Drying characteristics, quality and safety aspects of bamboo shoots using difference drying methods

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Abstract: Physical and chemical properties of bamboo shoots revealed that the middle part of bamboo shoots was suitable for drying and consumption. The optimum conditions for cyanide reduction were boiling at 100 ℃ for 30 min. Modified Halsey and Modified Oswin models were the best fit for fresh and boiled bamboo shoots, respectively. Drying constant was increased with high drying temperature or microwave power as well as boiling treatment. The three parameter model was the most effective model to describe the drying behaviors of bamboo shoots. Boiled bamboo shoots and dried using microwave power at 720 W could decrease drying time up to 20 fold and increase the retention of total phenolics (11.08%), 2, 2-diphenyl-1-picrylhydrazyl (DPPH) (20.75%) and 2, 2'-azino-bis (3-ethylbenzthiazoline-6-sulphonic acid) (ABTS) (2.13%) compared to conventional tray drying at high temperature of 60 ℃ and provide the lowest cyanide residue and shortest drying time.

Keywords: antioxidant activity, bamboo shoot, cyanide residue, freeze drying, microwave drying, tray drying

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1 Introduction

Bamboo shoots or bamboo sprouts are the edible shoots of many bamboo species including *Dendrocalamus asper* Backer, *Bambusa vulgaris* and *Phyllostachys edulis*. Bamboo shoots contain low fat and cholesterol but high protein, carbohydrate, fiber, minerals and vitamins (Chongtham et al., 2011). Like all high moisture foods, bamboo shoots have quite short shelf life and are very prone to microbial degradation (Bal et al., 2011). Due to seasonal availability of bamboo shoots, processing for removal of cyanide residue in raw bamboo shoots while the increase of the value added products assumes great significance for business potential (Satya et al., 2010).

In biological materials including foods, water exists with either unhindered or hindered mobility, is referred to as free and bound water, respectively. There are limited data available on the drying properties of bamboo shoots. Choudhury et al. (2011) presented adsorption and desorption isotherms for raw bamboo (*Dendrocalamus longis*-pathus) shoots using BET, Caurie and GAP equations. Drying is a conventional process of removing moisture from a food product which is accomplished by heat. In this process, there are two transport phenomena, including moisture movement and heat transfer, which occur simultaneously. Some researchers have conducted experimental investigations on the drying of bamboo shoots, including Wongsakpairod (2000) for comparison of superheated steam with low temperature and high temperature hot air drying; Li et al. (2002) for the comparison of traditional convective hot air flow drying with vacuum freeze drying; Madamba (2003) for a convection oven and tray drying; Xu et al. (2005) for two-stage hybrid method of drying; Bal et al. (2010) for microwave drying in the range from 140 to 350 W; Kumar et al. (2013) for thin-layer drying using convection tray drying at 55 ℃, 65 ℃ and 75 ℃; Badwaik et al. (2014) for osmo-vacuum dehydration; Zheng et al. (2014) for freeze drying and hot

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air drying; Zheng et al. (2014) for hot air thin layer drying at 80 ℃. However, there are limited data on the drying characteristics and antioxidant activities of bamboo shoot to compare the data among different dryers including tray, microwave and freeze dryers.

1.1 Moisture isotherm models

Moisture isotherms are useful tools to predict microbial activity and chemical changes that occur in foods. This relationship shows how equilibrium moisture content (X_e) varies with water activity (a_w). Moreover, the relationship varies with temperature (T), as well as whether moisture is removed from a moist food or adsorbed into a dry food. Numerous models have been developed for predicting the relationship between moisture content (X), water activity (RH_e) and temperature whereas C_1, C_2 and C_3 are empirical constants, of which four are shown in Table 1. The goodness of fit for the models was evaluated using the coefficient of determination (R^2) and standard error of estimate (SEE). The highest R^2 and lowest SEE (Equation 1) values were used to choose the most appropriate models.

$$\text{SEE} = \sqrt{\frac{\sum_{i=1}^{N}(X_{pre,i} - \overline{X}_{\exp,i})^2}{d.f.}} \quad (1)$$

The degree of freedom (d.f.) of the fitting Equation is n-1.

Table 1 Sorption isotherm equations

Model	X_e=f(RH_e,T)	RH_e=f(X_e,T)
Modified Oswin (Oswin, 1946)	$(C_1+C_2T)/[(1/RH_e-1)^{(1/C3)}]$	$1/[(\{[C_1+(C_2T)]/X_e\}^{C3})+1]$
Modified Henderson (Thompson *et al.*, 1968)	$\{\ln(1-RH_e)/[-C_1(T+C_2)]^{(1/C3)}\}$	$1-\exp\{[-C_1(T+C_2)](X_e^{C3})\}$
Modified Halsey (Iglesias and Chirife, 1976)	$[-\ln(RH_e)/\exp(C_1+[C_2T]^{(-1/C3)}]$	$\exp\{-\exp[C_1+(C_2T)]X_e^{-C3}\}$
Modified Chung Pfost (Pfost *et al.*, 1976)	$(1/-C_3)\ln[(T+C_2)\ln(RH_e)/-C_1]$	$\exp\{(-C_1/(T+C_2)](\exp(-C_3X_e)\}$

1.2 Drying models

Numerous drying models have been developed to describe thin layer drying, of which five models are shown in Table 2. It is assumed that the rate of moisture loss of material is proportional to the difference between moisture content and equilibrium moisture content (X_e). MR is moisture ratio (X-X_e/X_o-X_e).

Table 2 Thin-layer drying models

Model	Equation	References
Newton	$MR=exp(-Kt)$	Lewis (1921)
Henderson and Pabis	$MR=A\ exp(-Kt)$	Henderson and Pabis (1961)
Modified Page	$MR=exp(-Kt)^N$	Overhult *et al.* (1973)
Zero model	$X=X_0\ exp(-Kt)$	Phoungchandang and Woods (2000)
Three-parameter model	$MR=A\ exp[(-Kt)^N]$	Phoungchandang and Kongpim (2012)

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

$$K = a\exp\left(-\frac{b}{\text{T}+273.15}\right) \quad (2)$$

The K values usually depend on temperature, and are often related to temperature through an Arrhenius model:

$$K = K_0\exp\left(-E_a/R\text{T}\right) \quad (3)$$

Where, K_0, E_a and R are pre-exponential factor, activation energy and universal gas constant, respectively.

