Microwave blanching and drying characteristics of *Centella asiatica* (L.) urban leaves using tray and heat pump-assisted dehumidified drying

W. Trirattanapikul · S. Phoungchandang

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Abstract The appropriate stage of maturity of *Centella asiatica* (L.) Urban leaves was investigated. Mature leaves with large diameter contained high total phenolics and % inhibition. Microwave blanching for 30 s retained the highest total phenolics and the microwave blanching for 30 s and 45 s retained the highest % inhibition. Modified Henderson and Modified Chung-Pfost models showed the best fit to both fresh and blanched leaves for equilibrium moisture content, $X_e = f(RH_e, T)$ and equilibrium relative humidity, $RH_e = f(X_e, T)$, respectively. The Modified Page model was the most effective model in describing the leaf drying. All drying was in the falling rate period. The drying constant was related to drying air temperature using the Arrhenius model. Effective moisture diffusivities increased with increasing temperature and blanching treatments as well as dehumidification by heat pump-assisted dehumidified dryer. The heat pump-assisted dehumidified drying incorporated by the microwave blanching could reduce the drying time at 40 °C by 31.2 % and increase % inhibition by 6.1 %. Quality evaluation by total phenolics, % inhibition and rehydration ratio showed the best quality for *C. asiatica* leaves pretreated by microwave blanching and dried at 40 °C in heat pump-assisted dehumidified dryer.

Keywords *Centella asiatica* · Desorption isotherms · Heat pump-assisted dehumidified drying · Microwave blanching · Tray drying

Nomenclature

a b Empirical constants in drying models

A B	Empirical constants
C_1 - C_{12}	Empirical constants
D_{eff}	Effective moisture diffusivity m^2/s
K	Drying constant min^{-1}
L	Half thickness of <i>C. asiatica</i> leaf m
n	Number of data point
N	Drying exponent
R^2	Coefficient of determination
RH	Relative humidity decimal
SEE	Standard error of estimate
t	Time min
T	Temperature °C
X	Moisture content % d.b.

Principles of drying kinetics

Centella asiatica (L.) Urban is a slender creeping plant (Kartnig 1988). Popularity of *C. asiatica* is mostly due to its reputation as a wound healing agent and brain stimulant (Bonte et al. 1994). *C. asiatica* can grow wild in both tropical and sub-tropical countries (Yoshinori et al. 1982). It is used in the ayurvedic system of medicine to treat various ailments like headache, body ache, insanity, asthma, leprosy, ulcers, eczemas and wound healing (Chopra et al. 1956; Shukla et al. 1999; Suguna et al. 1996). In addition, it is also believed to be able to purify blood, cure indigestion and nervousness, treat skin disorders and as a diuretic and antihypertensive agent (Jayatilake and MacLeod 1987; Ramaswamy et al. 1970). *C. asiatica* has the propensity to modulate both endogenous and neurotoxicant induced oxidative impairments in the brain and may be effectively employed as neuroprotective adjuvant to abrogate oxidative stress in vivo (George and Muralidhara 2008a, b).

In biological systems, such as foods, water is believed to exist with either unhindered or hindered mobility, referred to

W. Trirattanapikul · S. Phoungchandang (✉)
Department of Food Technology, Faculty of Technology,
Khon Kean University,
123 Mittapab Road,
Khon Kaen 40002, Thailand
e-mail: sinpho84@yahoo.com

as free and bound water, respectively. The relationship between total moisture content and water activity of the food, over a range of values, and at a constant temperature, yields a moisture sorption isotherm (Al-Muhtaseb et al. 2002). Drying is the process of removing moisture from a food product which is accomplished by heat. In this process, two transport phenomena occur. They are moisture movement and heat transfer, which occur simultaneously. Many researchers have performed several numerical and experimental investigations on the heat pump dehumidified dryer for drying different biomaterial products. Simulation models of the heat pump-assisted dehumidified dryer were developed by Alves-Filho et al. (1997) for fruit and root drying, Achariyaviriya et al. (2000) for fruit drying and Phoungchandang (2008) for some herbs. Design of the heat pump-assisted dehumidified dryer were performed by Ogura et al. (2005) for a control strategy for chemical heat pump dryer, Saensabai and Prasertsan (2007) for condenser coil optimization and component matching and Pal and Khan (2008) for calculation steps for the design of different components. However, various types of products have been dried in experimental heat pump dehumidified dryers. Dried products include biomaterials (Alves-Filho and Strommen 1996), sawn rubber wood and bananas (Prasertsan and Saen-saby 1998), banana (Chua et al. 2001), holy basil leaves (Phoungchandang et al. 2003), garlic (Boonnattakorn et al. 2004), mangoes (Chottanom and Phoungchandang 2005), ginger (Hawlder et al. 2006; Phoungchandang et al. 2009; Phoungchandang and Saentaweek 2011), composite food products (Rahman et al. 2007), red pepper (Alves-Filho et al. 2007), protein (Alves-Filho et al. 2008), kaffir lime leaves (Phoungchandang et al. 2008a), white mulberry leaves (Phoungchandang et al. 2008b) and ivy gourd leaves (Potisate and Phoungchandang 2010).

