EVALUATION OF DRYING AND MOISTURE SORPTION CHARACTERISTICS MODELS FOR SHIITAKE MUSHROOM (*Lentinussquarrosulus* Mont.) AND GREY OYSTER MUSHROOM (*Pleurotussajor-caju* (Fr.) Singer)

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Abstract

This paper presents the evaluation of moisture sorption isotherm models and thin-layer drying models for shiitake mushroom (*Lentinussquarrosulus* Mont.) and grey oyster mushroom (*Pleurotussajor-caju* (Fr.) Singer). The equilibrium moisture content of both mushroom samples was determined at temperatures of 40, 50, and 60°C with variation of water activity (0.1–0.8). The thin-layer drying experiments were conducted using air temperatures of 40, 50, and 60°C, while air velocity was kept constant at 0.6 m/s. The experimental data of the moisture sorption isotherms as well as the drying kinetics were fitted to various well-known theoretical models using nonlinear regression analysis. The suitable choice of prediction was made based on the coefficient of determination, the root mean square error, and the chi-square. Among several models, the so-called Lewicki-3 model containing 3 parameters was found to be a good choice to predict the EMC of both mushroom samples, whereas the 2-term model showed the best consistency of the observed moisture contents with the model-predicted ones. Furthermore, it was found from the drying rate curves that the falling-rate period was mostly observed in both mushroom samples, meaning that diffusion dominated the moisture transfer in the samples. The net isosteric heat of sorption was eventually calculated using the Clausius-Clapeyron equation in order to determine the energy requirement for drying both the shiitake mushroom and the grey oyster mushroom.

Keywords: Thin-layer drying, desorption isotherm, equilibrium moisture content, isosteric heat

Introduction

In nature, among more than 2000 species of mushrooms, only fewer than 25 species are widely accepted as edible fungi of commercial importance (Shivhare *et al*., 2004; Cuptapun *et al*., 2010). Besides being known as a good source of protein, vitamins, and minerals

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(Kalač, 2009; Cuptapun *et al*., 2010; Kakon *et al*., 2012), mushrooms contain nutraceuticals (Elmastas *et al*., 2007; Ribeiro *et al*., 2007; Cuptapun *et al*., 2010) responsible for their antioxidant, antitumor (Wasser and Weis, 1999; Cuptapun *et al*., 2010), and antimicrobial properties (Hatvani, 2001; Barros *et al*., 2007; Turkoglu *et al*., 2007; Cuptapun *et al*., 2010). As a result, consumption of mushrooms has increased substantially not only due to their nutritional value, but also their delicacy and favor (Shivhare *et al*., 2004). Shiitake mushroom (*Lentinussquarrosulus* Mont.) and grey oyster mushroom (*Pleurotussajor-caju* (Fr.) Singer) are extensively grown in Thailand and applied as food ingredients in many recipes such as spicy soups. However, fresh mushrooms have a short shelf life due to containing a high moisture content in the range of 87 to 95% (wet basis) (Walde *et al*., 2006; Arumuganathan *et al*., 2009; Rhim and Lee, 2011). Therefore, they need either to be marketed soon after harvest or to be preserved using specific processes such as drying and storing under suitable conditions (Tulek, 2011).

Drying involves the removal of moisture from food to the level at which the spoilage microorganisms are inactivated. It is known as an effective way to preserve edible mushrooms. Conventional convective drying is a process in which mass and heat transfers take place simultaneously. Water inside the food material is transferred by diffusion to the food surface and subsequently to the air stream (Tulek, 2011).

Due to the practical significance in both the drying and storage of foods, the relationship between the total moisture content and water activity of food, over a range of values and at a constant temperature, namely a moisture sorption isotherm, plays a role as it is important both in the design of the drying process and for microbiological safety (Shivhare *et al*., 2004). The moisture sorption isotherm is a plot of the equilibrium moisture content (EMC), defined as the moisture content when the vapor pressure of water present in the food material has reached the equilibrium with its surroundings, as a function of water activity (Shivhare *et al*., 2004; Lee and Lee, 2008).

Mathematical modeling, serving as an effective technique for the design and optimization of the processes, has been widely used for analyzing the drying processof agricultural and food products (Cao *et al*., 2003). Many attempts focusing on this technique have been made to account for the thin layer drying and equilibrium moisture content for mushrooms, as reviewed in the following paragraphs.

Many studies can be found in the literature on the thin-layer drying and moisture sorption isotherm characteristics of various varieties of mushrooms (Pal and Chakraverty, 1997; Shivhare *et al*., 2004; Naik *et al*., 2006; Xanthopoulos *et al*., 2007; Rhim *et al*., 2011; Tulek, 2011), but only a few works focusing on mathematical modeling for the shiitake mushroom and the grey oyster mushroom, particularly the species widely grown in the hot-humid climate of Thailand, have been reported (Artnaseaw *et al*., 2010). Several mathematical models have been proposed in order to describe the thin-layer drying characteristics for mushrooms. Tulek (2011) employed different theoretical models to predict the drying kinetics of *Pleurotus ostreatus* mushrooms dehydrated with variations of temperature ranging from 50 to 70°C. Among them, the model proposed by Midilli *et al*. (2002) was found to be the most suitable one corresponding to the parameters of model performance. Consistency of the experimental data with the results predicted by 7 well-known thin-layer drying models was investigated by Xanthopoulos *et al*. (2007). A range of temperatures from 50-65°C and air velocities from 1.0-5.0 m/s were tested. Based on the goodness-of-fit parameters, the logarithmic model showed good promise between the results from prediction and observation. Not only the conventional convective hot-air drying, but also other methods were used in order to investigate the drying characteristics of mushrooms. Artnaseaw *et al.* (2010) used a new design of a vacuum heat pump dryer to study the drying characteristics of shiitake mushrooms under varying conditions of the temperature (50-65°C) and the vacuum pressure (1-4 bar). Among various thin-layer drying models used in that work, the one proposed by Midilli *et al.* (2002) seemed to be the better choice for prediction. Depending on the products being used, Cao *et al.* (2003) found that the modified plate drying model was an adequate model to analyze the drying characteristics of maitake mushrooms *(Grifola frondosa)* with variations of temperature (35-55°C) and relative humidity (30-70%).

