Article

Green Drying: Continuous Dehumidified-Air Dryer

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Abstract. Non-thermal drying, such as dehumidified-air drying has been introduced to overcome the drawbacks of conventional thermal and direct contact adsorption drying. However, existing approach of this method is not so user friendly as the dehumidified-air cannot be supplied continuously due to the depletion of desiccants. The desiccants also need a high temperature for the regeneration. Therefore, a continuous dehumidified-air dryer is focused in this study. The dehumidified-air was produced alternately by adsorbents, which located in two chambers. The adsorbents were then regenerated at ambient temperature by pressure-swing concepts. This continuous dehumidified-dryer was commissioned by drying *A. paniculata*, at the dehumidified-air 10 to 30 L/min and 30 to 50°C. The sample was dried at less than 10 hours, and about 75 % of *andrographolide* had been maintained. The Page model was well describing the drying behaviour, and the diffusivity coefficient was determined as 1.88 x 10-13 m²/s.

Keywords: Dehumidified-air, *A. paniculata*, drying, pressure-swing, drying kinetics.

1. Introduction

Drying is the most common method used to extent the shelf life of biological product. A good drying process not only remove moisture but also maintain the nutrition value and give rise to other alterations that affect biological product's quality, such as changes in appearance and alterations in aroma.

Elevation of temperature is always used to accelerate the drying as the examples sun drying, even with the innovative methods such as roof-integrated solar drying [1], heat pump [2, 3], convective drying [4, 5], cabinet drying [6, 7], vacuum drying [8] and vacuum-microwave drying [9]. These approaches are not particularly suitable for the thermal labile material. This has encouraged researchers study on non-thermal drying such adsorption drying [10-13] and dehumidified-air convective drying [14]. However, the drying process needs to be halted when the adsorbents are exhausted with moisture. Therefore, this study is to address those drawbacks by incorporating a pressure swing adsorption dryer to produce dehumidified-air continuously. In the pressure swing system, partial of the dehumidified-air was used to contact the drying material and partially was used to regenerate the adsorbent. *Andrographis paniculata* is used to commission this continuous dehumidified-air dryer. *A. paniculata* which is known as hempedu bumi in Malaysia. Studies have shown that *A. paniculata* prevents the formation blood clots and that use of the herb prevents reclogging of arteries after angioplasty. It also has the potential benefits for treating cancer, human immunodeficiency virus (HIV) and other viruses [4].

2. Materials and Methods

2.1. Materials

Fresh *A. paniculata* were obtained from Malaysian Agricultural Research and Development Institute (MARDI, Serdang). The leaves together with stem were cut into 1.0-2.0 cm. The standard of *andrographolide*, 98 % was purchases from Sigma-Aldrich, USA. Acetonitrile (HPLC grade) and Methanol (Analytical grade) were supplied by Merck (Darmstadt, Germany).

2.2. Continuous Dehumidified-Air Drying

Prior to drying experiments, about 30 minutes, the dryer was run to reach steady state condition at the desired operating conditions. The schematic diagram of the continuous dehumidified-air dryer is shown in Fig. 1. The air compressor (SVP202, Swan, Taiwan) (1) supplied air (6-4 bars) to the adsorption air dryer, which comprised of 2 chambers (2, 3) that contained adsorbents (molecular sieve, 3A) to pick up the moisture in the air. The regeneration of adsorbent was done through pressure swing at a cycle of 2 minutes, and the dehumidified-air (relative humidity = 0-1 %) was continuously supplied, this had been controlled by solenoid valves (2W030-08, Airtac, Taiwan) (4, 5). The dehumidified-air volumetric flow rate was controlled by a needle valve (6) and measured with a volumetric flow meter (822-2-OV1-PV1-V1MP-CRWM, Sierra, USA) (7). The temperature of dry air was adjusted by heater (8) and temperature controlling system (temperature controller (CH402, RKC, Japan), 9 and thermocouple, 12). As a safety fixture, a pressure switch (AP-C30W, Keyence, Japan) (10, 11) was used to disable the functionality of heater if the air pressure were not enough (less or no air was supplied). The drying materials, *A. paniculata,* 30.00 ± 1.00 g, were put in basket (15) and dried at drying chamber (volume of 1000 mL) (14). The dehumidified-air was continuously passing through the drying materials and exited at (17) until the drying process was completed. The properties of air before and after contacting with drying materials were recorded by data loggers (13, 16) (EL-USB-2-LCD, Lascar, UK). The drying was continued until no different between the humidity of air before and after the drying sample.