The drying exponent (N), in turn, is described as a function of temperature and relative humidity (RH).

$$N = A \times \mathrm{RH}^{B} \times \exp\left(C / \mathrm{T}\right) \quad (4)$$

Where, B and C are empirical constants.

One approach for determining the effective moisture diffusivity, D_{eff}, is by fitting the drying data to a diffusion model for a slab shape object.

$$\frac{X - X_e}{X_0 - X_e} = \frac{8}{\pi^2} \exp\left[-\frac{\pi^2 D_{eff}\, \mathrm{t}}{4L^2} \right] \quad (5)$$

Where, L and t are half thickness of bamboo slices and time.

A modified form of the Arrhenius equation may be used to show whether the rate constant varies with the sample amount (m) and microwave power (P) (Dadali et al., 2007).

$$K = K_0 \exp\left(-E_a \cdot m / \mathrm{P}\right) \quad (6)$$

The objectives of this study were to investigate physical and chemical properties of raw bamboo shoots to select the most suitable part for drying process, reduction of cyanide residue in fresh bamboo shoots, desorption isotherms, moisture diffusivities and drying constant over a range of temperature and humidity for bamboo shoots by tray and microwave drying. The effects of drying temperatures, microwave outputs and freeze drying on the final qualities of dried bamboo shoots including colour values, rehydration ratio, total phenolics, antioxidant activities and cyanide residue were also performed.

2 Materials and methods

2.1 Materials and its Physical and chemical properties

Bamboo shoots (*Dendrocalamus asper* Backer) or sweet bamboo shoots were harvested from a private garden in Khon Kaen Province, Thailand. Physical and chemical properties of the bamboo shoots were determined in terms of bamboo part; such as upper, middle and lower parts. Moisture content (AOAC, 2000), proximate analysis, such as protein, fat, ash, crude fiber (AOAC, 2000) and colour values (CIE LAB) were determined.

2.2 Study of boiling time on cyanide residue

The bamboo shoots were cleaned in 5 ppm chlorinated tap water and peeled. The suitable parts of bamboo shoot were cut into 10 cm thickness and were boiled at 100℃ for 0, 30, 60, 90 and 120 min respectively. Then, the boiled bamboo shoots were used to determine cyanide residue by using the modified method of Chueachot (2008).

2.3 Desorption isotherms

Three hundred grams of the fresh and boiled bamboo shoots were placed on pre-weighed drying trays and placed in a Model UOP8 heated-air tray dryer (Armfield Limited, Ringwood Hampshire, England). Samples were dried at an air temperature of 50℃ to seven different levels of moisture content (Phoungchandang and Woods, 2000). The corresponding water activity was measured at each moisture content using an AquaLab Series 3TE water activity meter (Decagon Device Inc., Pullman, Washington). The device determined both temperature and dew point, using a chilled-mirror technique, from which water activity was recorded. The temperature in the hermetic chamber of the meter was regulated with a controller to within 0.3℃, and could be set between 5℃ and 50℃. Desorption isotherms were determined at 20℃, 35℃ and 50℃, respectively.

2.4 Methods

2.4.1 Tray drying

The suitable parts of bamboo shoots were sliced into 2 mm thickness and the bamboo shoot slices of 300 g were dried in a heated-air tray dryer (TD) (Model UOP8, Armfield Limited, Ringwood Hampshire, England) at temperatures of 40℃, 50℃ and 60℃ and air speed of 0.5 m/s. The air passed over a bank of electrical heaters to create the desired drying air temperature. An anemometer (Model 3K-27V No. 7680-00, SATO KEIRYOKI, Tokyo, Japan) with an accuracy of 0.01 m/s was used to determine air velocity. A relative humidity meter (Vaisala model HMP-5D, DELTA OHM-VIAG, Galilei, Italy) with a precision of 0.1% RH was used to determine the relative humidity (RH) of the drying air.

The tray dryer was designed for *in situ* weighing of the samples in thin layer. During the drying period, the weight of the sample was recorded every 5 min using a data logger (DT 800 Data Taker, Scoresby, Victoria, Australia). Drying was terminated when the moisture content of the samples reached 16.0% (d.b.). The final moisture content was terminated so as to give an a_w less than 0.6.

2.4.2 Microwave drying

Microwave drying (MD) was accomplished in a microwave system (Electrolux 30 liter, EMS3067x, AB Electrolux, Stockholm, Sweden) with a magnetron operating at a frequency of 2,450 MHz (λ=12.14 cm). The microwave system was set to deliver power at 270 W (30% setting), 450 W (50% setting) and 720 W (80% setting). The suitable part of fresh or boiled bamboo shoot slices of 100 g were placed on the 35 cm diameter glass turntable and caused to rotate at regular time intervals at 4 r/min. The direction of the rotations was able to be changed with the exterior on/off switch.

During MD drying, the moisture content was monitored by periodically removing the turntable (with sample) and weighing it on a digital balance to the nearest 0.01 g. The weighing process was completed within 10 s. Drying was terminated when the moisture content of the samples was reduced such that the a_w was less than 0.6.

2.4.3 Freeze drying

Freeze drying (FD) was performed in a GAMMA 2-16LSC laboratory freeze dryer (Martin Christ Gefriertrocknungsanlagen, Osterode am Harz, Germany). The suitable part of fresh or boiled bamboo shoot slices of 300 g were placed on the unheated shelves and frozen at -50 ℃. FD was initiated at 0.15 mbar (15 Pa), with the condenser operating at -85 ℃. Sublimation energy was supplied by ambient radiation reaching the samples through the clear glass drying chamber. Drying was completed within 24 h.

2.5 Mathematical modeling of drying data

The changing product weight was used to calculate moisture content and moisture ratio (X-X_e/X_o-X_e) as a function of time. The moisture ratio data were fitted by five different thin-layer models as is shown in Table 2. Regression analysis was used to determine the constants, *K*, *A* and *N* using SPSS 19 statistical software (SPSS Inc., Chicago, IL). The drying constant *K* was determined at each drying temperature. The drying constant, K could be related to temperature using the Arrhenius model (Equation 2). For MD, E_a was determined using Equation 6. The effective diffusivity (D_{eff}) was calculated using the simplified solution of Fick's second law (Equation 5). The best model describing the thin layer drying for bamboo shoots was chosen for that with the highest R^2 and lowest SEE.