In addition to the drying characteristics, the moisture sorption isotherm is taken into consideration as of practical significance in both the drying and storage of foods and agricultural products. Several mathematical models have been proposed for food and plant-based materials as found in the literature (Lewicki, 1997, 1998; McLaughlin and Magee, 1998; Al-Muhtaseb *et al.*, 2002; Arslan and Toğrul, 2005; Argyropoulos *et al.*, 2012; Staudt *et al.*, 2013). To our knowledge, few works have been published on mushroom drying and its moisture sorption isotherm models. Shivhare *et al.* (2004) determined the moisture sorption isotherms of *Agaricus bispocus* and *Pleurotus florida* mushrooms at temperatures ranging from 30 to 70°C with the use of different saturated salt solutions, corresponding to different water activity. In that work, the Chung and Pfost model showed the best agreement between the experimental data and the model-prediction results, while the GAB (Guggenheim, Anderson, de Boer) model was found to be a good choice for isotherms of shiitake mushroom (*Lentinus edodes*) at 25 and 40°C described by Rhim and Lee (2011). Apati *et al.* (2010) reported that the moisture sorption isotherms of *Pleurotus ostreatus* mushroom determined at 30, 40, and 50°C could be predicted satisfactorily using both the GAB and BET (Brunauer, Emmett, Teller) models. However, a good selection of models could be made depending on the conditions and samples, as found in the work of Lee and Lee (2008) in which the Oswin model was found to be the best model for *Inonotus obliquus mushroom* in a range of temperatures from 20-50°C.

Even though many works have been previously carried out in accordance with drying and moisture sorption characteristic models for mushrooms, only a limited number of works for mushrooms have been reported (Pal and Chakraverty, 1997; Walde *et al.*, 2006; Giri and Prasad, 2007; Arumuganathan *et al.*, 2009; Srivastava *et al.*, 2009; Rhim and Lee, 2011), particularly working on the shiitake mushroom and the grey oyster mushroom, which are extensively grown in Thailand.

Therefore, the objective of this work was to present the evaluation of proposed drying characteristic models and moisture sorption isotherm models which were considered as suitable ones for the shiitake mushroom and the grey oyster mushroom. Finally, the net isosteric heat of sorption was calculated using the classical Clausius-Clapeyron equation to determine the energy requirement for drying.

Materials and Methods

Mathematical Descriptions

Moisture Sorption Isotherm Models

The proposed moisture sorption equations, tested for their consistency with the experimental sorption data, were categorized into 2 groups based on temperature dependency. The models are presented in terms of moisture content, M_e dry basis (g/g dry solid), and water activity (a_w) with different parameters:

1. At constant temperature (for more details concerning each of the following models, the reader is referred to Shivhare *et al.*, 2004; Arslan and Toğrul, 2005; Martinelli *et al.*, 2007)

<u>2 parameters</u>

Oswin

$$M_e = A\left(\frac{a_w}{1-a_w}\right)^B \tag{1}$$

Caurje

$$M_e = e^{(A+Ka_w)} \tag{2}$$

Smith

$$M_e = A + (B \text{ In } (1-a_w)) \tag{3}$$

Lewicki-2 (Lewicki, 1997)

$$M_e = A((1-a_w)-1)^{B-1} \tag{4}$$

BET

$$M_e = \frac{X_m\, Ca_w}{[(1-a_w)(1-a_w+Ca_w)]} \tag{5}$$

Halsey

$$a_w = e^{(-A/M_e^B)} \tag{6}$$

Henderson

$$(1-a_w) = e^{-AM_e^B} \tag{7}$$

<u>3 parameters</u>

GAB

$$M_e = \frac{X_m\, CKa_w}{[(1-Ka_w)(1-Ka_w+CKa_w)]} \tag{8}$$

Lewicki-3 (Lewicki, 1998)

$$M_e = A\left[\left(\frac{1}{(1-a_w)^B}\right)-\left(\frac{1}{1-a_w^C}\right)\right] \tag{9}$$

<u>4 parameters</u>

Peleg

$$M_e = Aa_w^C + Ba_w^D \tag{10}$$

2. Temperature dependency: 3 parameters (for more details concerning each of the following models, the reader is referred to Argyropoulos *et al.*, 2012)