The experiments were conducted with 30, 40 and 50 °C and 10, 20, and 30 L/min with three replicates for each treatment in order to verify the results obtained.
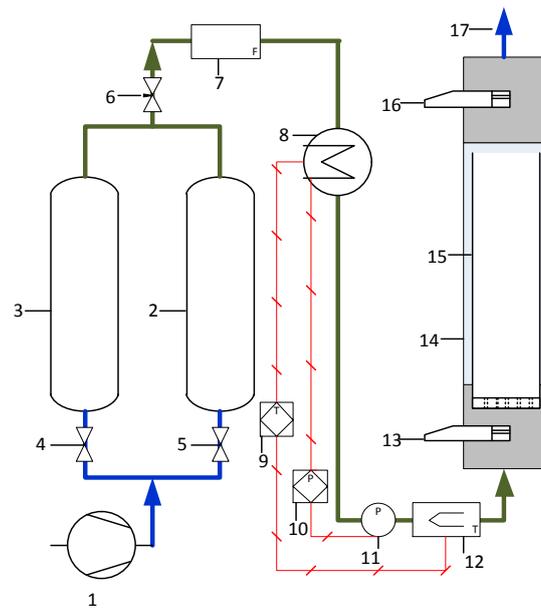
Fig. 1.   Schematic diagram of continuous dehumidified-air dryer.

2.3.   Moisture Content Analysis

Moisture content (MC) of fresh and dry *A. paniculata* was measured using a digital moisture analyser (Mettler Toledo, XM12D, Switzerland). This method was validated with the oven method for moisture determination AOAC official method 930.15 with $\pm$ 1-2 % deviation. Approximately 0.50 g of the sample was cut into small pieces and placed over the tray of moisture analyser. The MC determination was completed when constant value was achieved. The MC of fresh and dry *A. paniculata* was expressed in percentage of a wet basis (wb). All the measurements were done in triplicate with adequate repeatability.

2.4.   Extraction of *A. paniculata*

The extraction of *andrographolide* was done on fresh and dried *A. paniculata*. 3.0$\pm$ 1.0 g of fresh and dried *A. paniculata* was ground by using a blender. The ground *A. paniculata* was percolated with methanol overnight. Whatman No.1 filter paper was used to filter the solvent to produce the first part of methanol extract. The remaining marc was extracted again and overnight one more time in order to extract completely out the bioactive compound. Rotary evaporator (EYELA, N-1001S-WD, Japan) was used to remove approximately 90 % of solvent from extract. The concentrated methanol extract was dried to yield the fully dried crude extract of *A. paniculata* in the oven (30 °C). The dried crude extract was stored at chiller of 4 °C until it was used for analysis.

2.5.   Determination of *Andrographolide*

The content of *andrographolide* was determined by using the High Performance Liquid Chromatography (HPLC) [15]. The mobile phases used in this analysis were acetonitrile and water in a fraction of 7:3. The compounds were separated with a Restek HPLC C18 column, 5 μm, 250 mm x 4.6 mm (Restek Chromatography, DB-C18, USA) and the column was maintained at 25 °C. The mobile phase was at 0.5 mL/min and 15 min running time (501, Waters, USA). The diagnosis was operated at 230 nm using ultraviolet detector (486, Waters, USA). Known amount of crude extract was taken and dissolved it in the mobile phase to perform in 1.0 mg/mL. The sample was filtered by syringe filter (13 mm diameter, 0.2 μm pore size, Nylon, Whatman, UK) before inject to HPLC.

2.6. Drying Kinetics

The weights of the sample at the corresponded times were weighed and used to study the drying kinetics. The moisture ratio (*MR*) and drying rate (*DR*) of AP during drying were determined as

$$MR = \frac{M_t - M_e}{M_o - M_e} \tag{1}$$

$$DR = \frac{M_{t+dt} - M_t}{dt} \tag{2}$$

where M_t is the moisture content of the sample at any time, M_e is the equilibrium moisture content, M_o is the initial moisture content, t is the drying time. However, the *MR* was simplified to Mt/Mo [16, 17] because M_e is relatively much smaller than M_t and M_o.

