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MATHEMATICAL MODELING AND EFFECT OF ISOTHERMAL DRYING ON MUSHROOM (*BOLETUS PINOPHILUS*)

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Abstract. Eleven kinds of mathematical models were used to obtained moisture data. From obtained results, the semi-theoretical models chosen in this work proved to be quite good to describe the drying behavior of isothermal drying. In the experiment, Modified Henderson and Pabis model was most appropriate for fitting $MR-t$ curve of isothermal drying of hot-air drying, its correlation coefficients is above 0.999; for chi-square is below 0.0075; for root mean square error is below 0.0077.
Keywords: mushrooms; isothermal drying; mathematical model

Introduction

Mushrooms are of commercial importance due to their nutritional and medicinal value (Çelen et al., 2010). In recent years, mushrooms are favorable all over the world not only because of their texture and flavour, their chemical, nutritional and functional properties such as antiallergic, antiatherogenic, antihypoglycemic properties are also well documented (Kalač, 2009; Leskosek-Cukalovic et al., 2010; Palacios et al., 2011).

Mushroom (*Boletus pinophilus*) (Fig. 1) is a good source of nutrition because of its higher protein, dietary fibers and important mineral contents (Heleno et al., 2010). Besides, mushroom (*Boletus pinophilus*) contains many different phytochemical contents such as phenolic compounds, tocopherols, ascorbic acid and carotenoids (Reis et al., 2012). Therefore, mushroom (*Boletus pinophilus*) is a healthy food in our daily diet. Mushrooms contain moisture in the range of 6.75 to 18.9 kg dry basis (87% to 95% wet basis) (Arora et al., 2003).

Figure 1. *Boletus pinophilus*

Due to their high moisture content they cannot be stored for more than 24 hours at ambient onditions. Hence they need to be preserved by some method. Drying is the most commonly used method for long term preservation of agricultural products including mushrooms, because it extends the food self-life, preserving all of their features (Pandey et al., 2000; Tulek, 2011). Drying can be defined as the process of moisture removal due to simultaneous heat and mass transfer between the product and the drying air by means of evaporation. The major objective of drying process of foods is the reduction of the moisture content until reaching the desired level, which allows safe storage over an extended period (Walde et al., 2006). Several drying techniques such as sun/solar drying, hot air drying in conventional tray/cabinet dryers, fluidized bed drying, microwave drying, freeze drying and osmotic drying have been used successfully for mushrooms. Each technique has advantages and drawbacks but hot air drying is the most widely known technique (Gothandapani et al., 1997).

The purpose of this study was to investigate isothermal drying (ID) of mushrooms by using eleven mathematical models to predict the water content. The purpose of drying is to reduce the water content to 3%.

Materials and methods

Samples

Fifteen mushroom samples were collected in 2014 and 2015 from the Batak mountain, Bulgaria personally by the authors. Fresh stipe of mushroom were removed, samples were stored at 4°C within 12 h before drying. Prior to dehydration, mushrooms were thoroughly washed to remove the dirt and graded by size ((6 ± 0.5) cm in diameter) to eliminate the variations in respect to the exposed surface area.

Slices of desired thickness were obtained by carefully cutting mushrooms vertically by using a vegetable slicer and the slices from middle portions of mushroom were used for drying experiments without any pretreatments. Besides, prior to initial moisture contents of the mushroom (*Boletus pinophilus*) were determined by AOAC standard (1984) to 90.4% (dry basis), respectively (Dospatliev & Ivanova, 2017).

Mathematical modelling

Thin layer drying models may be classified as theoretical, semi-theoretical and empirical ones. The first category considers simultaneous heat and mass transfer equations. The semi-theoretical models combine the theoretical equations with simplifications. Finally, the empirical models describe drying curves for experiment conditions (Özdemir & Devres, 1999). The internal moisture transfer principally occurs during the falling rate period of drying process; so it may be controlled by liquid diffusion mechanism which is described by the Fick's law (Panchariya et al., 2002):

$$\frac{\partial M}{\partial t} = D_{eff} \nabla^2 M \tag{1}$$

whereis the effective moisture diffusivity and M the moisture content at any time % d.b. Drying of many food products has been successfully predicted using Fick's law with slab geometry to calculate effective moisture diffusivity as follows (Tulek, 2011; Wakchaure et al., 2010):