Modified Chung-Pfost

$$M_e = -\frac{1}{A}\ln\left[\frac{(T+B)}{C}\ln(a_w)\right] \tag{11}$$

Modified Oswin

$$M_e = (A+BT)\left[\frac{a_w}{1-a_w}\right]^{1/C} \tag{12}$$

Modified Halsey

$$M_e = \left[\frac{-e^{(A+BT)}}{\ln(a_w)}\right]^{1/C} \tag{13}$$

Modified Henderson

$$\left[-\frac{1}{A(T+B)}\ln(1-a_w)\right]^{1/C} \tag{14}$$

Modified GAB

$$M_e = \frac{A\left(\frac{C}{T}\right)Ba_w}{(1-Ba_w)\left[1-Ba_w+\left(\frac{C}{T}\right)Ba_w\right]} \tag{15}$$

where *A, B, C, D,* and *K* are the moisture sorption constants (dimensionless), X_m is the monolayer moisture content (g/g dry solid), and T is the temperature (°C).

Thin-layer Drying Models

To account for the thin-layer drying characteristics, the single 1 parameter, 5 2 parameters, 3 3 parameters, and 2 4 parameters models used in this work are listed below (for more details concerning each of the following models, the reader is referred to Celma *et al.*, 2007):

1 parameter

Lewis

$$MR = e^{-kt} \tag{16}$$

2 parameters

Page

$$MR = e^{-kt^{n}} \tag{17}$$

Modified Page

$$MR = e^{(-(kt)^{n})} \tag{18}$$

Henderson and Pabis

$$MR = ae^{(-kt)} \tag{19}$$

2 term exponential

$$MR = ae^{(-kt)} + (1-a)e^{(-kat)} \tag{20}$$

Wang and Singh

$$MR = 1 + at + bt^2 \tag{21}$$

3 parameters

Logarithmic

$$MR = ae^{(-kt)} + c \tag{22}$$

Approximate of diffusion

$$MR = ae^{(-kt)} + (1-a)e^{(-kbt)} \tag{23}$$

Verma *et al.*

$$MR = ae^{(-kt)} + (1-a)e^{(-gt)} \tag{24}$$

4 parameters

2 term

$$MR = ae^{(-k_0t)} + ba^{(-k_1t)} \tag{25}$$

Midilli *et al.*

$$MR = ae^{(-kt^{n})} + bt \tag{26}$$

where MR is the moisture ratio ($MR = (M_t - M_e)/(M_i - M_e)$), M_t is a moisture content at a certain time, M_e is an equilibrium moisture content, Miis an initial moisture content, t is the drying time, $a, b, c, k,$ and k_0 are the equation's constant, and n is a power constant.

A non-linear regression analysis was initially used to determine the best fitted values of the parameters for each drying condition. The quadratic functions were subsequently formulated to provide the exact fitting relationship between the drying temperature and the parameters obtained in the drying equation. The accuracy of fit was evaluated by the coefficient of determination (R^2), the root mean square error (RMSE), and the reduced chi-square (χ^2). The RMSE and χ^2 can be calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(V_{obs,i} - V_{pre,i}\right)^2}{N-z} \tag{27}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(V_{obs,i} - V_{pre,i}\right)^2} \tag{28}$$

where V_{obs} and V_{pre} are the observed value at any water activity and the corresponding predicted one according to the model being used, N is the number of observations, and z is the number of parameters used in each equation.

Determination of the Net Isosteric Heat of Sorption

In addition to representing the equilibrium relationship between the moisture contents of foods and the water activity at a constant temperature and pressure (Shivhare *et al.*, 2004), sorption isotherm data also allows the determination of the differential heat of sorption by the application of the Clausius-Clapeyron equation on the isosteric equilibrium pressures at different temperatures (McLaughlin and Magee, 1998; Argyropoulos *et al.*, 2012). The net isosteric heat of sorption, q_{st}, is defined as the difference between the total heat of sorption of water from the material and the heat of vaporization. The net isosteric heat of sorption can be determined by the following expression derived from the Clausius-Clapeyron equation (Shivhare *et al.*, 2004; Argyropoulos *et al.*, 2012).

$$a_w = a_0 e^{\left(\frac{-q_{st}}{RT}\right)} \quad (29)$$

where q_{st} is the net isosteric heat of sorption (kJ/mol), R is the universal gas constant (kJ/mol.K), and a_0 is a constant. The q_{st}can be estimated by plotting the sorption isotherm as $ln(a_w)$ vs $(1/T)$ for certain values of moisture contents and subsequently calculating q_{st} from the slope (Shivhare *et al.*, 2004; Argyropoulos *et al.*, 2012).

Experimental Setup

Samples

In this work, fresh cultivated shiitake mushroom and grey oyster mushroom purchased from a mushroom farm in Mahasarakham, in the northeast of Thailand, were sorted according to uniform maturity and size. After being cleaned, their stalks (stripe) were removed by cutting. The average initial moisture content (dry basis) of the mushroom samples was determined using the AOAC method (AOAC, 2002).