Drying model

In this work, the general approaches of Sun and Woods (1994) for wheat, Phoungchandang et al. (2008a) for kaffir lime leaves and Phoungchandang et al. (2008b) for white mulberry leaves were adopted and developed from the review of isotherm determination in Sun and Woods (1993) for wheat. This involved fitting 4 well-established forms for the sorption model to the desorption data for *C. asiatica* leaves in order to establish the best fit. The following isotherm models were selected.

1. Modified Oswin model (MO)

$$X_e = \frac{C_1 + C_2 T}{\left[\frac{1}{RH_e} - 1 \right]^{1/C_3}} \quad (1)$$

$$\frac{1}{RH_e} = \left[\frac{C_1 + C_2 T}{X_e} \right]^{C_3} + 1 \quad (2)$$

2. Modified Henderson model (MH)

$$X_e = \left[\frac{\ln(1 - RH_e)}{-C_4(T + C_5)} \right]^{1/C_6} \quad (3)$$

$$RH_e = 1 - \exp[-C_4(T + C_5)X_e^{C_6}] \quad (4)$$

3. Modified Chung-Pfost model (MCP)

$$X_e = \frac{1}{-C_9} \ln \left[\frac{(T + C_8) \ln(RH_e)}{-C_7} \right] \quad (5)$$

$$RH_e = \exp \left[\frac{-C_7}{T + C_8} \exp(-C_9 X_e) \right] \quad (6)$$

4. Modified Halsey model (MHAL)

$$X_e = \left[\frac{-\ln(RH_e)}{\exp(C_{10} + C_{11}T)} \right]^{-1/C_{12}} \quad (7)$$

$$RH_e = \exp[-\exp(C_{10} + C_{11}T)X_e^{-C_{12}}] \quad (8)$$

Equations (2), (4), (6) and (8) for relative humidity (RH_e) are fitted by minimizing the standard error of estimate:

$$SEE = \sqrt{\frac{\sum_{i=1}^n (RH_e - RH_p)^2}{n - 1}} \quad (9)$$

Where, $n-1$ gives the number of degrees of freedom of the fitted equation. Equations (1), (3), (5) and (7) are all fitted by minimizing the SEE based on measured and predicted values of moisture content (X_e).

Drying constant

The relationship analogous to Newton law of cooling is often used in drying analysis in order to describe the falling rate period. The rate of moisture loss is assumed to be proportional to the moisture remaining to be lost and is shown as follows:

$$\frac{dX}{dt} = -K(X - X_e) \quad (10)$$

By integration, this yields the Newton (NT) or exponential drying model.

$$\frac{X - X_e}{X_0 - X_e} = \exp(-Kt) \quad (11)$$

A modified form of Page's (MP) drying model was employed to describe the experimental data.

$$\frac{X - X_e}{X_0 - X_e} = \exp(-(Kt)^N) \quad (12)$$

Phoungchandang and Woods (2000) proposed the Zero (ZR) model because the equilibrium moisture content of banana was close to 0.

$$X = X_0 \exp(-Kt) \quad (13)$$

The movement of moisture occurred by diffusion and analogous to that of heat conduction in solid. The Henderson and Pabis (HP) model was used to describe the falling rate during the drying period.

$$\frac{X - X_e}{X_0 - X_e} = A \exp(-Kt) \quad (14)$$

The drying constant (K) can be related to temperature using the Arrhenius model.

$$K = a \exp\left(-\frac{b}{T + 273.15}\right) \quad (15)$$

The drying exponent (N) can be related to relative humidity and temperature.

$$N = A \times RH^B \times \exp(C/T) \quad (16)$$

The drying data can be used to determine effective moisture diffusivity (D_{eff}) from diffusion model.

$$\frac{X - X_e}{X_0 - X_e} = \frac{8}{\pi^2} \exp\left[-\frac{\pi^2 D_{\text{eff}} t}{4L^2}\right] \quad (17)$$

The objectives of this work were to investigate maturity of *C. asiatica* leaves, desorption isotherms, microwave blanching, moisture diffusivities and drying constant over a range of temperatures and humidities for *C. asiatica* leaves by tray and heat pump-assisted dehumidified drying. The effects of microwave blanching treatment, drying temperature and the kinds of dryer on the final quality of dried leaves were also included.

Materials and methods

Maturity

C. asiatica leaves were harvested from Khon Kaen province, Thailand. The *C. asiatica* leaves were divided into three groups according to their diameters. Moisture content (AOAC 2000), color values (CIE L^* , a^* , b^*), % inhibition (Maisuthisakul et al. 2008), total phenolics (Maisuthisakul et al. 2008) and crude fiber (AOAC 2000) were determined.

Blanching treatments

Ten grams of blanched sample were cut into small pieces and placed in a mortar. Sufficient water was added to give the best consistency for through maceration. The sample was ground for 3 min. Water was added so that the total water added was 30 mL and mixed thoroughly. Mixture was filtered through cotton gauze and 2 mL of filtrate were added to 20 mL distilled water in $\frac{3}{4}$ in. diameter test tube. One mL of 0.5 % guaiacol solution and 1 mL of 0.8 % hydrogen peroxide were added to the mixture without mixing. The contents were mixed thoroughly by inverting the tube and color development was noted. If none developed in 3.5 min, the test was negative and the product was adequately blanched. If color developed after 3.5 min, the test was still considered negative (Luh and O'Neal 1975).

