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Drying Kinetics of Oyster Mushroom (*Pleurotus ostreatus*) in a Convective Hot Air Dryer

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ABSTRACT

The objective of this study was to investigate the drying kinetics of oyster mushroom, *Pleurotus ostreatus* Mushrooms were dried using a cabinet-type convective dryer. Air temperatures of 50, 60 and 70 °C were used for the drying experiments. The experimental drying data were fitted to different theoretical models to predict the drying kinetics. Nonlinear regression analysis was performed to relate the parameters of the model with the drying conditions. The performance of these models was evaluated by comparing the correlation coefficient (R^2), root mean square error (RMSE) and the chi-square (χ^2) between the observed and the predicted moisture ratios. Among all the models, the model of Midilli *et al*. was found to have the best fit in this study. Effective moisture diffusivities (D_{eff}), diffusivity constant (D_0) and activation energy (E_a) were calculated. The D_{eff} varied from 9. 619x10^{-10} to 1.556x10^{-9} m^{2}s^{-1} over the temperature range studied and E_a was 22.228 kJ mol $^{-1}$.

Keywords: Activation energy, Drying kinetics, Effective diffusivity, Oyster mushroom, Thin-layer drying models.

INTRODUCTION

The acceptance of cultivated mushrooms such as shitake mushroom (*Lentinus edodes*), oyster mushroom *Pleurotus ostreatus* (Jacq.: Fr.), Kumm and button mushroom (*Agaricus bisporus*) are well-established worldwide as a delicacy. Due to their unique and subtle flavour, these mushrooms have been used as food and food flavouring material in soups for centuries [1]. *Pleurotus ostreatus* is a mushroom of pleasant flavour and possesses several proteins, minerals (Ca, P, Fe, Mg), and low carbohydrate quantities and fat, constituting excellent dietary food [2].

Fresh mushrooms have a short shelf life. Therefore, it is necessary that they are either marketed soon after harvesting or preserved with special care using processes such as drying and storing in cold or controlled environmental storage. Drying is an effective method of preserving edible mushrooms because it preserves the mushrooms by removing enough water to inactivate the enzymes and micro-organisms. Mushrooms preserved by drying have a pleasant flavour and drying prevents deterioration. Moisture content of fresh mushrooms is 70-95% (wb), depending upon the harvest time and environmental conditions, while that of dried mushrooms is close to 10% (wb) [3]. Drying is a simultaneous mass and heat transfer process that induces changes in the material during the operation. Convective drying is considered a simultaneous heat and mass transfer process where water is transferred by diffusion from inside of the food material to the air–food interface and from the interface to the air stream by convection. Mathematical models have proved to be very useful for design and analysis of these transfer processes during drying. Simulation models and drying characteristics of the agricultural materials being dried are needed in the design, construction and operation of drying systems.

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Many researchers have developed simulation models for natural and forced convection drying systems [4-9. Thin layer drying equations are used to estimate drying times of several products and also to generalise drying curves. Several investigators have proposed numerous simulation models for thin layer drying of many agricultural products. For example, apple [10-11], apricot [12], carrot [9-13], grape [14-15], kiwifruit [16], leek [17], pepper, pumpkin, green bean and onion [18], pumpkin [19-20], spinach [21], wheat [22].

To the best of my knowledge, only few studies on the drying kinetics of oyster mushrooms are available in the literature [23-24]. Therefore, the objectives of this study were to [1] observe the effect of drying temperature on drying characteristics of oyster mushrooms, [2] select the best mathematical model for the drying curves and [3] calculate the effective moisture diffusivity and activation energy for oyster mushrooms.

MATERIALS AND METHODS

Materials

Fresh oyster mushrooms *Pleurotus ostreatus* (Jacq: Fr.) Kumm were obtained from the Mushroom Research Centre in Pamukkale University, Denizli, Turkey and were sorted by size. Stalks (stipe) of the mushrooms were removed by cutting. Then, cap (pileus) of the mushrooms with the approximate size of 150 mm width and 8 mm thickness were selected and used in the drying experiments. Before drying, the initial moisture content of the mushrooms were determined, then, the product was dried in an oven (Memmert, UNE 400, Schwabach, Germany) at 105 ^{o}C [25] until it reached a fixed weight.