Sorption Isotherms

The desorption isotherms of the mushroom samples were determined using a standard static gravimetric method at air temperatures of 40, 50, and 60°C with 5 saturated salt solutions of known water activity; LiCl, $MgCl_2$, KCl, $NaNO_2$, and NaBr, corresponding to a range of a_w from 0.1 to 0.8. The prepared fresh samples were put into a container saturated with saturated salt solutions. The sample weight was measured periodically until a constant value was reached, and subsequently the moisture content of the sample was determined by means of a hot-air oven (AOAC, 2002). The EMC of each mushroom sample was subsequently plotted against the water activity to obtain the sorption isotherm curves. To fit to the experimental data, the selected models mentioned in the previous section (Equations 1-15) were used. The parameters of those models were estimated using non-linear regression analysis. The selection of models could be made using the R^2, the RMSE, and the χ^2 by replacing M_e to V in Equations (27) and (28).

Thin-layer Drying Experiments

The thin-layer drying experiments for both mushrooms were performed using a temperature controlled hot air dryer at 40, 50, and 60°C with a constant air velocity of 0.6 m/s. About 150 g of each mushroom sample was placed uniformly on a mesh tray in order to obtain a thin layer. The change in the sample weight was measured every 3-10 min with the use of an electronic balance until it reached the equilibrium in which the weight change for extended drying remained constant. Tests under certain drying conditions were in duplicates.

In order to evaluate the suitable selection of the thin-layer drying models for the mushroom samples, the obtained experimental data were fitted to the selected well-known models (Equations 16-26) mentioned earlier, using the normalized drying curve (moisture content ratio, MR, vs time). Likewise, the R^2, RMSE, and χ^2 were used to provide a good choice of prediction with the substitution of MR to V in Equations (27) and (28).

Results and Discussion

Moisture Sorption Isotherms

The Sorption Isotherm Profiles

The sorption isotherm curves of the shiitake mushroom and the grey oyster mushroom samples measured at 40, 50, and 60°C for a range of water activity between 0.1 to 0.8 are presented in Figure 1(a) and 1(b), respectively. The points in these figures show the experimental results of sorption data, while the solid lines represent the trend line for a certain temperature. As seen in Figure 1 (a) and 1(b), the equilibrium moisture content exponentially increased with the higher water activity, whereas it decreased with increasing temperature, as expected (Shivhare *et al.*, 2004; Xanthopoulos *et al.*, 2007; Lee and ee, 2008).

Model Evaluation

As the main point of this research was to evaluate the well-known sorption isotherm models for both varieties of mushroom samples, the goodness-of-fit values (R^2, RMSE, and χ^2) are presented in Table 1. It could be found from this table that the so-called Lewicki-3 model proposed by Lewicki (1998), containing 3 parameters, seemed to be an adequate choice of the EMC prediction for both the shiitake mushroom and grey oyster mushroom, based on the high R^2 and the low RMSE and χ^2. The suitable equation including its parameters is shown in Table 2.

In addition to the evaluation of model fitting for moisture sorption isotherms at a constant temperature, 5 EMC models solved explicitly for water activity as a function of temperature and EMC, or for EMC as a function of temperature and water activity were mathematically analyzed to determine their performance. The values of the constants for each model of both mushroom samples are shown in Table 3. Similarly, the R^2, RMSE, and χ^2 values were employed to make a selection of the suitable equation. The results in Table 3 show that the modified Oswin equation was found to be an adequate expression to predict the EMC at different water activities and temperatures ranging from 0.1 to 0.8 and from 40 to 60°C, respectively.

Thin-layer Drying

Model Evaluation

Thin-layer drying experiments were performed at different temperature of 40, 50, and 60°C with a constant air velocity of 0.6 m/s. The initial moisture content of the mushroom samples, approximately 800-960% dry basis, was decreased until the equilibrium moisture content, M_e, was reached for each condition. The model parameters obtained from the thin-layer drying models proposed in the literature (Equations 16-26) are presented together with the goodness-of-fit values in Tables 4 and 5 for the shiitake mushroom and the grey oyster mushroom, respectively. It could be seen from these tables that the four parameters model, namely the 2-term equation, gave the best consistency with the experimental moisture ratio (MR) with the highest R^2 and the lowest RMSE and χ^2 for all drying conditions. Furthermore, the

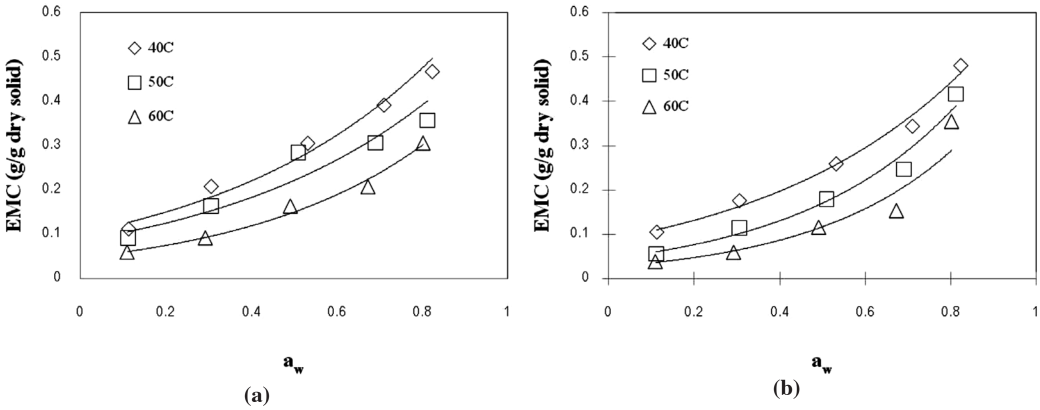

Figure 1. The moisture sorption isotherms of (a) shiitake mushroom and (b) grey oyster mushroom; points denote the experimental data, and solid lines represent the trend line for each drying air temperature