The *C. asiatica* leaves were cleaned in 5 mg/kg chlorinated water. Ten grams of the leaves were used in the blanching treatment. Three blanching treatments were conducted in the study which were as follow.

- (1) Fresh (No pre-drying treatment)
- (2) Blanching in boiling water for 15, 30, 45 and 60 s.
- (3) Blanching in microwave: *C. asiatica* leaves were blanched in a microwave oven (LG, MS 1822C, Korea) at 800 W (100 % setting) and the frequency of 2,450 MHz for 15, 30, 45 and 60 s.

After blanching, *C. asiatica* leaves were dipped immediately into water to avoid over blanching and the water was drained properly before drying.

Desorption isotherms

Fresh and blanched *C. asiatica* leaves were placed on a pre-weighted drying tray in order to proceed to the thin-layer drying process using a tray dryer (Armfield Limited, Hampshire, England) at 50 °C to obtain seven different levels of moisture content (Phoungchandang and Woods 2000). The dried leaves of 0.5 g were measured for equilibrium relative humidity at 20, 35 and 50 °C, respectively, by using Aqualab (Series 3TE, Devices, America) that is specially designed for temperature – controlled dew point of water activity or relative humidity at equilibrium state with an accuracy of 0.01 %. The temperature of the measurement chamber is regulated to set point by a controller with accuracy to 0.3 °C and its range is 15–50 °C.

Air-drying procedure

The tray dryer (Armfield limited, Hampshire, England) comprises an air duct mounted on a floor standing frame to give a comfortable working height for the operator. Air is drawn into the duct through a mesh guard by a motor driven

Fig. 1 Heat pump-assisted dehumidified dryer (Phoungchandang et al. 2003)

axial flow fan impeller whose speed can be controlled to produce a range of air velocity up to 1.5 m/s in the duct. The air passes over an electrically heated element controlled by a power regulator to provide a variation in air temperature up to a maximum of 80 °C at low air velocities.

The air passes into the central section of the duct where four trays of material to be dried are suspended in the air stream. The trays are carried on a support frame which is attached to a digital balance with an accuracy of 0.01 g mounted above the duct and on which the total weight is continuously indicated. The trays are inserted or removed from the duct through a latched side door with a glass panel for viewing purposes.

The heat pump-assisted dehumidified dryer used in the experiments was described by Phoungchandang et al. (2003) as shown in Fig. 1. The basic components of the heat pump system comprise an expansion valve, two heat exchangers (evaporator and condenser) and a compressor. The drying chamber dimension is 0.95×1.80×1.70 m. The compressor is refrigerated-cooled reciprocating type with a capacity of 250 W. The air passes over an electrical heated element with a capacity of 1,300 W. The velocity of air is regulated by a fan at 0.5 m/s. The air passes into the central section of the drying

chamber where four trays of material to be dried are suspended in the air stream.

The effect of drying air temperature on the drying process of *C. asiatica* leaves was investigated at a load of 30 g and were dried in thin layer at 40, 50 and 60 °C in a tray dryer (TD) (Armfield limited, Hampshire, England) and a heat pump-assisted dehumidified dryer (HPD) (Phoungchandang et al. 2003). An anemometer (MODEL 3K-27V No.7680-00, SATO KEIRYOKI, Tokyo, Japan) with an accuracy of 0.01 m/s was used to measure air velocity. The air velocity in both dryers was maintained constant at 0.5 m/s (Sun and Woods 1994). A relative humidity meter (VAISALA MODEL HMP-5D, DELTA OHM-VIAG, Galilei, Italy) with accuracy of 0.01 % RH was used to measure the relative humidity (RH) of drying air. An average relative humidity of drying air throughout the drying was used. An average relative humidity of drying air throughout the drying was used to predict equilibrium moisture content from a fitted desorption isotherm model. The weight loss of the sample was recorded every 5 min by using a data logger (DT 800 Data Taker, SCORESBY, Victoria, Australia). The drying was terminated when the moisture content (AOAC 2000) of the sample was reduced to 11.1 % w.b. (12.5 % d.b.) which corresponded with the relative humidity of 0.6 for a safe level.

Table 1 The relationship of moisture content, total phenolics, % inhibition, color values and crude fiber of fresh *C. asiatica* leaves

Maturity (Diameter, cm)	Moisture content (%d.b.)	Total phenolics (mg/gd.b.)	%inhibition	Color values			Crude fiber (%d.b.)
				L*	a*	b*	
3.6–4.5	628.3±5.65 ^a	5.5±0.06 ^a	22.2±0.56 ^a	37.4±10.25 ^a	−11.4±0.86 ^a	21.9±3.57 ^a	11.3±0.67 ^a
4.6–5.5	670.2±62.69 ^a	6.2±0.10 ^b	25.9±0.14 ^b	40.5±1.13 ^a	−11.6±0.92 ^a	21.3±3.07 ^a	10.9±0.60 ^a
5.6–6.5	649.5±45.38 ^a	6.3±0.14 ^b	25.7±0.22 ^b	39.9±1.22 ^a	−11.1±0.59 ^a	19.6±2.13 ^a	10.9±0.55 ^a

