Development of drying kinetics of moringa oleifera leaves in a combined heat pump - microwave system

Xây dựng mô hình động học quá trình sấy lá Chùm ngây bằng hệ thống bơm nhiệt kết hợp vi sóng

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Abstract

Nowadays, energy saving and environmental friendly technologies applied to drying processes is highly paid attention, especially for the natural products. Thus, novel and integrated technologies in processing of natural products are paid attention. In this study, the drying of *M. oleifera* leaves at low temperatures in a combined heat pump-microwave system is carried out. Due to the role of heat pump and microwave power, drying processes can be operated at low temperatures, high drying rates while the quality of the dried products such as vitamins, protein and color can be preserved. Experiments at different temperatures (35, 40, and 45°C) and different drying air velocities (0.575, 0.74, and 0.9 m/s) were conducted to find the effective operating conditions. The drying kinetic model of *Moringa Oleifera* leaves in a heat pump-microwave assisted system was then proposed for the application of process control and scale-up design.

Keywords:

Combined heat pump-microwave drying; Design; Kinetics; Modeling; Moringa oleifera.

Tóm tắt

Ngày nay, vấn đề tiết kiệm năng lượng và các mô hình công nghệ thân thiện môi trường áp dụng trong các quá trình sấy ngày càng được quan tâm, đặc biệt với các quá trình chế biến các hợp chất thiên nhiên. Do đó việc tích hợp các công nghệ mới cho quá trình sấy đang được triển khai và phát triển rộng rãi. Nghiên cứu này thực hiện việc sấy lá chùm ngây ở nhiệt độ thấp bằng hệ thống sấy bơm nhiệt kết hợp vi sóng. Các thực nghiệm sấy được thực hiện ở nhiều điều kiện khác nhau về nhiệt độ và vận tốc tác nhân sấy để tìm ra chế độ sấy phù hợp. Đồng thời nghiên cứu cũng đưa ra mô hình động học quá trình sấy lá chùm ngây bằng hệ thống sấy bơm nhiệt kết hợp vi sóng nhằm ứng dụng trong điều khiển quá trình.

Từ khóa:

Động học; Lá chùm ngây; Mô hình hóa; Sấy bơm nhiệt kết hợp vi sóng; Thiết kế.

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1. INTRODUCTION

Moringa oleifera (M. oleifera) is member of the Moringaceae family of perennial angiosperm plants which is cultivated throughout tropical and sub-tropical areas [1]. This edible plant has a wide variety of nutritional and medical virtues in all the plant's parts including roots, bark, leaves, flowers, fruits, and seeds [1, 2]. Moringa leaves can be used to cure almost 300 along with hundreds of other health benefits. On the other hand, around 90 nutrients, antioxidants and all the eight essential amino acids were found to be present in Moringa leaves [3, 4]. Moreover, Moringa is easily cultivable that makes it suitable remedy for malnutrition. Therefore, this plant is farmed quite widely in many countries including Vietnam for the purpose of nutritive and medicinal applications.

In order to utilize precious components from the plants, processing and preservation methods should be carried out. One of the common preservation techniques applied to plants leaves is drying and/or dehydration. In general, drying can cause some negative effects such as loss of nutrients and vitamins. However, under suitable technology and effective operating conditions, preservation by dying can improve the shelf life of the vegetable and medicinal plants without change in nutritional value [2, 5]. In this study, M. oleifera leaves were treated for preservation and further processing by drying method using a combined heat pump - microwave system. Various drying regimes at low temperature (35^{o}C - 45^{o}C) were conducted for the development of the drying kinetics.

2. MATERIALS AND METHODS

2.1. Materials

M. oleifera leaves used for the drying experiments were procured from Thach That, Hanoi. The leaves were then manually separated from the shoots, washed, and naturally dried at ambient condition prior to putting them to the combined heat pump - microwave drying system. The pre-treatment of the raw materials was carried out indoor to ensure that all of the precious components of M. oleifera leaves were kept unchanged. The initial and final moisture contents of pre-treated materials were determined by the standard method [6].