Table 1. The goodness-of-fit parameters obtained by each sorption isotherm model at aconstant temperature

	Model name	Shiitake mushroom			Grey oyster mushroom		
		R^2	RMSE	χ^2	R^2	RMSE	χ^2
40°C	Oswin	0.9887	0.01348	0.000303	0.9962	0.008031	0.000107
	Caurie	0.98366	0.016171	0.000436	0.98716	0.01486	0.000368
	Smith	0.97146	0.021373	0.000761	0.99375	0.010365	0.000179
	Lewicki (2 parameters)	0.98865	0.01348	0.000303	0.99625	0.008031	0.000107
	BET	0.69658	0.069689	0.008094	0.90673	0.040044	0.002673
	Haslay	0.96729	0.042104	0.002955	0.99089	0.017428	0.000506
	Henderson	0.99985	0.00172	4.93e-6	0.98752	0.021522	0.000772
	GAB	0.97838	0.018601	0.00865	0.99686	0.007347	0.000135
	Lewicki (3 parameters)	0.99898	0.00133	4.42e-6	0.99764	0.006368	0.000101
	Peleg	0.98890	0.013327	0.000888	0.93452	0.033554	0.005629
50°C	Oswin	0.9242	0.026912	0.001207	0.9865	0.014437	0.000347
	Caurie	0.91477	0.028541	0.001358	0.97304	0.020441	0.000696
	Smith	0.88507	0.033143	0.001831	0.97397	0.020086	0.000672
	Lewicki (2 parameters)	0.92422	0.026912	0.001207	0.98655	0.014437	0.000347
	BET	0.50344	0.068891	0.00791	0.98977	0.012595	0.000264
	Haslay	0.91996	0.062318	0.006473	0.98642	0.01577	0.000414
	Henderson	0.95719	0.022686	0.000858	0.97914	0.028429	0.001347
	GAB	0.97519	0.015399	0.000593	0.99321	0.010255	0.000263
	Lewicki (3 parameters)	0.97567	0.01525	0.000581	0.99147	0.011496	0.00033
	Peleq	0.97577	0.015217	0.001158	0.92078	0.035042	0.00614
60°C	Oswin	0.9903	0.008581	0.000123	0.9614	0.02212	0.000816
	Caurie	0.98509	0.01067	0.00019	0.94490	0.026442	0.001165
	Smith	0.98891	0.009204	0.000141	0.90590	0.034557	0.00199
	Lewicki (2 parameters)	0.99036	0.008581	0.000123	0.96144	0.02212	0.000816
	BET	0.94763	0.02	0.000667	0.96797	0.020162	0.000678
	Haslay	0.98242	0.020323	0.000688	0.98377	0.023583	0.000927
	Henderson	0.98380	0.012944	0.000279	0.93622	0.041167	0.002825
	GAB	0.98932	0.009033	0.000204	0.98953	0.011527	0.000332
	Lewicki (3 parameters)	0.99048	0.008525	0.000182	0.98605	0.013306	0.000443
	Peleg	0.94835	0.019862	0.001972	0.89098	0.037195	0.006918

quadratic relationship between the 2-term equation's parameters and drying temperature for both mushroom samples is shown in Table 6.

Figure 2(a) and 2(b) shows the comparison between the experimental drying curves and those predicted by the so-called 2-term equation for thin-layer drying at temperatures ranging from 40 to 60°C and at a constant air velocity of 0.6 m/s for the shiitake mushroom and the grey oyster mushroom, respectively. From these, the moisture contents of both mushroom samples decreased exponentially with the extended drying time. Figure 2(a) and 2(b) also reveals the dominant effect of air temperature on the drying rate, when the higher air drying temperature led to a shorter drying time, as normally found in drying characteristics (Pal and Chakraverty, 1997; Naik *et al.*, 2006; Xanthopoulos *et al.*, 2007; Rhim and Lee, 2011; Tulek, 2011). The drying characteristics of both mushroom samples are more clearly shown in Figure 3(a) and 3(b), presenting the drying rate as a function of the moisture content. As shown in these figures, the falling-rate period was mostly observed in both mushroom samples at a certain drying temperature. It means that the physical mechanism governing moisture movement in the samples is dominated by the diffusion of water vapor or bound water through the dry tissue to the drying air at a rate slower than the evaporation rate from the surface (Kaymak-Ertekin, 2002; Panchariya *et al.*, 2002; Xanthopoulos *et al.*, 2007; Doymaz, 2009; Tulek, 2011).