2.6 Colour measurements

The colour of the bamboo shoots was measured before and after drying using a HunterLab (UltraScan, XE U3115, Colour Global Co., Virginia, America). The colour values were measured using the CIE LAB colour space. The scale represented the range of L* from 0 to 100 (black to white), -a* (green) to +a* (red), and –b* (blue) to +b* (yellow). Total colour difference was also determined$\left(\Delta E^* = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right]^{1/2}\right)$.

2.7 Rehydration ratio

The ability of dried bamboo shoots to reabsorb water was measured using the rehydration ratio. Approximately 5 g of dry sample was rehydrated with 500 mL of distilled water at 30 ℃ for 20 minutes. The rehydration ratio was calculated as the weight of the drained sample (w_d) compared to the weight of dried sample (w) (Phoungchandang, 1986).

2.8 Cyanide residue

Preparation of standard curve of cyanide residue was conducted according to Chueachot (2008) with some modifications. The calibration curve was established using standard solution concentration containing 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4 and 1.6 mg/L of cyanide and were transferred into a series of 5 mL volumetric flask, to which 0.8 mL of 0.08 mol/L ninhydrin and 0.8 mL of 0.4 mol/L sodium carbonate were added; the solution was kept aside for about 30 min for completion of the reaction to give a deep-red colour, then added 0.4 mL of 1%(v/v) Tween 20 as micellar media and diluted to mark with 2.5 mol/L of sodium hydroxide. The deep-blue colour was kept aside about 30 min for complex stability. After mixing the solutions, the absorbance of each solution was determined by a spectrophotometer (UV-1800, Shimadzu, Japan) at 598 nm.

To determine the cyanide residue, about 5 g raw and 2 g dried bamboo shoot were mixed with 0.5 mol/L sulfuric acid (20 mL) on a mechanical shaker for 15 min. The mixture was heated to 60 ℃ for five min and filtered by a vacuum filter. Then, the extract was made up to 20 mL by sulfuric acid. Then, 0.25 mL of the extract was diluted to 25 mL by sulfuric acid (1:100 dilution) as stock solution. Then, 0.25 mL of stock solution was added with 0.8 mL of 0.08 mol/L ninhydrin and 0.8 mL of 0.4 mol/L sodium carbonate; the solution was kept aside for about 30 min, then added 0.4 mL of 1%(v/v) Tween 20 and diluted to 5 mL with 2.5 mol/L of sodium hydroxide. The aliquot was kept aside about 30 min. After mixing, the absorbance was determined by a spectrophotometer (UV-1800, Shimadzu, Japan) at 598 nm. The results were expressed as mg KCN/kg wet mass for fresh bamboo shoot and mg KCN/kg dry mass for dried bamboo shoot (Chueachot, 2008).

2.9 Antioxidant activities

About 5 g raw and 2 g homogenized dried bamboo shoot were extracted with 99.99% methanol (10 mL) on a mechanical shaker for two hr. The mixture was centrifuged at 10,000 g at 4 ℃ for 20 min. The extracts were filtered through a Whatman paper No. 1. The clear extracts were made up to 25 mL using 99.99% methanol. The clear extracts were analyzed both for determination of total phenolics and antioxidation activity.

2.9.1 Total phenolics

The amount of total phenolics in the extracts was determined according to Folin-Ciocalteu procedure (Turkmen et al., 2005) with some modifications. The extracts (300 µL) were introduced into test tubes; 1.5 mL of Folin-Ciocalteu’s reagent and 1.2 mL of sodium carbonate (7.5%) were added. The tubes were mixed and allowed to stand for 30 min. Absorbance at 765 nm was measured (UV-1800, Shimadzu, Japan). The results were expressed as mg gallic acid equivalents (mgGAE/100g dry mass).

2.9.2 DPPH assay

The DPPH assay was conducted according to the method of Martinez et al. (2012) with some modifications. A stock solution was prepared by dissolving 0.0240 g DPPH with 100 mL of 99.99% methanol. The working solution was obtained by mixing 40 mL stock solution with 240 mL of 99.99% methanol (ratio of 1:6) to obtain an absorbance of 0.94±0.02 units at 515 nm using a spectrophotometer (UV-1800, Shimadzu, Japan). The extracts (300 µL) were allowed to react with 4 mL of DPPH solution for 30 min in the dark. Then, the absorbance was determined at 515 nm. The results were expressed as mg Trolox equivalents (mgTE/100g dry mass).

2.9.3 ABTS assay

For ABTS assay, the procedure was followed by the method of Matinez et al. (2012) with some modifications. A stock solution of ABTS was prepared by dissolving 0.0360 g ABTS and made up to 10 mL with deionized water. A stock solution of $K_2S_2O_6$ was prepared by dissolving 0.0070 g $K_2S_2O_6$ and made up to 10 mL with deionized water. Then, the stock solution of ABTS and $K_2S_2O_6$ were mixed together with the ratio of 1:1. The $ABTS^+$ solution was allowed to stand for 12-16 h in the dark. Fresh $ABTS^+$ solution was prepared for each assay. Then, 1 mL of $ABTS^+$ solution was mixed with 60 mL 99.99% methanol to obtain an absorbance of 1.1±0.02 units at 734 nm using a spectrophotometer (UV-1800, Shimadzu, Japan). The extracts (300 µL) were allowed to react with 4 mL of $ABTS^+$ solution for 10 min in the dark. Then, the absorbance was determined at 734 nm. The results were expressed as mg Trolox equivalents (mgTE/100g dry mass).

3 Results and discussion

3.1 Physical and chemical properties of bamboo shoots

Physical and chemical properties of bamboo shoots (*Dendrocalamus asper* Backer) are shown in Table 3. It was found that the middle part of bamboo shoots contained rather high protein (19.77±3.09% d.b.) and crude fiber (10.62±0.59% d.b.) and provided the highest ash content of 12.63±0.08% d.b. which were suitable for consumption. The results of this work were agreed with Satya et al. (2010) that bamboo shoots contained high protein and minerals but low fat content. The amino acid content of bamboo shoots was much higher than found in other vegetables such as cabbage, carrot, onion and pumpkin. Therefore, the middle part of bamboo shoots was suitable for the drying process.

