mg GAE/g DW) | Caffeic acid (mg/ g DW) | Quercetin (mg/ g DW) |
|---|---|---|---|---|
| | 450 | $23.09 \pm 0.45^{a}$ | $0.08 \pm 0.01^{a}$ | $5.12 \pm 0.12^{a}$ |
| Fresh | 720 | $30.26 \pm 0.91^{b}$ | $0.24 \pm 0.01^{b}$ | $6.94 \pm 0.10^{b}$ |
| | 900 | $34.12 \pm 0.74^{c}$ | $0.78 \pm 0.10^{c}$ | $7.37 \pm 0.14^{b}$ |
| | 450 | $121.59 \pm 0.39^{d}$ | $1.04 \pm 0.04^{d}$ | $7.06 \pm 0.08^{b}$ |
| Blanched | 720 | $129.43 \pm 1.35^{e}$ | $1.15 \pm 0.05^{e}$ | $8.85 \pm 0.09^{c}$ |
| | 900 | $135.67 \pm 1.02^{f}$ | $1.44 \pm 0.02^{f}$ | $10.10 \pm 0.18^{d}$ |

Mean values in the same column with different superscripts are significantly different at $p \leq 0.05$ by Duncan's Multiple Range Test.
GAE: Gallic acid equivalent

## 4. Conclusion

Fresh and blanched *T. laurifolia* leaves were dried in a microwave dryer at 450, 720, and 900W. Drying data were fitted to four single-layer drying models: modified Page, Henderson and Pabis, modified zero, and three parameter. The result showed that the three-parameter model was the most accurate, due to it having the highest $R^2$ and lowest SEE and RMSE. The drying constants (K) for fresh and blanched leaves were within the ranges of 0.4024 to 0.7222 $min^{-1}$ and 0.5403 to 0.7828 $min^{-1}$, respectively. The drying constants increased as microwave power was increased. Increasing microwave power from 450 W to 900 W led reductions in drying time of 42.82% and 36.51% for fresh and blanched leaves, respectively. The $D_{eff}$ values were within the range of 1.346E-8 to 2.610E-8 $m^2/s$ and increased with increased microwave power and blanching treatment. Blanching and MWD provided better color values including hue angle (H*), browning index (BI), and total color difference ($\Delta E^*$). The fresh leaves dried at 900 W were more porous and exhibited fewer changes in cell structure than those subjected to other drying methods. Blanched *T. laurifolia* leaves had higher total phenolic, caffeic acid and quercetin content. In addition, the blanching treatment and MWD at 900 W led to the retention of 45.83% of caffeic acid and 27.03% of quercetin in the dried leaves. Blanching and drying in the microwave dryer at 900 W was the best treatment method, as it resulted in the greatest total retention of phenolics, caffeic acid, and quercetin.

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