Different superscripts in the same column mean that the values are significant different ($p \leq 0.05$) ($n=3$)

Table 2 Effect of blanching time and blanching methods on total phenolics and % inhibition of fresh *C. asiatica* leaves

Time (s)	Total phenolics (mg/g)		%inhibition	
	Boiling water blanching	Microwave blanching	Boiling water blanching	Microwave blanching
15	8.7±0.06 ^b	7.2±0.07 ^a	13.7±0.12 ^d	6.5±0.36 ^a
30	9.4±0.06 ^c	10.6±0.06 ^c	14.2±0.23 ^d	16.3±0.27 ^e
45	9.2±0.06 ^c	10.1±0.07 ^d	13.8±0.18 ^d	16.1±0.08 ^e
60	7.5±0.06 ^a	8.6±0.32 ^b	8.5±0.33 ^b	10.3±0.50 ^c

Different superscripts in the same column mean that the values are significantly different ($p \leq 0.05$) ($n=3$)

Sample extraction

Ten grams of fresh *C. asiatica* leaves and 2 g of dried *C. asiatica* leaves were ground and extracted in 100 mL pure ethanol with continuous shaking for 4.5 h at room temperature. The extracts were filtered through a Whatman paper No.1. The clear extracts were used to determine both total phenolics and antioxidant activity.

Total phenolics

The total phenolics (TPC) of extracts were determined using the Folin-Ciocalteu assay. Samples (300 μ L) were introduced into test tubes followed by 1.5 mL of Folin-Ciocalteu's reagent and 1.2 mL of sodium carbonate (7.5 %w/v). The tubes were allowed to stand for 30 min before absorbance at 765 nm was measured. TPC was expressed as gallic acid equivalent (GAE) in mg/g dry weight. The calibration equation for gallic acid was $y=0.008x+0.026$ ($R^2=0.996$) where y is the absorbance and x is the concentration of gallic acid in μ g/L (Maisuthisakul et al. 2008).

DPPH radical-scavenging activity

Seventy seven μ L of extracts were added to 3 mL of 2, 2-diphenyl-1-picrylhydrazyl (2.4 mg/100 mL ethanol). Deionized distilled water was used as control. The mixture was vortex-mixed for 1 min and allowed to stand for 15 min in a dark cabinet at room temperature before absorbance at 515 nm was measured. Pure ethanol was used to calibrate the spectrophotometer (LAMDA 25, PerkinElmer, America). To test the stability of DPPH, pure ethanol was used as a blank. Radical-scavenging ability was calculated as percentage inhibition of DPPH radical (Maisuthisakul et al. 2008).

$$\% \text{ Inhibition} = \frac{Abs_{control} - Abs_{sample}}{Abs_{control}} \times 100 \dots \quad (18)$$

Color measurement

The color of *C. asiatica* leaves was determined before and after drying using Hunter Lab (Ultra Scan, XE U3115, Color Global

Fig. 2 Desorption isotherms at 20, 35 and 50 °C as predicted using the fitted Modified Henderson model for (a) fresh and (b) microwave blanched *C. asiatica* leaves compared with the observed experimental data

Co., Virginia, America). The color was measured in terms of Hunter L*, a* and b* values. Hunter L* represented the lightness or darkness of the object and it was measured on a scale of 0 to 100. L* value of 100 represented white and L* of 0 represented black. Hunter a* represented redness (+) or greenness (-). Hunter b* represented yellowness (+) or blueness (-).

Total color difference ($\Delta E^* = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2 \right]^{\frac{1}{2}}$) was also determined.

Rehydration ratio

Five grams of dried *C. asiatica* leaves were added to 500 mL of distilled water at 30 °C, agitated and then allowed to rehydrate. At every 5 min intervals, the leaves were removed from the water, drained and weighed until the weight was constant. The experiments were carried out in triplicate and their average values were reported. Rehydration ratio was calculated by dividing rehydrated *C. asiatica* leaves with dry *C. asiatica* leaves.

Data analysis procedure

A completely randomized design was used to study the main factors of the leaf maturity. A completely randomized 3×4 factorial experiment was used to study the main factors of the blanching treatments and blanching time and interactions between main factors. Desorption isotherm data were fitted to four sorption isotherm models in Eqs. (1) to (8). Drying experiments were performed in triplicate and the average values were fitted to four drying models in Eqs. (11) to (14). The drying constant (K) was related to drying air temperature in Eq. (15). The drying exponent (N) was related to the relative humidity and drying air temperature in Eq. (16). Thickness of *C. asiatica* leaves (L) was determined using a micrometer (Mitutoyo, Japan). The effective diffusivities (D_{eff}) were calculated by using Eq. (17). The model parameters were processed by non-linear regression technique using SPSS 16.0 for Windows (SPSS, Inc., Chicago: IL). The quality of fit of the tested models was evaluated using the coefficient of determination (R^2) and standard error of estimate (SEE). A completely randomized 2×2×3 factorial experiment was used to study the main factors of the drying process; pretreatments, tray, heat pump-assisted dehumidified dryers and drying temperatures and interactions between main factors. Three replications were used to determine each parameter. SPSS 16 for Windows was used to calculate analysis of variance (ANOVA). Duncan's multiple range test was used to determine the significant treatments at a 95 % confidence interval.