Table 3 Physical and chemical properties of raw bamboo shoots

Part of shoot	Moisture content, %w.b.	Moisture content, %d.b.	Protein, %d.b.	Fat, %d.b.	Ash, % d.b.	Crude fiber, %d.b.	Density, kg/m^3	Color values				
								L*	a*	b*	C*	h* (°)
Upper	92.95^b± 0.11	$1,319.26^b$± 21.09	24.34^a± 1.78	0.36^a± 0.17	9.42^c± 0.06	8.61^c± 1.05	984.23^a± 7.76	82.23^a± 2.04	-0.98^b± 0.55	21.50^a± 4.53	21.52^a± 4.53	92.53^a± 1.50
Middle	93.23^a± 0.12	$1,377.98^a$± 25.95	19.77^b± 3.09	0.25^a± 0.12	12.63^a± 0.08	10.62^b± 0.59	991.44^a± 11.50	78.06^b± 1.88	0.15^a ±0.53	17.98^b± 2.37	17.98^b± 2.38	89.68^b± 1.54
Lower	93.25^a± 0.05	$1,381.61^a$± 11.89	11.43^c± 0.72	0.32^a± 0.08	10.76^b± 0.13	13.93^a± 0.49	993.22^a± 2.65	78.84^b± 2.01	0.44^a± 0.91	16.84^b± 2.65	16.86^b± 2.68	88.77^b± 2.49

Different superscripts in the same column mean that the values are significantly different ($p \le 0.05$)

3.2 The study of boiling time on cyanide residue

The bamboo shoots were cleaned in 5 ppm chlorinated tap water and peeled. The middle parts of bamboo shoots were boiled at 100 ℃ for 0, 30, 60, 90 and 120 min (Table 4). It was found that cyanide residue in bamboo shoots were decreased with increased boiling time ($p \le 0.05$). FSANZ (2004) reported that bamboo shoots, sliced into thin strips librated hydrogen cyanide, were removed by boiling. The acute lethal dose of hydrogen cyanide for human being was reported to be 0.5-3.5 mg/kg bw/day. Therefore, the optimum conditions for cyanide reduction were boiling at 100 ℃ for 30 min (Table 4). In the boiling process, peroxidase could be destroyed. Zheng et al. (2014) reported that blanching bamboo shoot slices at 95 ℃ for six min could completely inactivate peroxidase activities.

Table 4 Effect of boiling time on cyanide residue

Time, min	Cyanide, mgKCN/kg w.b.	Cyanide, mgKCN/kg d.b.	Dose, mg/kg bw/day	
			19-35 year old weight 58.28 kg	35-65 year old weight 60.37 kg
0	636.95^a±7.32	$8,753.76^a$±173.98	0.1223^a	0.1180^a
30	256.15^b±0.03	$3,601.63^b$±130.44	0.0492^b	0.0475^b
60	230.39^b±21.89	$3,019.53^c$±286.85	0.0442^b	0.0427^b
90	187.86^c±10.34	$2,594.79^c$±142.78	0.0361^c	0.0348^c
120	106.14^d±12.63	$1,402.14^d$±166.86	0.0204^d	0.0196^d

Different superscripts in the same column mean that the values are significantly different ($p \le 0.05$)

3.3 Desorption isotherms

The desorption isotherms were essential to defining the safe storage moisture content and used to determine X_e of dried bamboo shoots. Results within the range of 20 ℃ to 50 ℃ and 0.25-0.88 RH for fresh and boiled bamboo shoot slices are presented in Figure 1. Desorption isotherms models in Table 1 were fitted to the data using SPSS 19.0 for Windows. Both X_e=f(RH_e, T) and RH_e=f(X_e, T) model forms were fitted as minimum error or in the prediction of X_e or RH_e, generated different constants in the fitted model (Sun and Wood, 1994). The constants, C_1, C_2 and C_3 in the desorption isotherms (Table 5) were to support the sigmoid shape of desorption isotherm curves. For fresh bamboo shoots, Modified Halsay model was the best fit for both X_e=f(RH_e, T) and RH_e=f(X_e, T) functions having the lowest SEE of 0.9535 and 0.0255%d.b., respectively and the highest R^2 of 0.9963 and 0.9850, respectively. Whereas boiled bamboo shoots, Modified Oswin model was the best fit for both X_e=f(RH_e, T) and RH_e=f(X_e, T) functions having the lowest SEE of 1.0527 and 0.0145%d.b., respectively and the highest R^2 of 0.9959 and 0.9951, respectively (Table 5). Choudhury et al. (2011) presented adsorption and desorption isotherms for raw bamboo shoots at 20℃, 30℃ and 35℃; however, the work above was performed at low temperatures and was not suitable to apply at higher drying temperature. They reported that Caurie model was the best fit for bamboo shoots; however, the model had no temperature effect on desorption isotherms and could not be applied to this work.

Table 5 Constants of desorption isotherms for fresh and boiled bamboo shoots

Model	Fresh					Boiled				
	C_1	C_2	C_3	SEE, %d.b.	R^2	C_1	C_2	C_3	SEE, %d.b.	R^2
X_e=f(RH_e, T)										
Modified Henderson	0.00018127	343.4453	0.8391	2.4726	0.9754	0.0001346	277.1530	0.9570	1.2490	0.9942
Modified Halsay	**3.0454**	**-0.0044**	**1.1813**	**0.9535**	**0.9963**	3.7787	-0.0061	1.3459	1.6185	0.9902
Modified Chung-Pfost	460.0846	239.1822	0.0481	4.2350	0.9278	475.1137	234.1718	0.0461	2.6081	0.9747
Modified Oswin	17.8448	-0.0563	1.4307	1.3054	0.9932	**21.4386**	**-0.0771**	**1.6282**	**1.0527**	**0.9959**
RH_e=f(X_e, T)										
Modified Henderson	0.00013407	264.1404	1.0066	0.0433	0.9570	0.00009388	323.3716	1.0240	0.0228	0.9879
Modified Halsay	**3.0914**	**-0.0033**	**1.2138**	**0.0255**	**0.9850**	3.1750	-0.0028	1.1950	0.0169	0.9933
Modified Chung-Pfost	591.6520	275.6207	0.0573	0.0526	0.9365	716.3742	343.9352	0.0502	0.0343	0.9726
Modified Oswin	18.0387	-0.0506	1.5771	0.0329	0.9752	**20.1324**	**-0.0467**	**1.5894**	**0.0145**	**0.9951**

3.4 Modeling of drying kinetics

The experimental conditions for TD and MD of fresh and boiled bamboo shoots are illustrated in Table 7. The drying was terminated when the sample moisture content was decreased to 13.80% w.b. (16.0% d.b.) which provided the water activity of 0.5 (Figure 1) as considered for microbiological safe level. Foods with water activities below 0.61 will not support the growth of micro-organism (Garbutt, 1997). Bamboo shoots were dried using TD at drying temperature of 40℃, 50℃ and 60℃ and MD at 270, 450 and 720 W. In this work, the drying data were fitted