2.2. Drying equipment

The heat pump - microwave assisted dryer used in this work was designed and manufactured at Hanoi University of Science and Technology. The system consists of two-cycle heat pump, four magnetrons, a centrifugal blower, and thermostats installed in the drying chamber. Heat recovered from two-stage heat pump assisted drying could be higher up to 35% compared to single-stage heat pump while temperature of drying air is still kept at a certain low boundary making it suitable for the drying of vegetable and plant products. The materials to be dried are loaded on four rotated trays so that M. oleifera leaves on each tray can absorb the microwave power uniformly. Operation of the heat pump and the magnetrons are controlled by the drying temperature (temperature in the drying chamber) through a PLC control system. The schematic diagram of the system is depicted in Fig. 1. Temperature of the drying air can be regulated in the range of 25^{o}C - 60^{o}C and velocity of the air can be tuned between 0.1 and 1.0 m/s.

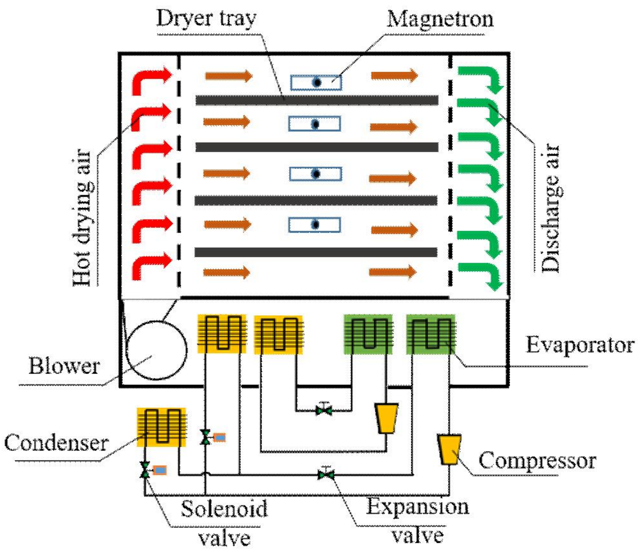

Fig. 1. Schematic diagram of the combined heat pump – microwave dryer used in this study

2.3. Drying experiments

Prior to the conduction of drying experiments, initial and final moisture contents of the raw materials were determined as mentioned above. The moisture content of M. oleifera leaves before drying was 76.25% (wet basis) and that of finished product was 5.0% (wet basis). Nine experiments at three different drying temperatures (35, 40, and 45^{o}C) with different drying air velocities (0.575, 0.74, and 0.9 m/s). The sample weight of raw materials was kept constant at 0.5 kg for each run. Before drying, the chamber was heated up to the desired temperature and the materials (M. oleifera leaves) were distributed uniformly on each dryer tray. During the drying time, moisture loss was recorded and the process was continued until the moisture content of the dried materials reached about 5.0%. The design of experiments is given in Table 1 for the study of M. oleifera leaves on a heat pump - microwave assisted system.

Table 1. Design of experiments for the drying characteristics of M. oleifera leaves.

Experiments	**No. 1**	**No. 2**	**No. 3**	**No. 4**	**No. 5**	**No. 6**	**No. 7**	**No. 8**	**No. 9**
Air velocity (m/s)		0.575			0.74			0.9	
Drying temperature (^{o}C)	35	40	45	35	40	45	35	40	45

2.4. Kinetic development

In order to study the kinetics of drying process, establishment of drying curves is required as the first step. This drying characteristic was created from experimental data through the calculation of the moisture ratio - a dimensionless variable describing the moisture loss with respect to drying time. The moisture ratio is usually determined by Equation (1) as follows.

$$m_r = \frac{m_t - m_e}{m_0 - m_e} \tag{1}$$

In most studies, authors often use the simplified moisture ratio expressing by Equation (2) since the value of equilibrium moisture content is small compared to that of other variables.

$$m_r = \frac{m_t}{m_0} \tag{2}$$

Kinetics parameters of air drying process are often estimated based on a mathematical model. Many semi-theoretical models were reported in the literature [7, 8] and some popular ones that can be applicable to the drying of fruits and vegetables were given in Table 2.

Table 2. Selected popular mathematical model of fruit and vegetable drying.