Table 3 Constants of desorption isotherms for fresh and microwave blanched *C. asiatica* leaves

Model	C ₁		C ₂		C ₃		SEE (% d.b.)		R ²	
	Fresh	Blanching	Fresh	Blanching	Fresh	Blanching	Fresh	Blanching	Fresh	Blanching
$X_e = f(RH_e, T)$										
MH	0.0003	0.00017	440.236	280.54781	0.713	1.26453	1.387	0.572	0.975	0.950
MHAL	1.629	2.68273	-0.003	-0.00392	0.900	1.44898	1.685	0.657	0.963	0.935
MCP	-2,211,678,545.214	-1,976,354,871.294	-1,630,873,677.454	-817,916,009,0104	15.199	7.15159	1.733	0.615	0.961	0.943
MO	9.193	8.23363	-0.028	-0.01978	1.131	1.88719	1.517	0.610	0.970	0.944
$RH_e = f(X_e, T)$										
MH	0.0004	0.00019	405.960	299.76860	0.647	1.16563	0.042	0.031	0.948	0.942
MHAL	1.057	2.02935	-0.002	-0.00297	0.682	1.14957	0.049	0.040	0.929	0.902
MCP	559.562	743.07748	388.733	303.26660	0.069	0.15051	0.040	0.028	0.953	0.951
MO	8.516	8.14954	-0.0277	-0.01932	0.930	1.63027	0.046	0.035	0.938	0.925

MH Modified Henderson model, MHAL Modified Halsey model, MCP Modified Chung-Pfost model and MO Modified Oswin model

Table 4 Results of statistical analysis on the modeling of *C. asiatica* leaves

Dryer	Pretreatment	Temp. (°C)	R ²				SEE (%d.b.)			
			NT	MP	HP	ZR	NT	MP	HP	ZR
TD	Fresh	40	0.9790	0.9843	0.9790	0.9794	0.0404	0.0350	0.0404	0.0399
		50	0.9866	0.9929	0.9874	0.9866	0.0362	0.0236	0.0351	0.0362
		60	0.9820	0.9915	0.9831	0.9820	0.0435	0.0298	0.0422	0.0435
	Microwave blanching	40	0.9724	0.9920	0.9761	0.9731	0.0530	0.0285	0.0494	0.0512
		50	0.9856	0.9900	0.9856	0.9855	0.0403	0.0335	0.0403	0.0403
		60	0.9710	0.9945	0.9737	0.9708	0.0648	0.0283	0.0616	0.0648
HPD	Fresh	40	0.9817	0.9878	0.9822	0.9822	0.0387	0.0316	0.0381	0.0381
		50	0.9776	0.9944	0.9808	0.9776	0.0483	0.0242	0.0447	0.0483
		60	0.9717	0.9944	0.9757	0.9724	0.0570	0.0250	0.0524	0.0559
	Microwave blanching	40	0.9671	0.9920	0.9710	0.9677	0.0611	0.0302	0.0564	0.0603
		50	0.9641	0.9936	0.9684	0.9639	0.0676	0.0902	0.0635	0.0676
		60	0.9562	0.9935	0.9595	0.9574	0.0822	0.0316	0.0791	0.0806

TD tray dryer, HPD heat pump-assisted dehumidified dryer, NT Newton, MP Modified Page, HP Henderson and Pabis and ZR Zero ($n=3$)

Results and discussion

Maturity

C. asiatica leaves were divided into three groups according to their diameters. Moisture content, total phenolics, % inhibition, color values (CIE L*, a*, b*) and crude fiber were determined. It was found that the mature leaves with large diameter of 4.6 to 6.5 cm contained high total phenolics and % inhibition as shown in Table 1. The result agreed with Phoungchandang and Kongpim (2012) that sweet basil leaves with large leaf area contained high total phenolics and % inhibition.

Blanching treatments

The mature *C. asiatica* leaves were blanched by boiling water immersion and microwave. The results revealed that the blanching methods affected the total phenolics and % inhibition ($p \leq 0.05$). Microwave blanching for 30 s retained the highest total phenolics and the microwave blanching for 30 s and 45 s retained the highest % inhibition as shown in Table 2. Therefore, microwave blanching for 30 s was used to inhibit enzymatic browning reaction of *C. asiatica* leaves in drying experiments. In addition, with respect to the direct blanching treatment, a rise ($p \leq 0.05$) in total phenolics was observed as the blanching time increased up to 30 s and

Fig. 3 Moisture ratio of (a) fresh and (b) microwave blanched *C. asiatica* leaves predicted from the Modified Page compared with the observed experimental data from HPD

decreased thereafter (Table 2). Vina et al. (2007) also found that microwave blanching induced the greatest increases in DPPH radical-scavenging activity values of Brussels sprouts and according to Turkmen et al. (2005), the moderate heat treatment induced by the microwave blanching may be considered to be a useful tool to improve health properties of Brussel sprouts. Lee et al. (2002) and Rossi et al. (2003) found that blanching of blueberry fruits induced a high anthocyanin retention and could be due to two factors: the reduction of enzyme-mediated antocyanin degradation, which is the result of the complete inactivation of native polyphenol oxidase, and a greater extraction yield linked to the increase of fruit skin permeability caused by the heat treatment (Kalt et al. 2000).