Table 2. The equation's constants of the Lewicki-3 model for both mushroom samples

$$M_e = A\left[\left(\frac{1}{(1-a_w)^B}\right)-\left(\frac{1}{1-a_w^C}\right)\right]$$

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	Shiitake mushroom			Grey oyster mushroom		
	40°C	**50°C**	**60°C**	**40°C**	**50°C**	**60°C**
A	0.582134	0.721350	0.195517	0.318901	0.156294	0.037461
B	0.168666	0.023174	0.451745	0.403864	0.685357	1.398721
C	0.721726	0.943847	0.526840	0.410657	0.354169	-3.82684
R^2	0.998980	0.975670	0.990480	0.997640	0.991470	0.986050

Table 3. The goodness-of-fit parameters obtained by 5 additional sorption isotherm models with variation of water activity and temperature

Model name	Shiitake mushroom			Grey oyster mushroom		
	R^2	**RMSE**	**χ^2**	**R^2**	**RMSE**	**χ^2**
Modified Henderson	0.95532	0.025409	0.004842	0.94314	0.042215	0.013366
Modified Chung-Pfost	0.95450	0.025048	0.004706	0.94472	0.039727	0.011837
Modified Haslay	0.94206	0.060962	0.027873	0.97112	0.053953	0.021832
Modified Oswin	0.96570	0.021901	0.003597	0.95465	0.028471	0.006079
GAB	0.78844	0.109333	0.089653	0.86637	0.093377	0.065395

This could be confirmed by the use of the net isosteric heat of sorption, an indication of the level of bound water in the foodstuff (McLaughlin and Magee, 1998). These values were estimated using the equilibrium water activity for moisture contents for a range of interest, computed from the selected models obtained from Table 1 at 3 different temperatures. The net isosteric heat of sorption (q_{st}) for different moisture contents as influenced by drying conditions for both mushroom samples is shown in Figure 4. The estimated isosteric heat of sorption decreased sharply as the moisture content increased. This could be explained that, at a low moisture content, the heat of sorption was greater than the heat of vaporization of water, indicating a large amount of bound water (Tsami *et al*., 1990; Mc Laughlin and Magee, 1998; Shivhare *et al*., 2004; Lee and Lee, 2008). From this, it could be confirmed by the qst that the falling rate period of drying (Figure 3) occurred resulting from not only a difference in the rate of evaporation from the surface to the drying air and the rate of free water vapor diffusion, but also the amount of bound water in the mushrooms. It could be also found in Figure 4 that the energy requirement for drying different varieties of mushroom was dissimilar, which agreed with the finding in Khalloufi

Table 4. The model parameters and the goodness-of-fit values for the shiitake mushroom at different drying air temperatures

Model name	T (°C)	Model parameter	R^2	RMSE	χ^2
1 parameter					
Lewis	40	k = 0.029188	0.98048	0.036948	0.001409
	50	k = 0.041502	0.98572	0.03132	0.001013
	60	k = 0.056298	0.99255	0.006317	4.12E-05
2 parameters					
Page	40	k = 0.059972, n = 0.801916	0.9994	0.006483	4.48E-05
	50	k = 0.077852, n = 0.809274	0.99946	0.006101	3.97E-05
	60	k = 0.089807, n = 0.845763	0.99939	0.006317	4.26E-05
Modified Page	40	k = 0.029928, n = 0.801919	0.9994	0.006483	4.48E-05
	50	k = 0.042655, n = 0.809275	0.99946	0.006101	3.97E-05
	60	k = 0.057867, n = 0.845764	0.99939	0.006317	4.26E-05
Henderson and Pabis	40	a = 0.917089, k = 0.026134	0.99002	0.026417	0.000744
	50	a = 0.926492, k = 0.037734	0.99146	0.024224	0.000626
	60	a = 0.945100, k = 0.052732	0.99531	0.017498	0.000327
2 term exponential	40	a = 0.222165, k = 0.102398	0.99842	0.010512	0.000118
	50	a = 0.242805, k = 0.131222	0.99882	0.009016	8.67E-05
	60	a = 0.223091, k = 0.198595	0.99959	0.005162	2.84E-05

Table 4. The model parameters and the goodness-of-fit values for the shiitake mushroom at different drying air temperatures (continued)

Model name	T (°C)	Model parameter	R^2	RMSE	χ^2
Wang and Singh	40	a = -0.018952, b = 0.000091	0.87503	0.093476	0.00932
	50	a = -0.021678, b = 0.000110	0.76794	0.126277	0.017009
	60	a = -0.024094, b = 0.000129	0.63566	0.15427	0.025386
<u>3 parameters</u>					
Logarithmic	40	a = 0.898269, k = 0.031204, c = 0.048491	0.99474	0.019181	0.000406
	50	a = 0.918683, k = 0.041998, c = 0.027494	0.99444	0.01954	0.000421
	60	a = 0.941272, k = 0.054889, c = 0.010919	0.99606	0.016043	0.000284
Approximate of diffusion	40	a = 0.290732, k = 0.099857, b = 0.206710	0.99973	0.004312	2.05E-05
	50	a = 0.331028, k = 0.119943, b = 0.237176	0.99976	0.004103	1.86E-05
	60	a = 0.231311, k = 0.199833, b = 0.219198	0.99961	0.005056	2.82E-05
Verma *et al.*	40	a = 0.290705, k = 0.099864, g = 0.020642	0.99973	0.004312	2.05E-05
	50	a = 0.331004, k = 0.119951, g = 0.028448	0.99976	0.004103	1.86E-05
	60	a = 0.231307, k = 0.199836, g = 0.043803	0.99961	0.005056	2.82E-05
<u>4 parameters</u>					
2 term	40	a = 0.707352, k0 = 0.020609, b = 0.290656, k1 = 0.098433	0.99974	0.004293	2.11E-05
	50	a = 0.666649, k0 = 0.028397, b = 0.331280, k1 = 0.118322	0.99976	0.004083	1.91E-05
	60	a = 0.768857, k0 = 0.043808, b = 0.231412, k1 = 0.200207	0.99961	0.005056	2.92E-05
Midilli *et al.*	40	a = 1.009895, k = 0.065472, n = 0.776738, b = -0.000080	0.99952	0.005775	3.81E-05
	50	a = 1.008999, k = 0.083632, n = 0.787605, b = -0.000062	0.99960	0.00525	3.15E-05
	60	a = 1.000400, k = 0.091045, n = 0.840433, b = -0.000023	0.99942	0.006156	4.33E-05