Experimental Procedure

Drying experiments were performed in a cabinet laboratory type dryer (Figure1). The cabinet dryer was made by Yucebas Machine Analytical Equipment Industry (Izmir, Turkey). The dryer consists of a centrifugal fan to supply the air flow, an electric heater, and an electronic proportional controller (ENDA, EUC442, Istanbul, Turkey). The air temperature was controlled by means of a proportional controller. The temperature and relative humidity in the drying chamber was measured by temperature sensor (accuracy ±1%) and relative humidity sensor (accuracy

Figure 1. Laboratory type cabinet dryer used for oyster mushroom drying.

±2%) (Elimko, E-RHT-10, Istanbul, Turkey). The air velocity in the drying chamber was measured with a Tri-Sense hot wire probe anemometer (accuracy±2%) (Tri-Sense, 37000-90, Cole-Parmer Instrument Co., Illinois, USA). Air flow was perpendicular to the drying surfaces of the samples and the hot air used in the drying process was circulated in the cabinet. Air used in the drying was automatically exhausted when the relative humidity was more than 20%.

The dryer was started about 1 h before before each drying run to achieve steady-state conditions. After the dryer reached this condition, about 200 g of the samples were uniformly put into the sample basket in a single layer and were dried there. The drying experiments were performed at 50, 60 and 70 ^{o}C air temperatures. The air velocity was kept constant at 0.2 ms^{-1} in all drying experiments. Relative humidity of the ambient air changed between 19% and 21%. During drying, the samples were removed at intervals and weighed, before being returned to the dryer. Removing, weighing, and replacing the mushrooms took about 1 min. The weight loss of the samples was recorded by using an analytical balance (Denver, P-314, Göttingen, Germany) in a range of 0–310(±0.001 g) at 30 min intervals, for the first hour, followed by hourly intervals until no measurable weight loss was observed.

At the end of each drying experiment, the final moisture content of the sample was determined. Moisture contents were reported on the wet basis. The amount of dry matter was calculated by using the mean final moisture content and the weight of the dried mushrooms. The moisture contents were also expressed on the dry basis.

All the experiments were replicated three times at each air temperature and the average values were used.

Mathematical Modelling of Drying Curves

The moisture ratio (MR) of oyster mushrooms during the single layer drying experiments was calculated by using the following equation (1).

$$\mathrm{MR} = \frac{M - M_e}{M_0 - M_e} \quad (1)$$

The drying rates of oyster mushrooms were calculated by using Eq.(2).

$$\text{Drying rate} = \frac{M_{t+\mathrm{d}t} - M_t}{\mathrm{d}t} \quad (2)$$

Where, M is the moisture content at any time, in g water/g dry matter; M_0 is initial moisture content, M_e is equilibrium moisture content, M_t and M_{t+dt}, are moisture content at t and moisture content at t+dt, respectively, and t is drying time (min). The values of the equilibrium moisture content, M_e, are relatively small compared to M or M_0, and hence can be neglected [5 and 10].

The drying curves obtained were processed for drying rates to find the most convenient model among the seven different expressions proposed by earlier authors given in Table 1.

The regression analysis was performed using the Minitab 13 statistical software. The correlation coefficient (R^2) was one of the primary criteria for selecting the best equation to define the drying curves of the dried oyster mushrooms. In addition to R^2, various statistical parameters such as reduced chi-square (χ^2) and root mean

Table1. Selected singlt layer drying models for describing oyster mushroom drying data.