Desorption isotherms

Result within the range of 20 to 50 °C and 0.3 to 0.8 RH for fresh and microwave blanched *C. asiatica* leaves are presented in Fig. 2. Equations (1) to (8) were fitted to the data using SPSS 16.0 for Windows. Both $X_e = f(RH_e, T)$ and $RH_e = f(X_e, T)$ equation forms were fitted as minimizing the error or in the prediction of X_e or RH_e , generated different constants in the fitted equation (Sun and Woods 1994). For $X_e = f(RH_e, T)$ function, the Modified Henderson model showed the best fit for both fresh and microwave blanched *C. asiatica* leaves having the lowest SEE of 1.387 % d.b. and 0.572 % d.b., respectively and the highest R^2 of 0.975 and 0.950, respectively. For $RH_e = f(X_e, T)$ function, the Modified Chung-Pfost model showed the best fit for both fresh and microwave blanched *C. asiatica* leaves having the lowest SEE of 0.040 % d.b. and 0.028 % d.b., respectively and the highest R^2 of 0.953 and 0.951, respectively (Table 3). The Modified Henderson and Modified Chung-Pfost models were the best fit for high fibrous plants (Chen and Morey

1989; Phoungchandang et al. 2003; Phoungchandang et al. 2008b; Phoungchandang and Kongpim 2012). *C. asiatica* leaves contained rather high fiber content of 10.9 to 11.3 % d.b. (Table 1).

Modeling of drying kinetics of *C. asiatica* leaves

The experimental conditions for tray and heat pump-assisted dehumidified drying of *C. asiatica* leaves are summarized in Table 5. The drying was terminated when the moisture content of the sample was reduced to 11.1 % w.b. (12.5 % d.b.) which corresponded with the relative humidity of 0.6 (Fig. 2) for a safe level. The drying data obtained were fitted by four drying models namely the Newton (NT), Modified Page (MP), Henderson and Pabis (HP) and Zero (ZR) models. The X_e of *C. asiatica* leaves predicted from the Modified Henderson model were used to determine drying constant (K) and drying exponent (N). Both K and N were determined by minimizing sum of squares of the differences between the observed and fitted values of moisture ratio as well as coefficient of determination (R^2). Interestingly, the “Zero model” used the simplified form of moisture ratio as X/X_0 instead of $(X-X_e)/(X_0-X_e)$ by taking the equilibrium moisture content (X_e)=0 in Eq. (13) (Phoungchandang and Woods 2000). The R^2 for the model were rather high (more than 0.957) with low SEE (lower than 0.081 % d.b.), indicating the good fit comparable with the NT and HP model as shown in Table 4 (Phoungchandang et al. 2003; 2008a; b; 2009; Phoungchandang and Saentaweek 2011). The results in Table 4 and Fig. 3 revealed that the Modified Page model was the best model to describe the mass transport of moisture in drying of *C. asiatica* leaves. All drying was in the falling rate period because drying rates were decreased entirely the drying processes (Fig. 4). During the falling rate period,

Fig. 4 Drying rate of (a) fresh and (b) microwave blanched *C. asiatica* leaves using HPD at 40, 50 and 60 °C

the rate of water movement from the interior to surface falls below the rate at which water evaporates to the surrounding air, and the surface therefore dries out. The results agreed with the previous research (Phoungchandang et al. 2003; 2008a; b; 2009; Phoungchandang and Saentaweek 2011). The exponent (N) was added to drying constant and drying time of the NT model to increase the dependence of temperature and relative humidity of the drying air (Phoungchandang 2008; Phoungchandang et al. 2008a, b; 2009). The K values increasing with temperature obtained from HPD were higher than that from TD because of the lower RH of drying air at the same drying temperature (Table 5). It should be noted that RH and temperature of drying air influenced K and N values. The drying constant (K) increased with microwave blanching treatment. The results indicated that microwave blanching had a significantly positive effect on the drying constant (Table 5). The results in Table 5 revealed that microwave blanching and HPD could reduce drying time up to 31.2 % at the drying temperature of 40 °C. Because of the heat treatment, the leaf structure was softened so that moisture removal was faster than fresh leaves (Phoungchandang et al. 2003; Potisate and Phoungchandang 2010) (Table 5). Fitting the Arrhenius relationship to the results for K and drying air temperature, calculated over the full drying period (Table 5), gave the equation for TD and HPD and also for fresh and blanched leaves (Table 5). The relationship of the exponent (N), RH and temperature of drying air (Eq. (16)) for TD and HPD was shown in Table 5.