Model name	Model equation
Newton	$m_r = \exp(-kt)$
Page	$m_r = \exp(-kt^n)$
Page modified	$m_r = \exp(-(kt)^n)$
Wang and Singh	$m_r = 1 + at + bt^2$
Logarithmic	$m_r = a\exp(-kt) + c$
Two-term exponential	$m_r = a\exp(-kt) + (1-a)\exp(-kat)$
Midilli	$m_r = a\exp(-kt^n) + bt$

It was suggested that the Page modified model was widely applicable in the drying of vegetable leaves; therefore, this model was selected for the kinetics development in this study. The kinetics parameters was determined by nonlinear regression method in which the goodness of fit between numerical results and experimental data was evaluated based on the coefficient of determination (R^2), root mean squared error (RMSE), and chi-square (χ^2) analyses. The higher value of R^2 and the lower values of χ^2 and RMSE are, the better predicted parameters are. Detailed calculations of these statistical parameters (R^2, χ^2, and RMSE) can be found elsewhere [9].

3. RESULTS AND DISCUSSION

3.1. Drying characteristics of olefeira leaves on a combine heat pump - microwave system

The moisture ratio calculated from nine experimental data for the drying of M. oleifera leaves on a heat pump - microwave assisted system at different operating conditions was shown in Fig. 2 as a function of drying time. For each run, microwave power was generated periodically to keep the temperature in the drying chamber constant. Thus, the energy generated from the magnetons can maintain the temperatures of the leaves as well as that of drying air in the chamber.

It is observed that, at the drying temperature of 45 ^{o}C rate of the dying process was fastest when hot air was fed at 0.74 m/s (see Fig. 2(b)). At lower or higher air velocities (0.575 and 0.9 m/s) the drying rate tended to decrease. This phenomenon can be explained that, if velocity of the hot air is not high enough the mass transfer rate of the surface moisture to the air bulk was slow down making the overall drying rate decreasing. On the other hand, at high inlet velocity of the hot air, a large amount of moisture in the air flow may be in equilibrium with the amount of water vapor in the drying chamber which is leading to the reduction in the drying rate.

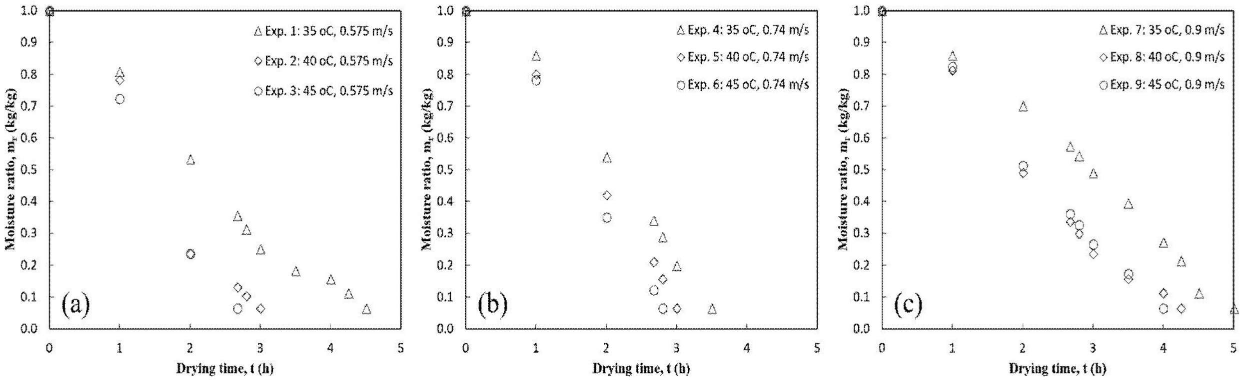

Fig. 2. Drying curves of M. oleifera leaves at various operating conditions:
(a) v_{air} = 0.575 m/s, (b) v_{air} = 0.74 m/s; (c) v_{air} = 0.9 m/s.

As the same hot air velocity, the drying rate increased with drying temperature. This was obliviously understandable since the evaporation rate of moisture in the leaves was proportional to the surface temperature. It was found in this study that, the highest drying rate of M. oleifera leaves on the combine heat pump - microwave system was carried out at the temperature of 45 ^{o}C under the hot air velocity of 0.574 m/s.

3.2. Estimation of kinetics parameters

Data of moisture ratios obtained from experimental measurement as a function of drying time was fitted to Page modified model for the determination of drying kinetic parameters. As given in Table 1, Page modified model consists of two empirical constants (k and n). These two parameters were determined by a nonlinear regression method. Values of these constants for nine experimental runs along with statistical evaluation values (R2, χ^2, and RMSE) were given in Table 3.