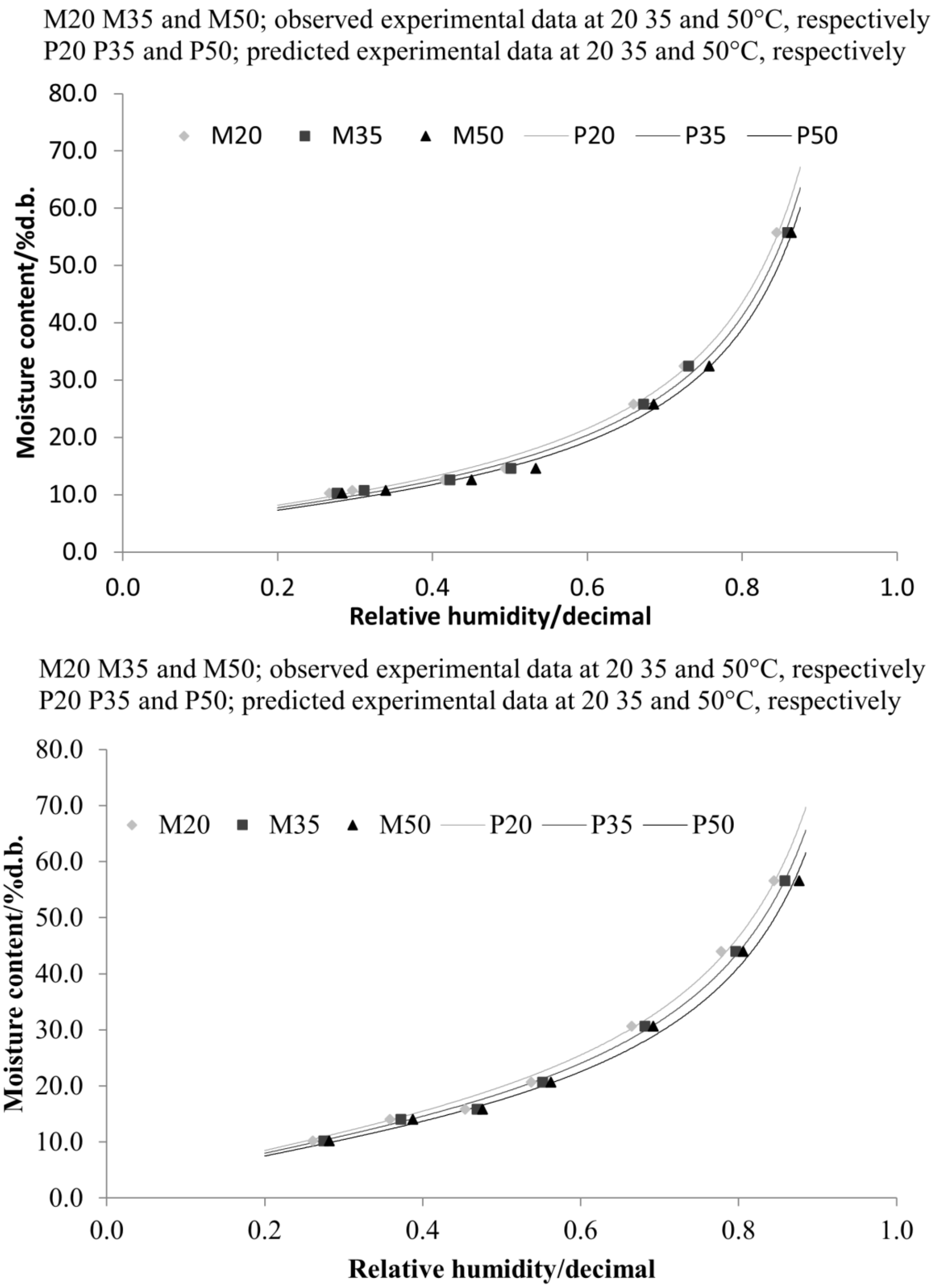

Figure 1 Desorption isotherm at 20 ℃, 35 ℃ and 50 ℃ as predicted using the fitted Modified Halsey model for fresh bamboo shoot (a) and Modified Oswin model for boiled bamboo shoot (b) compared with the observed experimental data

by five drying models as is shown in Table 2. In TD, the X_e of fresh and boiled bamboo shoots predicted from the Modified Halsey and Modified Oswin, respectively were used to determine *K*, *A* and *N*. For MD, the X_e was assumed to be zero and the moisture ratio was simplified to be a form of X/X_e. The *K*, *A* and *N* were determined by minimized sum of squares of the differences between the observed and fitted values of moisture ratio as well as R^2. The results in Table 6 and Figure 2 showed that TP model was the best fit to explain the mass transport of moisture in drying of fresh and boiled bamboo shoots as well as MD because of the lowest SEE and highest R^2.

Table 6 Results of statistical analysis on the drying modeling of bamboo shoots

Dryer	Predrying treatment	Temperature, ℃ or Watt, W	R^2					SEE				
			NT	MP	HP	ZR	TP	NT	MP	HP	ZR	TP
TD	Fresh	40 ℃	0.9758	0.9976	0.9846	0.9790	0.9985	0.0465	0.0146	0.0372	0.0427	0.0118
		50 ℃	0.9712	0.9971	0.9812	0.9746	0.9980	0.0519	0.0166	0.0421	0.0481	0.0137
		60 ℃	0.9679	0.9969	0.9786	0.9712	0.9980	0.0557	0.0173	0.0458	0.0521	0.0142
	Boiled	40 ℃	0.9640	0.9968	0.9772	0.9683	0.9979	0.0582	0.0174	0.0465	0.0537	0.0142
		50 ℃	0.9760	0.9985	0.9852	0.9760	0.9990	0.0467	0.0119	0.0369	0.0467	0.0094
		60 ℃	0.9739	0.9981	0.9837	0.9775	0.9987	0.0489	0.0132	0.0390	0.0448	0.0113
MD	Fresh	270 W	-	0.9968	0.9514	0.9230	0.9980	-	0.0189	0.0738	0.0895	0.0150
		450 W	-	0.9957	0.9345	0.9111	0.9968	-	0.0225	0.0904	0.1006	0.0198
		720 W	-	0.9964	0.9287	0.9008	0.9971	-	0.0227	0.1012	0.1150	0.0211
	Boiled	270 W	-	0.9948	0.9496	0.9227	0.9967	-	0.0235	0.0703	0.0923	0.0187
		450 W	-	0.9957	0.9406	0.9025	0.9968	-	0.0230	0.0840	0.1081	0.0203
		720 W	-	0.9962	0.9315	0.9054	0.9971	-	0.0230	0.0983	0.1113	0.0213