The effective moisture diffusivities (D_{eff}) were calculated by using the method of slope (Eq. (17) and Table 5). They were determined by fitting the experimental data in terms of $\ln(\text{MR})$ versus t (Chottanom and Phoungchandang 2005; Phoungchandang et al. 2008a, b; 2009; Potisate and Phoungchandang 2010). The results revealed that microwave blanching and higher drying temperature provided higher D_{eff} in both TD and HPD. At the same drying temperature, HPD provided higher D_{eff} than TD (Table 5). Effective moisture diffusivities from this work were in the range of $2.91\text{E-}11$ to $1.73\text{E-}10 \text{ m}^2/\text{s}$ and $3.91\text{E-}11$ to $1.82\text{E-}10 \text{ m}^2/\text{s}$ for TD and HPD, respectively. Zogzas et al. (1996) reported that the moisture diffusivities in food stuff were in the range of $10\text{E-}10$ to $10\text{E-}9 \text{ m}^2/\text{s}$ and were increased with the increasing temperature of drying air.

Total phenolics and inhibition

The amount of total phenolics of dried leaves varied from 2.2 ± 0.12 to $4.7 \pm 0.08 \text{ mg/g d.b.}$ and % inhibition varied from 14.9 ± 3.31 to 88.0 ± 0.89 (Table 6). The results revealed that microwave blanched *C. asiatica* leaves dried in HPD at 40 to 50 °C contained the highest total phenolics and at 40 °C increased % inhibition by 6.1 % (Table 6). The microwave blanching and HPD provided the highest total

Table 5 Drying time, RH, X_c , K, N, D_{eff} and constant in Arrhenius model and Eq. (16)

Dryer	Pre-treatment	Temp. (°C)	Drying time (min)	RH in the dryer (decimal)	X _e (%d.b.)	K (min ⁻¹)	N	D _{eff} (m ² /s)	R ²	Arrhenius model			Eqn. (16)					
										A	B	R ²	SEE (min ⁻¹)	A	B	C	R ²	SEE
TTD	Fresh	40	135	0.2439	2.2991	0.0160	1.1307	2.9085E-11	0.9087	71,463.1097	4,714.1812	0.8898	0.0056	3.1908	0.2082	-29,7469	1.0000	0.0000
		50	65	0.1385	0.9247	0.0391	1.1662	7.3887E-11	0.9173									
		60	45	0.1052	0.5948	0.0491	1.2161	9.1822E-11	0.8996									
	Microwave blanching	40	80	0.2801	4.1756	0.0304	1.3042	5.8367E-11	0.8933	181,842.0248	4,833.8485	0.9491	0.0066	117,138.5951	2.7091	-319.2309	1.0000	0.0000
		50	40	0.1525	2.3681	0.0651	1.1429	1.2428E-10	0.9201									
		60	25	0.1076	1.7207	0.0885	1.4083	1.7334E-10	0.8852									
HPD	Fresh	40	100	0.1345	0.9098	0.0214	1.1463	3.9064E-11	0.9065	14,238.3000	4,168.2565	0.9673	0.0027	0.8003	-0.2989	-9.6193	1.0000	0.0000
		50	60	0.1086	0.6421	0.0386	1.2822	7.3245E-11	0.8945									
		60	40	0.1030	0.5772	0.0514	1.3451	9.6012E-11	0.8762									
	Microwave blanching	40	55	0.1601	2.5306	0.0427	1.3663	8.2649E-11	0.8834	37,235.2010	4,293.9864	0.9956	0.0018	0.0819	-0.9986	39.0428	1.0000	0.0000
		50	35	0.1224	1.9636	0.0612	1.4331	1.1759E-10	0.8709									
		60	20	0.1019	1.6441	0.0947	1.5514	1.8165E-10	0.8554									

TD tray dryer and HPD heat pump-assisted dehumidified dryer ($n=3$)

Table 6 Total phenolics, % inhibition, color values and rehydration ratio of *C. asiatica* leaves from tray and heat pump dehumidified dryer