Model name	Model	References
Lewis	MR=exp($-kt$)	4 and 28
Page	MR=exp($-kt^n$)	5, 13 and 43
Modified Page	MR=exp(($-kt)^n$)	15, 36 and 44
Henderson and Pabis	MR=$a$exp($-kt$)	12, 21and 45
Logarithmic	MR=$a$exp($-kt$)+c	12, 15 and 19
Two-term	MR=$a$exp($-k_0t$)+(b)exp($-k_1t$)	10 and 42
Midilli *et.al.*	MR=$a$exp($-kt^n$)+bt	8, 17 and 41

square error (RMSE) were used to determine the best of the fit [18, 26, 27, and 28]. When the calculated reduced χ^2 values are close to zero, compatibility is better. The RMSE gives the deviation between the predicted and the experimental values and is required to reach zero. These statistical parameters can be calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N - z} \quad (3)$$

$$\text{RMSE}=\left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2\right]^{1/2} \quad (4)$$

Where $MR_{\exp,i}$ is the ith experimental moisture ratio, $MR_{pre,i}$ is the ith predicted moisture ratio, N is the number of observations, and z is the number of constants in the drying model.

Effective Moisture Diffusivity and Activation Energy

Drying of most food materials occurs in the falling rate period [29], and moisture transfer during drying is controlled by internal diffusion [30]. For most biological materials, Fick's second law of diffusion has been widely used to describe the drying process during the falling rate period [30 and 31] as follows:

$$\frac{\partial M}{\partial t} = \nabla\left[D_{\text{eff}}\left(\nabla M\right)\right] \quad (5)$$

Where, D_{eff} is the effective moisture diffusivity representing the conductive term of all moisture transfer mechanisms. This parameter is usually determined from experimental drying curves [31]. The solution of Fick's second law in slab geometry is given by Crank [32] as shown in Eq. (6), assuming moisture migration being only by diffusion, constant temperature and effective moisture diffusivity, and negligible shrinkage:

$$\text{MR} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{\text{eff}}t}{4L^2}\right) \quad (6)$$

Where, L is the half thickness of the slab in the samples (m) and n is a positive integer. In practice, only the first term of Eq. (6) is used, yielding :

$$\text{MR} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{\text{eff}}t}{4L^2}\right) \quad (7)$$

The effective moisture diffusivity can be determined from the slope of the normalized plot of the unaccomplished moisture ratio, ln (MR) vs time, using the following equation: [33 and 34].

$$D_{\text{eff}} = \frac{-\text{Slope}4L^2}{\pi^2} \quad (8)$$

Temperature dependence of the effective diffusivity has been shown to follow an Arrhenius relationship [30; 35]:

$$D_{\text{eff}} = D_0 \exp\left(\frac{-E_{\text{a}}}{RT}\right) \quad (9)$$

Where, D_0 is the pre-exponential factor of the Arrhenius equation (m^2s^{-1}), E_{a} is the activation energy (kJ mol^{-1}), R is the universal gas constant (kJ mol^{-1} K), and T is the absolute air temperature (K). The activation energy is determined from the slope of the Arrhenius plot, ln (D_{eff}) vs. $1/T$.

RESULTS AND DISCUSSION

Effect of Moisture Content and Drying Time on Drying Rates

The drying rate of mushrooms was 3.296, 4.071, and 5.285 g water/g dry matter/h in the first half an hour and 0.065, 0.021, and 0.020 g water/g dry matter/h in the final stage of drying time at 50, 60 and 70 ^{o}C of hot air, respectively. Drying rate decreased continuously with time and with decreasing moisture content. The changes in the drying rate with moisture content during the drying period for the mushroom samples at various temperatures are given in Figure 2. As indicated in these curves, there is no constant drying rate period in the drying of mushrooms. The whole drying process takes place in the falling rate period. This shows

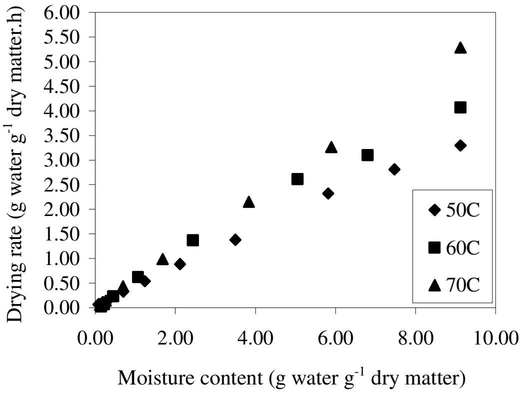

Figure 2. Effect of drying air temperature and moisture content on the drying rate of mushrooms.