Table 5. The model parameters and the goodness-of-fit values for the grey oyster mushroom

Model name	T (°C)	Model parameter	R^2	RMSE	χ^2
1 parameter					
Lewis	40	k = 0.029188	0.99499	0.0197047	0.0004008
	50	k = 0.041502	0.97868	0.037392	0.0014433
	60	k = 0.056298	0.98726	0.0288797	0.0008609
2 parameters					
Page	40	k = 0.059972, n = 0.801916	0.99923	0.0077379	6.39E-05
	50	k = 0.077852, n = 0.809274	0.99785	0.0118799	0.0001505
	60	k = 0.089807, n = 0.845763	0.99941	0.0061892	4.09E-05
Modified Page	40	k = 0.029928, n = 0.801919	0.99923	0.0077379	6.39E-05
	50	k = 0.042655, n = 0.809275	0.99785	0.0118799	0.0001505
	60	k = 0.057867, n = 0.845764	0.99941	0.0061892	4.089E-05
Henderson and Pabis	40	a = 0.917089, k = 0.026134	0.99665	0.0161176	0.0002771
	50	a = 0.926492, k = 0.037734	0.98480	0.0315709	0.0010632
	60	a = 0.945100, k = 0.052732	0.99175	0.0232448	0.0005763
2 term exponential	40	a = 0.222165, k = 0.102398	0.99787	0.0128647	0.0001765
	50	a = 0.242805, k = 0.131222	0.99535	0.0174535	0.0003249
	60	a = 0.223091, k = 0.198595	0.99843	0.0101552	0.00011
Wang and Singh	40	a = -0.018952, b = 0.000091	0.93259	0.0722985	0.0055755
	50	a = -0.021678, b = 0.000110	0.74504	0.1293088	0.0178355
	60	a = -0.024094, b = 0.000129	0.69700	0.1408564	0.0211632
3 parameters					
Logarithmic	40	a = 0.898269, k = 0.031204, c = 0.048491	0.99962	0.0053942	3.21E-05
	50	a = 0.918683, k = 0.041998, c = 0.027494	0.99641	0.0153438	0.0002598
	60	a = 0.941272, k = 0.054889, c = 0.010919	0.99669	0.0147165	0.000239

Table 5. The model parameters and the goodness-of-fit values for the grey oyster mushroom (continued)

Model name	T (°C)	Model parameter	R^2	RMSE	χ^2
Approximate of diffusion	40	a = 0.290732, k = 0.099857, b = 0.206710	0.99983	0.0036448	1.47E-05
	50	a = 0.331028, k = 0.119943, b = 0.237176	0.99988	0.0028505	8.97E-06
	60	a = 0.231311, k = 0.199833, b = 0.219198	0.99951	0.0056816	3.56E-05
Verma *et al.*	40	a = 0.290705, k = 0.099864, g = 0.020642	0.99983	0.0036448	1.47E-05
	50	a = 0.331004, k = 0.119951, g = 0.028448	0.99988	0.0028505	8.97E-06
	60	a = 0.231307, k = 0.199836, g = 0.043803	0.99951	0.0056816	3.56E-05
<u>4 parameters</u>					
2 term	40	a = 0.707352, k0 = 0.020609, b = 0.290656, k1 = 0.098433	0.99985	0.0033587	1.29E-05
	50	a = 0.666649, k0 = 0.028397, b = 0.331280, k1 = 0.118322	0.99989	0.0027057	8.37E-06
	60	a = 0.768857, k0 = 0.043808, b = 0.231412, k1 = 0.200207	0.99957	0.0053201	3.23E-05
Midilli *et al.*	40	a = 1.009895, k = 0.065472, n = 0.776738, b = -0.000080	0.99981	0.0038155	1.66E-05
	50	a = 1.008999, k = 0.083632, n = 0.787605, b = -0.000062	0.99927	0.0069129	5.46E-05
	60	a = 1.000400, k = 0.091045, n = 0.840433, b = -0.000023	0.99976	0.0039524	1.78E-05

Table 6. The quadratic relationship between parameters of the 2 term model and drying air temperature for both mushroom samplesre

	Quadratic relationship
Shiitake mushroom	$a = 0.0007150T^2 - 0.068380T + 2.299274$
	$b = -0.000702T^2 + 0.067284T - 1.276760$
	$k_0 = 0.000038T^2 - 0.002652T + 0.065687$
	$k_1 = 0.000310T^2 - 0.025909T + 0.638837$
Grey oyster mushroom	$a = 0.0002290T^2 - 0.035141T + 1.795169$
	$b = -0.000267T^2 + 0.038691T - 0.882491$
	$k_0 = -0.000424T^2 + 0.041978T - 0.965667$
	$k_1 = 0.000343T^2 - 0.030181T + 0.671433$

et al. (2000).