The thin layer empirical and semi-empirical mathematical models (Table 1) were evaluated to determine the best model for describing the drying kinetics of *A. paniculata*. By using SOLVER, an optimization tool in Microsoft Excel 2007, the parameters of the different models were determined. The coefficient determination (R²) was used as the criterion for choosing the best model to describe the drying curve. In addition, root mean square error (RMSE) was used to determine the quality of the fit.

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(MR_{cal,i} - MR_{exp,i} \right)^2 \right]^{\frac{1}{2}} \tag{3}$$

where $MR_{cal,i}$ is the *i*th calculated moisture ratio, $MR_{exp,i}$ is the *i*th experimental moisture ratio.

Table 1. Selected empirical and semi-empirical models for thin-layer drying.

Model name	Model		Reference
Newton	$MR = \exp(-kt)$	(4)	[18]
Page	$MR = \exp\left(-kt^n\right)$	(5)	[19]
Henderson and Pabis	$MR = a \exp(-kt)$	(6)	[20]
Logarithmic	$MR = a \exp\left(-kt\right) + c$	(7)	[21]
Two-term	$MR = a \exp\left(-kt\right) + b \exp\left(-k_o t\right)$	(8)	[22]
Two-term exponential	$MR = a \exp\left(-kt\right) + \left(1 - a\right)\exp\left(-kat\right)$	(9)	[23]
Fick's second law	$MR = \frac{6}{\pi^2} \sum_{i=1}^{i=\infty} \frac{1}{i^2} \exp\left[-i^2 \pi^2 \left(\frac{D_{eff} t}{L^2} \right) \right]$	(10)	[24]

Note: a, b, c = coefficient; k, k_o = drying constant; L = half thickness of slab (m).

2.7. Statistical Analysis

Experimental data are presented as mean values with standard deviations. Values were considered significant at p<0.05, and a statistical program, Minitab 14 (Minitab Inc., USA) was used to perform the calculations.

3. Results and Discussion

3.1. Effect of Drying Conditions on Drying Time

As shown in Table 2, the dehumidified-air dryer able to dry the sample in ambient temperature (30 °C) at drying time less than 23 hours. From the previous experience, the completion of drying takes few days for the conventional air drying. This enhancement could be explained as the dehumidified-air, which is in extremely low humidity provoke the mass transfer. The moisture transfer rate was faster when dehumidified-air flow rate increased. This might due to the replacement of moist air is relatively faster at higher flow rate, in which maintain the higher drying force. This observation is same as the finding from Ahmadi Chenarbon et al. [25] who does on hot air drying of herbal leaves.

The findings also showed that drying time became shorter as the temperature of dehumidified-air increased and it is common finding observed by other researchers [26, 27].This is because an extra energy is provided to the drying process that increases the moisture transfer, especially to the bound water transferring.

Table 2. Drying time (hour) at different temperatures and air flow rates.

Air Flow, L/min	Temperature, °C		
	30	40	50
10 (1 %RH)	22.50[cz] ±0.71	17.50[bz] ±0.71	15.50[ay] ±0.71
20 (1 %RH)	15.50[cy] ±0.50	8.90[by] ±0.57	7.23[ax] ±0.25
30 (1 %RH)	9.35[cx] ±0.49	7.47[bx] ±0.50	6.63[ax] ±0.51

Note: *The average final moisture content of sample was 6.41±0.97 % (wet basis). Values were expressed as mean ± standard deviation.*
a-b Means with the different letter within same row were significant different at the level p<0.05.
x-z Means with the different letter within same column were significant different at the level p<0.05.

3.2. Effect of Drying Conditions on *Andrographolide*

The quality of *A. paniculata* was evaluated based on the remainder of bioactive compound of the dried samples by using HPLC as the comparative analysis and the average *andrographolide* in fresh sample was around 0.1798 mg per mg of dried crude extract. From the results obtained (Table 3), there was a trend in which with increasing drying temperature, the percentage loss of *andrographolide* contents increased. This observation is in agreement with Rocha et al. [28] that drying temperatures is the most influential variable to preserve the active ingredients of medicinal plants. On the other hand, there was no clear trend for percentage loss of *andrographolide* contents with increasing drying air flow rate.

Table 3. Percentage loss of *andrographolide*.