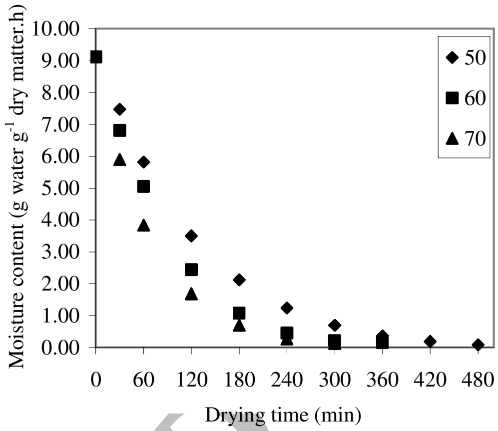

Figure 3. Effect of drying air temperature and drying time on moisture content of mushrooms.

that diffusion is the dominant physical mechanism governing moisture movement in the mushrooms. The results were consistent with observations made by different authors on drying various vegetables [21, 36 and 37].

The moisture content of the samples as a function of drying time are presented in Figure 3 for 50, 60 and 70 °C drying air temperatures. As seen in this figure, all lines have two stages. The moisture content rapidly reduces and then slowly decreases with increase in drying time. In addition, it is obvious from the Figure 3 that drying temperature has an important effect on the total drying time. The rate of moisture loss was higher at higher temperatures and the total drying time was reduced substantially with the increase in air temperature. However, drying at high temperature is not suggested due to harmful effects on food components like proteins, vitamins, colour, etc. The drying time required to reduce the moisture content to any given level was dependent on the drying condition, being highest at 50 °C and lowest at 70 °C. By drying, the time required to reduce the moisture content of mushrooms from the initial value of 90.12 ± 0. 13% (wb) to a final value about 10 % (wb) were 480, 360 and 300 min at 50, 60 and 70 °C, respectively. Similar results have been observed in the drying curves of different fruits and vegetables: carrot, corn, tomato, mushroom, garlic, onion, spinach, pepper, pumpkin, green pea, leek and celery [38]; aromatic plants [34]; rosehip [39]; pumpkin [19]; spinach [21]; eggplant [40-41], among others.

Evaluation of the Models

Thin-layer drying models, the Lewis model [4,28], Page model [5,13], modified Page model [15,36], the Henderson and Pabis model [12,21], logarithmic model [12,15,19], the two-term model [10,42] and Midilli model (Midilli *et al.* [8]) were used to describe drying characteristics of mushrooms in a thin layer convective-type dryer. Correlation coefficient (R^2), root means square error (RMSE) and reduced chi-square (χ^2) were used as the criteria for the accuracy of the fit. Details of the statistical analysis are presented in Table 2. As seen in this table, all the seven drying models yielded a correlation coefficient (R^2) greater than the acceptable R^2 value of 0. 93 at all drying air temperatures [42]. Among the seven drying models, Midilli *et al.* [8] model yielded the highest R^2 values for all the drying temperatures, followed by the two-term model. In addition, the results indicated that, the lowest values of RMSE and chi-square were obtained in the case of

Table 2. Statistical results of different drying models and their constants and coefficients at various air temperatures.