TD tray dryer, MD microwave dryer, NT Newton, MP Modified Page, HP Henderson and Pabis, ZR Zero, TP Three parameter

Table 7 Drying time, RH, X_e, K, A, N, D_{eff}, E_a and constants in the Arrhenius model

											Arrhenius model (Equation 2)				Arrhenius model (Equation 6)				Exponent N model (Equation 4)				
Dryer	**Predrying treatment**	**Temp, ℃ or Watt, W**	**Drying time, min**	**RH in the dryer, decimal**	X_e, %d.b.	K, min^{-1}	A	N	D_{eff}, m^2/s	R^2	A	B	R^2	SEE, min^{-1}	K_0	E_a, W g^{-1}	R^2	SEE, min^{-1}	A	B	C	R^2	SEE
TD	Fresh	40 ℃	675	0.3426	10.8201	0.0038	0.9620	1.3886	1.3751E-9	0.8970	8,641.4496	4,585.8525	0.9998	0.000046					2.7577	0.1275	-21.8695	0.6484	0.0340
		50 ℃	445	0.1997	7.5239	0.0059	0.9597	1.4380	2.1345E-9	0.8918													
		60 ℃	280	0.1078	5.6067	0.0091	0.9600	1.4703	3.2032E-9	0.8856													
	Boiled	40 ℃	550	0.3207	11.3903	0.0042	0.9597	1.4923	1.5060E-9	0.8737	1,361.5886	3,963.7252	0.9954	0.000240					0.4969	-0.2155	34.0670	0.9592	0.0154
		50 ℃	380	0.2096	7.7209	0.0066	0.9693	1.3790	2.3385E-9	0.8937													
		60 ℃	255	0.1191	4.9222	0.0092	0.9724	1.3856	3.2731E-9	0.8854													
MD	Fresh	270 W	63	-	-	0.0323	0.9630	1.8361	1.0743E-8	0.7970					0.3540	6.7780	0.9943	0.0057					
		450 W	25	-	-	0.0740	0.9679	1.9116	2.4646E-8	0.7861													
		720 W	14	-	-	0.1389	0.9718	2.0068	4.7736E-8	0.7886													
	Boiled	270 W	55	-	-	0.0326	0.9564	1.8225	1.1164E-8	0.8092					0.3497	6.6669	0.9957	0.0050					
		450 W	25	-	-	0.0755	0.9676	1.9959	2.5483E-8	0.7794													
		720 W	14	-	-	0.1392	0.9746	2.0381	4.7777E-8	0.7832													

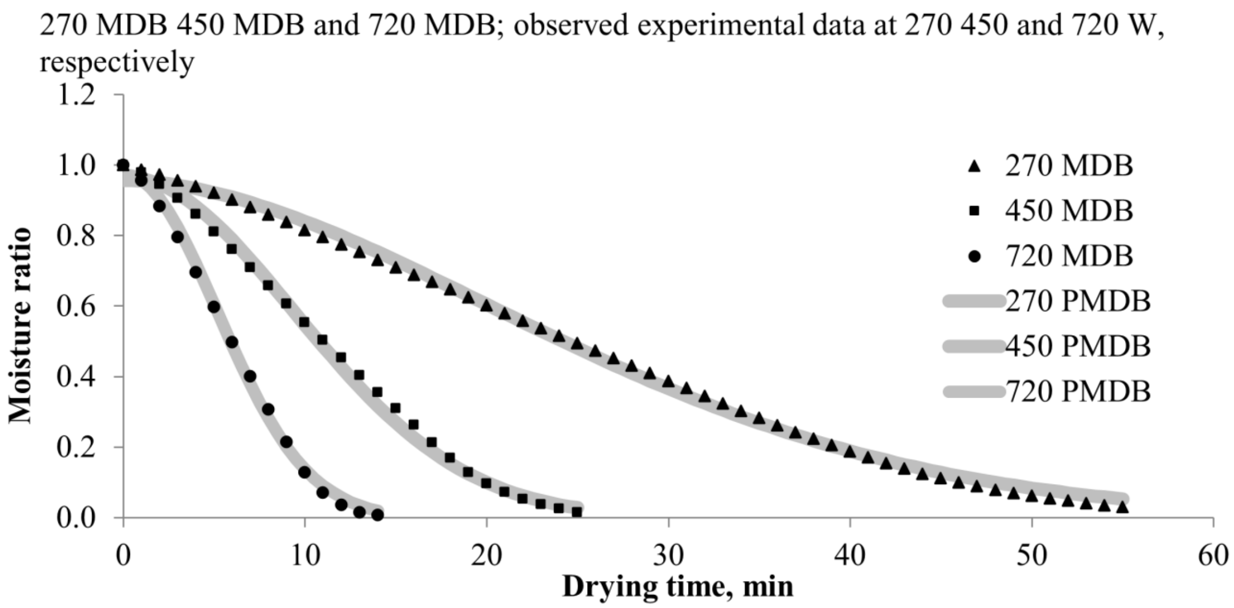

Figure 2 Moisture ratio of boiled bamboo shoots predicted from the Three parameter model compared with the observed experimental data from MD at 270, 450 and 720 W