Table 3. Predicted constants of Page modified model and statistical analysis of oleifera leave drying

Experiments	**No. 1**	**No. 2**	**No. 3**	**No. 4**	**No. 5**	**No. 6**	**No. 7**	**No. 8**	**No. 9**
Air velocity (m/s)	0.575			0.74			0.9		
Drying temperature (^{o}C)	35	40	45	35	40	45	35	40	45
k	0.387	0.551	0.593	0.402	0.477	0.523	0.290	0.403	0.390
n	1.655	2.127	2.163	2.308	2.175	2.281	2.146	1.732	1.822
R^2	0.9973	0.9937	0.9999	0.9941	0.9951	0.9982	0.9856	0.9989	0.9962
RMSE	0.0002	0.0009	1.4E-6	0.0006	0.0006	0.0003	0.0013	0.0001	0.0004
χ^2	3.0E-5	0.0002	7E-7	0.0001	0.0001	0.0001	0.0001	1.5E-5	0.0001

The regression results from Table 2 showed that values of R^2 were higher than 0.98 and χ^2 were lower than 3E-4. These statistical values indicated that the Page modified model with the estimated constants agreed well with measured data.

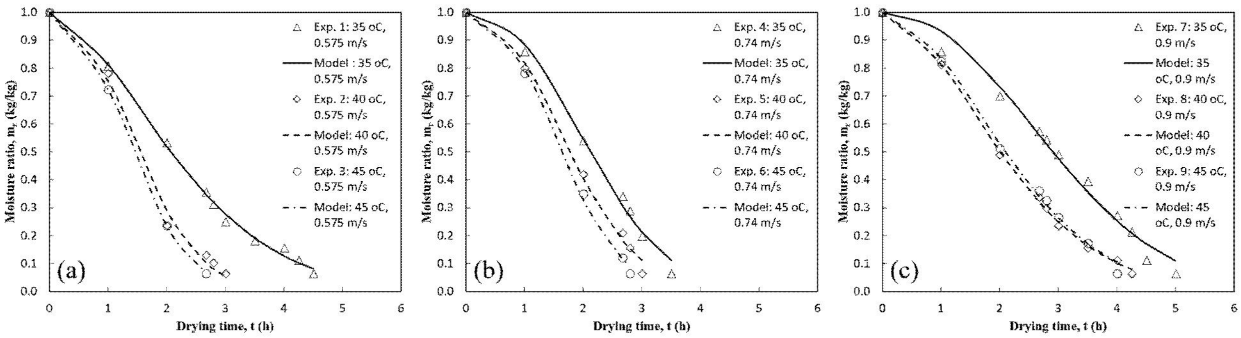

Fig. 3. Kinetic modeling of oleifera leave drying on a combined heat pump – microwave system in comparison with experimental data: (a) v_{air} = 0.575 m/s, (b) v_{air} = 0.74 m/s; (c) v_{air} = 0.9 m/s

Fig.3 showed numerical results of the moisture ratio equation developed from the Page modified model in comparison with experimental data. As expected, the mathematical modeling fitted well with measured data except for the experiment number nine. This slight deviation was probably due to some uncertainty during data recorded process. In overall, the Page modified model, however, was well represented the drying characteristics of M. oleifera leaves on a heat pump - microwave assisted system. Therefore, the model is applicable in scale-up design and process control as well.

4. CONCLUSIONS

Drying characteristics of Moringa oleifera leaves on a combined heat pump - microwave system were studied. Nine different operating conditions were selected for the design of experiments in which drying temperature varied in the range of 35 to 45^{o}C and velocities of the hot air inlet were 0.575, 0.74, and 0.9 m/s. The most effective operating condition obtained from the experimental data with respect to the drying air were 45^{o}C and 0.74 m/s. Based on measured data, Page modified model was utilized for the kinetics development. The estimated model constants made the mathematical model agree well with experiment data. Thus, the Page modified model along with the proposed parameters are applicable for the purpose of process control and scale-up design.

NOMENCLATURE

m_0	: Initial moisture content (-)
m_t	: Moisture content at time t (-)
m_e	: Equilibrium moisture content (-)
a, b, c	: Empirical constants (-)
k	: Model parameter (h^{-1} or h^{-n})
t	: Drying time (h)
v_{air}	: Hot air velocity (m/s)

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