Model	Temperature (°C)	Constants and coefficients				χ^2	RMSE	R^2	P
Lewis	50	k=0.594				0.0024342	0.04934	0.9359	1.80×10^{-6}
	60	k=0.606				0.0006898	0.02626	0.9524	1.36×10^{-5}
	70	k=0.774				0.0003582	0.01893	0.9705	5.52×10^{-7}
Page	50	k=0.210	n=1.1708			0.0001212	0.01044	0.9890	4.04×10^{-8}
	60	k=0.888	n=0.9392			0.0005462	0.02217	0.9563	5.17×10^{-6}
	70	k=1.236	n=0.9245			0.0000542	0.00694	0.9906	2.63×10^{-7}
Modified Page	50	k=0.474	n=1.1708			0.0001207	0.01042	0.9890	4.04×10^{-8}
	60	k=0.678	n=0.9392			0.0005470	0.02219	0.9563	5.17×10^{-6}
	70	k=0.900	n=0.9245			0.0000543	0.00695	0.9906	2.63×10^{-7}
Henderson and Pabis	50	a=1.5410	k=0.528			0.0352792	0.17819	0.9496	1.80×10^{-6}
	60	a=0.6566	k=0.672			0.0165652	0.12210	0.9413	1.36×10^{-5}
	70	a=0.7561	k=0.726			0.0078518	0.08354	0.9769	5.52×10^{-7}
Logarithmic	50	a=1.3050	k=0.624	c=0.0030		0.0125993	0.10040	0.9788	4.06×10^{-7}
	60	a=1.4410	k=0.918	c=0.0125		0.0260340	0.14432	0.9946	2.29×10^{-8}
	70	a=1.0650	k=0.960	c=0.0033		0.0006981	0.02330	0.9995	7.74×10^{-8}
Two-term	50	a=0.9837	k_0=0.686	b=0.0196	k_1=0.052	0.0002158	0.01314	0.9983	3.38×10^{-8}
	60	a=1.0454	k_0=0.726	b=0.0222	k_1=0.060	0.0008705	0.02639	0.9928	4.35×10^{-7}
	70	a=1.0053	k_0=0.864	b=0.0454	k_1=0.312	0.0006963	0.02327	0.9945	5.56×10^{-8}
Midilli *et al.* [8]	50	a=1.0005	k=0.4511	n=1.0755	b=-0.0010	0.0000106	0.00272	0.9993	6.72×10^{-8}
	60	a=0.9996	k=0.5829	n=1.2289	b=0.0015	0.0000274	0.00438	0.9991	1.51×10^{-7}
	70	a=1.0000	k=0.8403	n=1.0255	b=0.0003	0.0000252	0.00409	0.9998	8.27×10^{-8}

Midilli *et al.* [8] model. This model could be shown as: $MR=a\exp(-kt^n)+bt$

Where, MR is the moisture ratio, k is drying rate constant (h^{-1}), t is time (h), a, n and b are experimental constants. While RMSE changed between 0. 00272-0. 00438, chi-square values were between 0. 0000106-0. 0000274 and R^2 values were between 0. 9991 and 0.9998. This model represented the experimental values of moisture ratio satisfactorily. Hence, Midilli *et al.* [8] model was selected in the present study to predict the drying characteristics of mushroom. Figure 4 depicts the drying curve of this model in terms of changes in the moisture content with drying time as well as the experimental data of thin-layer drying of mushrooms at air temperatures of 50, 60 and 70 °C. Figure 5 compares the predicted and the observed values of moisture ratio. The linear nature of the curve, at 45° slope from the origin, indicates that, the predicted model is a good fit for the actual drying data. Similar results on drying of various fruits and vegetables have been reported by some other authors [12 and 20].

Effective Diffusivities and Activation Energy

Effective diffusivities of dried mushroom at different temperatures were obtained from the gradient of the graph as shown in Figure 6. Plots of ln (MR) versus drying time (t) gave straight lines for 50 °C, 60 °C, 70 °C, with slopes of 0.0089 min^{-1}, 0.0121 min^{-1}, 0.0144 min^{-1}, respectively. The respective Correlation Coefficients (R^2) from the regression analyses of the straight lines were 0.9956, 0.9937 and 0.9994 at the three temperatures tested, respectively.