The TP model was the best model to describe the drying curve of bamboo shoot slices because the exponent, N was put at the drying constant and drying time in order to increase the dependence of drying temperature and relative humidity of the drying air. In addition, the constant, A was also put to an exponential term to describe experimental data affected by diffusion of moisture (Phoungchandang and Kongpim, 2012). All drying in both TD and MD (Figure 3) was in the falling rate period because drying rates were decreased throughout the drying process. The results were agreed with other research (Phoungchandang and Saentaweesuk, 2011; Trirattanapikul and Phoungchandang, 2014). The drying constant was increased with high drying temperature or high microwave power as well as boiling treatment (Table 7). The results in Table 7 revealed that boiling of bamboo shoots and MD at 720 W could reduce drying time up to 20 fold compared to conventional TD at 60℃. Fitting the Arrhenius relationship to the results for *K* and drying air temperature in TD, calculated over the full drying period, gave the equation for TD (Table 7). For MD, a modified form of the Arrhenius model might be used to show whether the K varied with the *m* and P (Dadali et al., 2007) as is shown in Table 7. The relationship of the *N*, RH and temperature of drying air (Equation 4) for TD is shown in Table 7. The D_{eff} were calculated by the method of slope (Equation 5) by using the drying data. The D_{eff} was increased with increasing drying temperature, increasing microwave power or boiling treatments (Table 7). High drying temperature (Phoungchandang and Saentaweesuk, 2011; Trirattanapikul and Phoungchandang, 2014) or high microwave output (Potisate et al., 2014; Potisate and Phoungchandang, 2015) could increase the vapor pressure inside the bamboo shoots. Moreover, boiling treatments also softened the tissues of the bamboo shoots; therefore, increased the drying rate and D_{eff}. The D_{eff} of fresh bamboo shoots and dried using TD were in the range from 1.38×10^{-9} to 3.20×10^{-9} m^2/s and boiled bamboo shoots were in the range from 1.51×10^{-9} to 3.27×10^{-9} m^2/s. The D_{eff} of fresh bamboo shoots and dried using MD were in the range from 1.07×10^{-8} to 4.77×10^{-8} m^2/s and boiled bamboo shoots were in the range from 1.12×10^{-8} to 4.78×10^{-8} m^2/s. Activation energy, E_a could be calculated using the Arrhenius model (Equation 6) and were in the range from 6.7780 to 6.6669 W/g for MD (Table 7). Moisture diffusivities in food stuff were in the range of 10^{-10} to 10^{-9} m^2/s and were increased with the increasing temperature of drying air for TD (Zogzas et al., 1996). The D_{eff} of bamboo shoot slices and dried in MD of this work were higher than Bal et al. (2010) because microwave outputs (140 to 350 W) used in their work were less than this work (270 to 720 W) (Table 7).

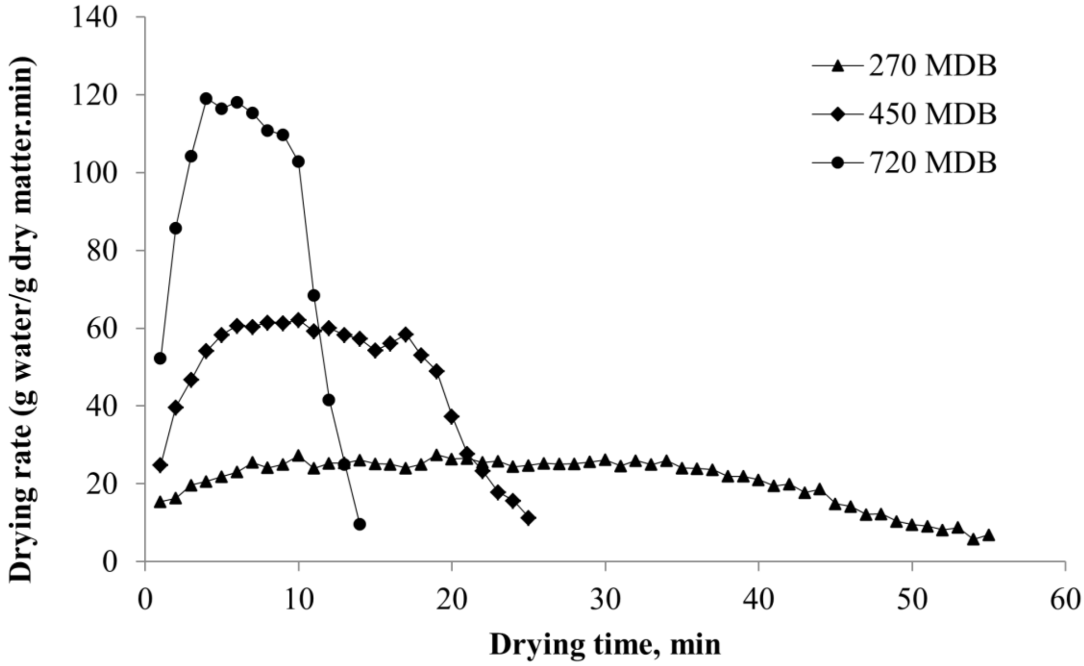

Figure 3 Drying rate of boiled bamboo shoot using MD at 270, 450 and 720 W

3.5 Physical and chemical properties of dried bamboo shoots

Physical and chemical properties of dried bamboo shoots are illustrated in Table 8. Completely Randomized Design (CRD) was used to study the main factors of the drying process. Quality evaluation included colour values, rehydration ratio, cyanide residue, total phenolics, DPPH and ABTS antioxidant activity.

Boiling of bamboo shoots provided higher ΔE* than fresh bamboo shoots. The results revealed that non-enzymatic reaction affected the colour of dried bamboo shoots. Maillard reaction occurrence could be due to protein in bamboo shoots (Table 3) and reducing sugar (Meyer, 1973).

Boiled bamboo shoots and dried using FD provided the highest rehydration ratio followed by fresh bamboo shoot and dried using FD. The results of this work were agreed with Potisate et al. (2014) because low drying temperature of FD could not damage plant tissues and provide porous structures of FD products.

Boiled bamboo shoots and dried using high drying temperature or high microwave power provided lower cyanide residue than fresh bamboo shoots. Moreover, boiled bamboo shoots and dried at microwave power of 270-720 W provided the lowest cyanide content compared to TD and FD. FSANZ (2004) found that bamboo shoots, sliced into thin strips librated hydrogen cyanide, which was removed by boiling.

Fresh bamboo shoots and dried using FD provided the highest total phenolics, DPPH and ABTS antioxidant activity due to low drying temperature (Potisate et al., 2014). Fresh bamboo shoots and dried using MD at 720 W also provided the highest total phenolics. Vina et al. (2007) found that microwave treatment induced the greatest increases in DPPH antioxidant activity of Brussels sprouts. Potisate and Phoungchandang (2015) also found that total phenolics and DPPH in dried *Moringa oleifera* leaves were increased with the increase of microwave power from 150 W to 900 W due to the liberation of phenolic compounds during the thermal process. Boiled bamboo shoots and dried using MD at microwave power at 720 W could increase the retention of total phenolics (11.08%), DPPH antioxidant activity (20.75%) and ABTS antioxidant activity (2.13%) compared to conventional TD at 60 ℃ (Table 8). The results of this work were agreed with Potisate et al. (2014) and Potisate and Phoungchandang (2015). In this work, boiled bamboo shoots and dried using MD at 720 W provided high C* and h* values of yellow-orange colour, the lowest cyanide residue, high total phenolics and the shortest drying time.