Dryer	Pretreatment	Temp (°C)	Total phenolics (mg/g d.b.)	% inhibition	Color values				Rehydration ratio
					L*	a*	b*	ΔE^*	
TD	Fresh	40	2.8±0.06 ^{bc}	32.7±0.88 ^c	43.1±0.66 ^d	-3.7±0.56 ^b	17.4±0.55 ^{bcd}	9.0±0.48 ^a	2.9±0.08 ^a
		50	2.6±0.07 ^b	23.5±0.65 ^b	41.7±1.19 ^{cd}	-3.2±0.49 ^b	18.3±0.75 ^{cd}	8.9±0.79 ^a	2.9±0.14 ^a
		60	2.2±0.12 ^a	14.9±3.31 ^a	37.8±3.60 ^{ab}	-2.7±0.98 ^b	19.6±1.79 ^d	9.9±0.32 ^a	2.9±0.12 ^a
	Microwave blanching	40	3.3±0.04 ^c	81.9±0.75 ^g	38.6±1.43 ^{abc}	-7.6±0.19 ^a	14.8±0.94 ^a	7.8±0.33 ^a	5.6±0.25 ^f
		50	3.2±0.09 ^{de}	60.6±0.95 ^e	37.4±0.26 ^{ab}	-8.0±0.20 ^a	15.4±1.20 ^{ab}	7.4±0.90 ^a	5.0±0.51 ^{de}
		60	3.1±0.02 ^{de}	78.7±0.63 ^f	36.2±1.11 ^a	-8.3±0.70 ^a	15.9±1.64 ^{ab}	7.5±1.66 ^a	4.5±0.07 ^{cd}
HPD	Fresh	40	3.1±0.06 ^{de}	40.7±0.88 ^d	42.9±3.24 ^d	-3.5±0.28 ^b	18.2±0.38 ^{cd}	9.2±0.53 ^a	4.7±0.50 ^d
		50	3.0±0.05 ^{cd}	21.5±1.05 ^b	40.8±1.51 ^{bcd}	-3.3±0.47 ^b	18.5±0.46 ^{cd}	8.8±0.39 ^a	3.9±0.63 ^{bc}
		60	2.9±0.06 ^{cd}	30.6±0.52 ^c	37.0±2.18 ^a	-3.2±0.48 ^b	18.5±0.88 ^{cd}	9.6±1.01 ^a	3.5±0.26 ^{ab}
	Microwave blanching	40	4.7±0.08 ^g	88.0±0.89 ^h	38.5±0.53 ^{abc}	-7.9±0.46 ^a	14.9±0.35 ^a	7.5±0.57 ^a	6.0±0.60 ^f
		50	4.5±0.10 ^g	79.6±0.44 ^f	37.4±3.23 ^{ab}	-7.7±1.49 ^a	15.3±2.50 ^{ab}	7.8±3.69 ^a	5.5±0.51 ^{ef}
		60	3.7±0.29 ^f	60.5±1.39 ^e	35.7±0.41 ^a	-7.7±0.60 ^a	17.2±1.26 ^{bd}	7.4±0.75 ^a	4.6±0.12 ^d

Different superscripts in the same column mean that the values are significant different ($p \leq 0.05$) ($n=3$)

TD tray dryer and HPD heat pump-assisted dehumidified dryer

phenolics and % inhibition due to short drying time and also low drying temperature (Table 5) (Phoungchandang et al. 2003; Phoungchandang et al. 2008a; 2009).

Color values

The effect of drying temperature and microwave blanching on color values of dried *C. asiatica* leaves were also investigated and the results are presented in Table 6. CIE LAB (Ultra Scan, XE U3115, Color Global Co., Virginia, America) system was used for the classification of color values. Total color difference (ΔE^*) are shown in Table 6. The total color difference were not significantly different ($p > 0.05$). The results revealed that browning reaction due to drying temperature as well as enzymatic browning reaction did not affect the color of dried *C. asiatica* leaves. The microwave blanching inhibited enzymatic browning reaction and help improve the green color of dried *C. asiatica* leaves. However, the low drying temperature and short drying time as well as microwave blanching (Table 5 and 6) could retain the green pigment in the dried leaves. The results agreed with Potisate and Phoungchandang (2010).

Rehydration ratio

The rehydration ratio is important to determine the time required to attain the original fresh *C. asiatica* leaves prior to cooking. High rehydration ratio illustrates the high water reabsorption of dried products indicating less damage of the cell structure of plant tissues. The rehydration ratio of microwave blanching treatment and drying at low temperature of 40 °C was 6.0 ± 0.60 which provided the highest

rehydration ratio ($p \leq 0.05$). The high rehydration ratio could be because of undamaged of plant cells due to short drying time at low drying temperature as shown in Tables 5 and 6. The result agreed with Phoungchandang et al. (2003) for the drying of holy basil leaves, Phoungchandang et al. (2009) for the drying of ginger, Potisate and Phoungchandang (2010) for the drying of ivy gourd leaves and Balasubramanian et al. (2011) for the drying of betal leaves.

Conclusions

The appropriate stage of maturity of *C. asiatica* leaves was determined. The mature leaves with large diameter of 4.6 to 6.5 cm contained high total phenolics and % inhibition. Microwave blanching for 30 s retained the highest total phenolics and the microwave blanching for 30 s and 45 s retained the highest % inhibition. Therefore, microwave blanching for 30 s was used to inhibit enzymatic browning of *C. asiatica* leaves. Modified Henderson and Modified Chung-Pfost models showed the best fit to both fresh and microwave blanched leaves for $X_e = f(RH_e, T)$ and $RH_e = f(X_e, T)$, respectively. The Modified Page model was the most effective model to describe the mass transport behavior of both fresh and microwave blanched leaves. Microwave blanching and HPD could reduce drying time; therefore, increase drying constant and drying rate. The drying constant (K) in the Modified Page model was related to drying air temperature using the Arrhenius model. The effective moisture diffusivities were in the range $2.91\text{E-}11$ to $1.73\text{E-}10$ m²/s and $3.91\text{E-}11$ to $1.82\text{E-}10$ m²/s for TD and HPD, respectively. The results revealed that the HPD at 40 °C

incorporated by the microwave blanching could reduce the drying time by 31.2 % and increase % inhibition by 6.1 %. Quality evaluation by total phenolics, % inhibition and rehydration ratio showed the best quality for microwave blanching leaves and dried in HPD at 40 °C.

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