The effective diffusivities obtained by Eq. (8) at 50 °C, 60 °C, and 70 °C were 9.619 x 10^{-10} m^2s^{-1}, 1.308 x 10^{-9} m^2s^{-1}, and 1.556 x 10^{-9} m^2s^{-1}, respectively. These values fall within the range of 10^{-9}–10^{-11} m^2s^{-1} [42], which has been reported for most food materials. Table 3 shows the effective diffusivities of other fruits and vegetables. Additionally, the relationship of the effective diffusivities and drying

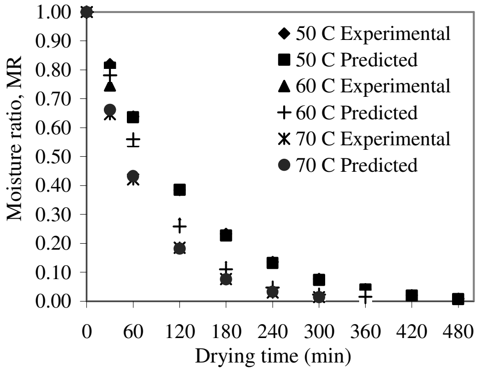

Figure 4. Midilli model fitted to the drying data.

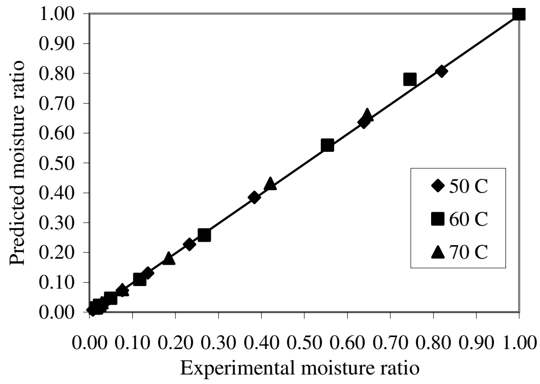

Figure 5. Comparison of experimental data with values predicted by Midilli model.

temperatures follow the Arrhenius equation as shown in Figure 6.

The logarithm of effective diffusivity (D_{eff}) as a function of the reciprocal of the absolute temperature (T) is plotted in Figure 7 and is shown as a linear relationship between (ln D_{eff}) and ($1/T$). The calculated diffusivity constant (D_0) and activation energy (E_a) were 3.848 x 10^{-6} m^2s^{-1} and 22.228 kJ mol^{-1}, respectively. The activation energy is relatively low compared to that of other fruits and vegetables, as shown in Table 3.

CONCLUSIONS

The drying kinetics of oyster mushroom in a cabinet-type dryer at three air temperatures [50, 60 and 70 °C), was investigated. As was expected, an increase in temperature reduced the drying time. Drying of oyster mushroom occurred only in the falling rate period: no constant rate period of drying was observed in the present study. Experimental data were compared with the values predicted by seven thin-layer drying models. All the drying models considered in this study could adequately represent the thin-layer drying behaviour of oyster mushrooms, although the Midilli *et al.* [8] model represented the process better than the other drying models. The effective moisture diffusivity of mushrooms was found to range between 9.619x10^{-10} to 1.556x10^{-9} m^2s^{-1} within the temperature range of 50, 60 and 70 °C and it could be represented in an Arrhenius-type relationship with good accuracy. Activation energy was also found to be 22.228 kJ mol^{-1}.

Table 3. Effective diffusivity and activation energy of different fruits and vegetables.

Fruits/vegetables	Effective diffusivity (m^2s^{-1})	Activation energy (kJ mol^{-1})	References
Chempedak	3.291 x 10^{-10} – 4.534 x 10^{-10}	6.80	46
Pumpkin	3.880 x 10^{-10} – 9.380 x 10^{-10}	78.93	19
Spinach	6.590 x 10^{-10} – 1.927 x 10^{-10}	34.35	21
Mulberry	2.320 x 10^{-10} – 2.760 x 10^{-9}	21.2	47
Prune	4.300 x 10^{-10} – 7.600 x 10^{-10}	57.00	48
Wheat	1.218 x 10^{-10} – 2.861 x 10^{-10}	37.01	22
Black tea	1.140 x 10^{-11} – 2.980 x 10^{-11}	406.03	36
Carrot	7.295 x 10^{-11} – 1.501 x 10^{-10}	22.43	9
Mushroom	4.08 x 10^{-10} – 1.78 x 10^{-9}	-	49