Air Flow, L/min	Temperature, °C		
	30	40	50
10	38.40[ay] ±0.77	47.16[bx] ±0.27	48.99[cx] ±0.62
20	37.89[axy] ±11.76	54.90[by] ±4.02	53.48[by] ±1.13
30	25.39[ax] ±7.96	52.90[by] ±2.05	54.67[by] ± 4.31

Note: *a, b, c Means with the different letter within same row were significant different at the level p<0.05.*
x, y, z Means with the different letter within same column were significant different at the level p<0.05.

3.3. The Appropriate Adsorption Drying Condition of *A. paniculata*

From the effect of different drying conditions on drying time, the drying condition of 50 °C, 30 L/min; 50 °C, 20 L/min, 40 °C, 30 L/min; 40 °C, 20 L/min; and 30 °C, 30 L/min the drying times were less than 10 hours. While, drying condition of 30 °C, 30 L/min was the most appropriate to use since the loss of *andrographolide* content was the least. Furthermore, the low temperature used also results in a significant reduction in energy consumption per kg of moisture removed [9].

3.4.   Drying Kinetics

The drying behaviour of the appropriate drying conditions (30°C, 30 L/min) was studied more detail and illustrated in Fig. 2. It could be seen that, the moisture content reduced continually with the drying time. This drying behaviour was fitted remarkably well with Page model (R^2= 0.9992, Table 4) as shown in Figure 2. There was no constant drying rate (Fig. 2), which usually found many drying process. Apparently, drying seems to be taken place at falling drying period. This could be due to the rapid moisture removal from the surface of the *A. paniculata* and showed the diffusion-dominant drying phenomena [21]. The diffusivity coefficient was determined as 1.88×10^{-13} m²/s by using Fick's second law.
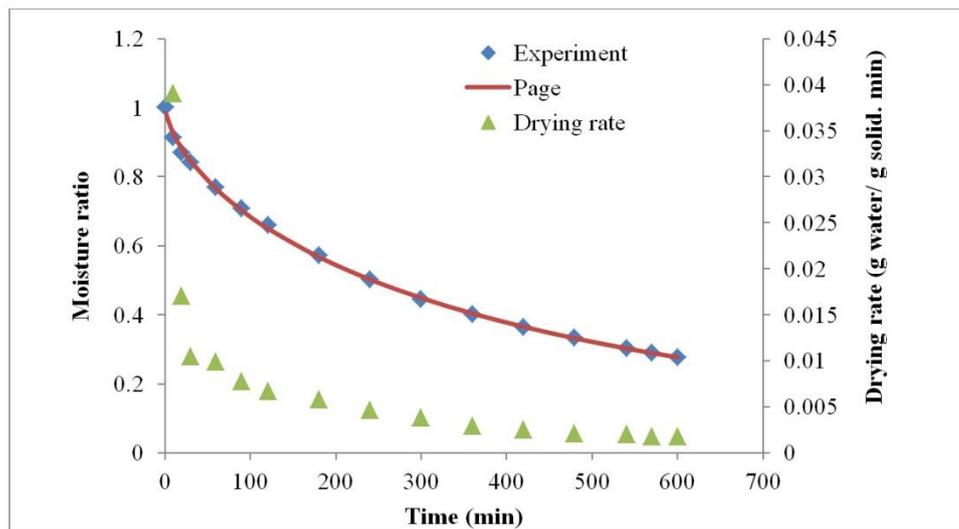
Fig. 2.   Drying bahaviour, curve fitting (left axis) and drying rate (right axis) at 30 °C, 30 L/min.

Table 4.   Fitting of various thin layer drying model.

Model name	R^2	RMSE
Newton	0.9571	0.05938
Page	0.9992	0.00667
Henderson and Pabis	0.9797	0.03509
Logarithmic	0.9942	0.01825
Two-term	0.9978	0.01137
Two-term exponential	0.9839	0.03375
Approximation of diffusion	0.9975	0.01196
Modified Henderson and Paris	0.9971	0.01294
Fick's second law	0.9860	0.02556

4. Conclusions

The dehumidified-air dryer was successfully commissioned as to dry *A. paniculata*. The dryer dried the sample at ambient temperature for less than 10 hours. The drying time was affected by temperature and air flow rate. However, the percentage reduction of *andrographolide* was only reduced as the temperature increased. As an appropriate drying conditions for *A. paniculata* by using continuous dehumidified-air dryer, 30°C and 30 L/min was suggested. The Page model was well describing the drying behaviour, and the diffusivity coefficient was determined as 1.88×10^{-13} m²/s.

Acknowledgement

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