Table 8 Physical and chemical properties of dried bamboo shoots from TD, MD and FD

Dryer	Predrying treatment	(℃) or (Watt)	After drying								
			Color values				Rehydration ratio	Cyanide (mg/kg d.b.)	Total Phenolics (mgGAE/100g d.b.)	DPPH (mgTE/100g d.b.)	ABTS (mgTE/100g d.b.)
			L*	C*	h* (°)	ΔE*					
TD	Fresh	40 ℃	67.28^{bc}	21.76^{g}	81.02^{cd}	11.85^{e}	2.71^{e}±0.20	11.48^{b}±0.70	396.30^{hi}±14.91	60.26^{g}±8.27	145.27^{e}±8.07
		50 ℃	70.02^{bc}	21.50^{g}	83.30^{bc}	9.16^{ef}	2.56^{e}±0.16	11.28^{b}±0.76	489.72^{fgh}±24.35	88.15^{ef}±1.44	145.67^{e}±4.98
		60 ℃	71.92^{bc}	20.64^{g}	85.31^{b}	6.89^{f}	2.66^{e}±0.18	6.60^{de}±0.39	512.88^{fg}±20.80	124.42^{d}±0.98	163.84^{d}±4.03
TD	Boil	40 ℃	55.44^{def}	38.96^{bc}	85.39^{b}	30.94^{b}	4.28^{d}±0.17	4.35^{h}±0.23	370.44^{i}±16.84	58.17^{g}±1.40	123.00^{f}±0.25
		50 ℃	52.01^{def}	38.98^{bc}	86.34^{b}	33.54^{ab}	4.19^{d}±0.55	5.54^{efg}±0.30	438.60^{ghi}±6.45	62.78^{g}±5.06	129.02^{f}±1.91
		60 ℃	50.80^{ef}	37.02^{bcd}	85.32^{b}	33.30^{ab}	4.10^{d}±0.26	5.16^{fgh}±0.16	432.54^{ghi}±46.04	76.74^{f}±6.39	129.22^{f}±2.38
MD	Fresh	270 W	73.04^{b}	28.47^{f}	87.53^{b}	11.63^{e}	2.40^{e}±0.23	9.22^{c}±0.12	760.96^{bc}±123.55	154.00^{c}±6.17	180.16^{c}±2.14
		450 W	66.09^{c}	30.74^{ef}	85.20^{b}	18.12^{d}	2.92^{e}±0.27	6.87^{d}±0.07	638.22^{de}±57.62	149.91^{c}±7.28	172.42^{cd}±2.14
		720 W	58.18^{d}	33.46^{de}	77.04^{de}	25.64^{c}	2.64^{e}±0.15	6.16^{def}±0.02	886.94^{a}±24.64	155.66^{c}±0.07	168.94^{d}±0.27
MD	Boil	270 W	49.84^{ef}	40.78^{b}	78.16^{d}	36.66^{a}	4.94^{c}±0.24	5.00^{gh}±0.03	465.07^{ghi}±11.66	96.60^{e}±15.10	167.18^{d}±4.14
		450 W	55.67^{de}	47.00^{a}	79.56^{cd}	36.86^{a}	3.82^{d}±0.48	4.68^{gh}±0.18	519.12^{fg}±11.85	122.64^{d}±10.05	170.34^{d}±4.58
		720 W	49.08^{f}	37.62^{bcd}	73.92^{e}	35.56^{a}	2.95^{e}±0.10	4.60^{gh}±0.23	569.72^{ef}±1.88	150.24^{c}±0.66	167.33^{d}±0.33
FD	Fresh		89.24^{a}	12.78^{h}	97.46^{a}	12.53^{e}	9.02^{b}±0.04	18.04^{a}±1.24	806.44^{ab}±6.24	213.21^{a}±3.00	263.50^{a}±1.99
	Boil		87.74^{a}	34.78^{cde}	98.14^{a}	19.83^{d}	10.18^{a}±0.26	9.87^{c}±0.55	698.74^{cd}±17.53	197.90^{b}±0.67	234.86^{b}±4.01

Different superscripts in the same column mean that the values are significantly different ($p \leq 0.05$)
TD tray dryer, MD microwave dryer, FD freeze dryer

4 Conclusions

The middle part of bamboo shoots contained rather high protein and crude fiber and the highest ash content. The optimum conditions for cyanide reduction were boiling at 100 ℃ for 30 min. Modified Halsey and Modified Oswin models were the best fit for fresh and boiled bamboo shoots, respectively. All drying in both TD and MD was in the falling rate period. The K was increased with high drying temperature or high microwave power as well as boiling treatment. The TP model was the most effective model to describe the drying behaviors of both fresh and boiled bamboo shoots. The K in the TP model was related to drying air temperature using the Arrhenius model. A modified form of Arrhenius model could be used to relate the K to the m and P providing an E_a in MD. The D_{eff} was increased with increasing drying temperature, increasing microwave output and boiling treatment. FD showed the highest qualities of dried bamboo shoots. Boiled bamboo shoots and dried using microwave power at 720 W could decrease drying time up to 20 fold and increase the retention of total phenolics (11.08%), DPPH (20.75%) and ABTS (2.13%) compared to the conventional tray drying at 60 ℃ and provide the lowest cyanide residue and shortest drying time,

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Nomenclatures

A, B, C, a, b empirical constant (dimensionless)

C_1, C_2, C_3 empirical constant

D_{eff} effective moisture diffusivity, m^2/s

E_a activation energy, W/g

K drying constant, min^{-1}

K_0 pre-exponential factor, min^{-1}

L half thickness of bamboo shoot slice, m

MR moisture ratio $\left(\dfrac{X - X_e}{X_0 - X_e}\right)$ or $\left(\dfrac{X}{X_0}\right)$ (dimensionless)

N drying exponent (dimensionless)

P microwave power, W

R^2 coefficient of determination (dimensionless)

RH relative humidity, decimal

RH_e equilibrium relative humidity, decimal

T temperature, ℃

t time, min

X moisture content, %d.b.

X_0 initial moisture content, %d.b.

X_e equilibrium moisture content, %d.b.

$X_{exp,\, i}$ experimental moisture content, the *ith*, %d.b.

$X_{pre,\, i}$ predicted moisture content, the *ith*, % d.b