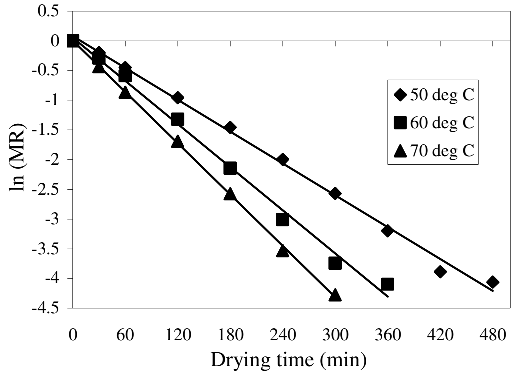

Figure 6. Experimental and predicted logarithmic moisture ratio at different drying times.

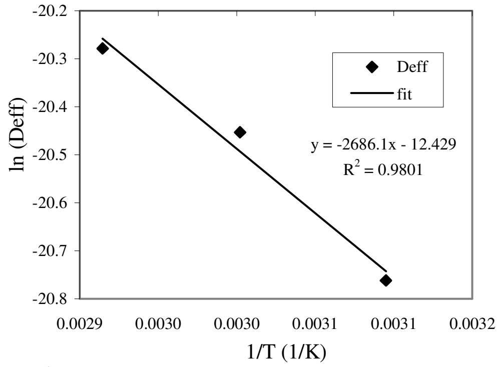

Figure 7. Arrhenius type relationship between effective moisture diffusivity and reciprocal of the absolute temperature.

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Nomenclature

a,b,c,n	constants of models
D_{eff}	effective diffusivity (m^2s^{-1})
D_0	pre-exponential factor of the Arrhenius equation (m^2s^{-1})
E_a	activation energy (kJ mol^{-1})
k, k_0, k_1	rate constants in models, h^{-1}
L	half-thickness of the slab in samples, m
MR	moisture ratio
M	moisture content, g water/g dry matter
M_i	initial moisture content, g water/g dry matter
M_e	equilibrium moisture content, g water/g dry matter
n	positive integer, constant
N	number of experimental data points
R	gas constant, kJ mol^{-1} K
R^2	correlation coefficient
RMSE	root mean square error
t	drying time, min
z	number of constants in models
χ^2	reduced chi-square

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سینتیک خشک شدن قارچ صدفی (*Pleurotus ostreatus*) در جریان هوای داغ

ی. تولک

چکیده

هدف از این تحقیق مطالعه سینتیک خشک شدن قارچ صدفی (Pleurotus ostreatus) بود که با استفاده از خشک کن کابینتی و جریان هوای داغ خشک شدند. برای خشک کردن از هوای با دماهای ۵۰، ۶۰ و ۷۰ درجه سانتی‌گراد استفاده شد. از اطلاعات بدست آمده با استفاده از مدلهای نظری مختلف برای پیش‌بینی سینتیک خشک شدن استفاده شد. از آنالیز رگرسیون غیر خطی عوامل و شرایط مؤثر از خشک کردن استفاده شد. کارائی مدلها با مقایسه ضریب تبیین R^2 ، انحراف معیار (RMSE) و مربع کمی (Chi- Square) (χ^2) بین نسبت رطوبت مشاهده شده و پیش‌بینی شده ارزیابی شد و مدل میدبلی و همکاران (Midilli, *et al*.) برازش بیشتری با داده های بدست آمده در این تحقیق داشت. ضریب انتشار مؤثر رطوبت (D_{eff})، ثابت انتشار (D_0) و انرژی فعال‌سازی (E_a)محاسبه شده ثابت انتشار بین $۱۰^{-۱۰} \times ۹/۶۱۹$ تا $۱۰^{-۹} \times ۱/۵$ متر مربع بر ثانیه در بازه دمایی مورد استفاده متغیر بود و مقدار ضریب E_a برابر ۲۲/۲۲۸ $kJ\ mol^{-1}$ بود.