The net isosteric heat of sorption of water in the shiitake mushroom and the grey oyster mushroom can be expressed mathematically as an exponential function of moisture content as follows:

Shiitake mushroom

$$q_{st} = 12.016e^{-5.667MC} \text{ ; } R^2 = 0.994 \quad (30)$$

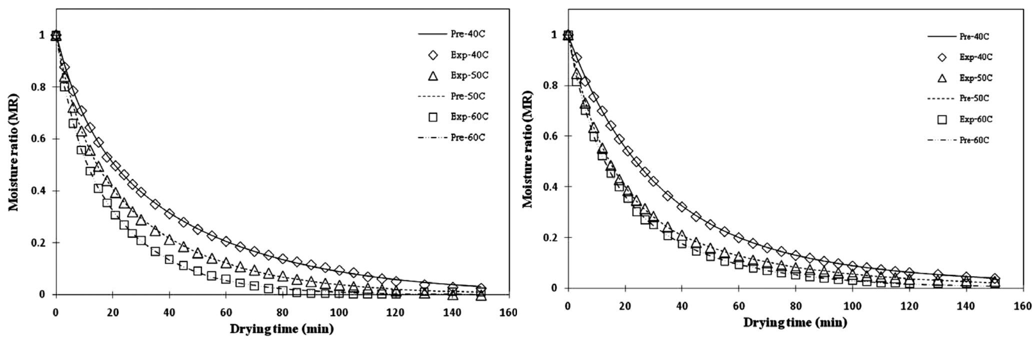
Grey oyster mushroom:

$$q_{st} = 25.87e^{-10.58MC} \text{ ; } R^2 = 0.9994 \quad (31)$$

where q_{st} is the net isosteric heat of sorption (kJ/mol), and MC is the moisture content (g/g dry solid).

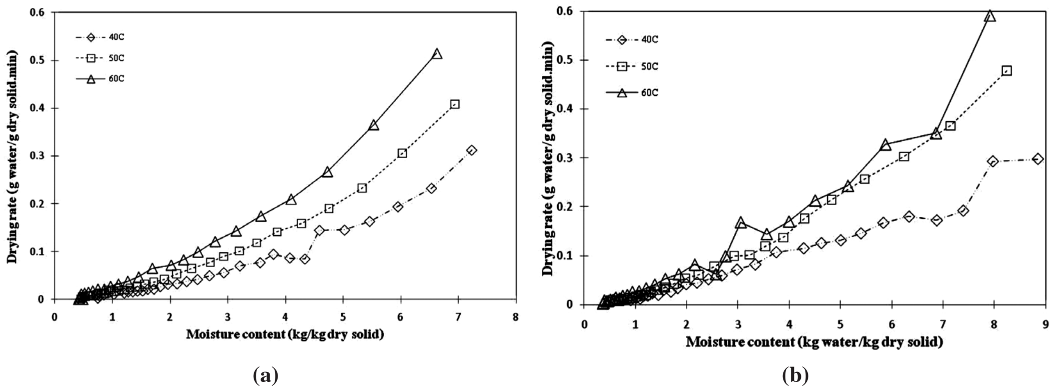
Conclusions

The EMC of the shiitake mushroom and the grey oyster mushroom decreased with an increase in temperature at a constant water activity, while it increased with higher water activity when the temperature remained constant. The EMC predicted by the so-called



(a) (b)

Figure 2. The drying kinetics curves for (a) the shiitake mushroom and (b) the grey oyster mushroom at different drying air temperatures; points represent the experimental data (Exp), and lines represent the model-predicted results (Pre)



(a) (b)

Figure 3. The drying rate curves for (a) the shiitake mushroom and (b) the grey oyster mushroom at different drying air temperatures

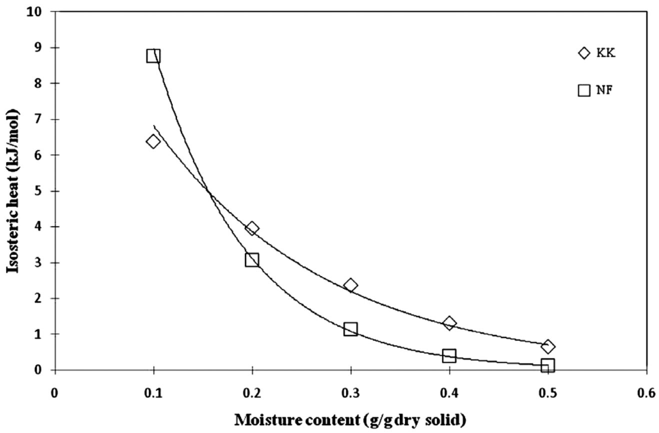


Figure 4. The net isosteric heat of sorption as a function of moisture content for both mushroom samples; points denote the observed values, and lines represent the ones predicted by Equations. (30) and (31)

Lewicki-3 model agreed well with the experimental ones over 40-60°C and for water activity ranging from 0.1 to 0.8 for both mushroom samples. Among several proposed models, the 2-term thin-layer drying model was found to be the best fit to the experimental moisture contents of the shiitake mushroom and the grey oyster mushroom. The net isosteric heat of sorption decreased exponentially with an increase in the moisture content, and its difference was found for different varieties of mushroom.

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