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

where MR stands for $\frac{M - M_{eq}}{M_0 - M_{eq}}$ the dimensionless form of moisture content, $L$the thickness of the slab (m), n a positive integer and t the drying time in (s). Practically, only the first term of Eq. (2) is used giving us the form:

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t}{4L^2} \right) \quad (3)$$

The natural logarithm in both sides of Eq. (3) yields the linear solution (4):

$$\ln MR = \ln \frac{8}{\pi^2} - \ln \frac{\pi^2 D_{eff} t}{4L^2} \quad (4)$$

Diffusivities are typically determined by plotting experimental drying data in terms of $\ln MR$ versus drying time t in (4), because the plot gives a straight line with a slope as follows:

$$Slope = \frac{\pi^2 D_{eff} t}{4L^2} \quad (5)$$

Correlation coefficients and error analyses

In this study we considered ten semi-theoretical mathematical models (Lewis, Henderson and Pabis, Logarithmic, Two-term exponential, Page, Modified Page, Midilli et al., Diffusion approach, Modified Henderson and Pabis, Verma et al.) and one empirical model (Wang and Singh).

The thin layer drying equations on Table 1 consist a useful literature survey in mathematical modeling and may be tested to select the best model for drying curves of mushrooms (Meisami-asl& Rafiee, 2009). The mushrooms drying curves obtained were processed to find the most suitable thin-layer drying model by regression analysis.

The goodness of fit of the tested mathematical models to the experimental data was evaluated with the correlation coefficient (R^2), the reduced chisquare (χ^2) and the root mean square error (RMSE). The higher the R^2 values and the lower the (χ^2) and RMSE values, the better is the goodness of fit (Ertekin & Yaldiz, 2004; Özdemir & Devres, 1999). The reduced chi-square (χ^2) and the root mean square error (RMSE) can be calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N-n} \tag{6}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2} \tag{7}$$

where $MR_{\exp,i}$ is the i^{th} experimental moisture ratio, $MR_{pre,i}$ is the i^{th} predicted moisture ratio, N is the number of observation and n is the number of constants. In this study, the nonlinear or linear regression analysis was performed with SPSS (Statistical Package for Social Science) program for Windows.

Table 1. Mathematical models for the drying curves

№	Model name	Model equation	References
1.	Lewis	$MR = \exp(-k \cdot t)$	O'Callaghan et al., 1971
2.	Henderson and Pabis	$MR = a \cdot \exp(-k \cdot t)$	Moss & Otten., 1989
3.	Logarithmic	$MR = a \cdot \exp(-k \cdot t) + c$	Xanthopoulos et al., 2007; Yaldiz et al., 2001
4.	Two-term exponential	$MR = a \cdot \exp(-k_0 \cdot t) + b \cdot \exp(-k_1 \cdot t)$	Babalis et al., 2006; Sharaf-Eldeen et al., 1980
5.	Page	$MR = \exp(-k \cdot t^n)$	Basunia & Abe, 2001
6.	Modified Page	$MR = a \cdot \exp(-k \cdot t^n)$	Diamante & Munro, 1993
7.	Wang and Singh	$MR = \quad + a \cdot t + b \cdot t$	Wang & Singh, 1978
8.	Midilli et al.	$MR = a \cdot \exp(-k \cdot t^n) + b \cdot t$	Tulek, 2011; Ertekin & Yaldiz, 2004
9.	Diffusion approach	$MR = a \cdot \exp(-k \cdot t) + (1-a) \cdot \exp(-k \cdot b \cdot t)$	Çelen et al., 2010
10.	Modified Henderson and Pabis	$MR = a \cdot \exp(-k \cdot t) + b \cdot \exp(-g \cdot t) + c \cdot \exp(-h \cdot t)$	Thompson et al., 1968
11.	Verma et al.	$MR = a \cdot \exp(-k \cdot t) + (1-a) \cdot \exp(-g \cdot t)$	Verma et al., 1985

Results and discussion

Fig. 1 shows the comparison of eleven mathematical models at the drying temperature of 105°C, and similar results could be also obtained at other drying temperatures. It can be seen that the eleven models present a little over or under estimation in comparison with the experimental data at different stages of drying process. For instance, the Wang & Singh model is above the experimental curve during the first 6 h of drying process, and below the experimental curve during the period between 6 and 14 h and above the experimental curve again after 14 h, while all other models fits the experimental data well during the whole drying process.

The moisture content data observed at the drying experiment were converted into the moisture ratio (*MR*) and fitted to the 11 models listed in Table 1. The statistical results of the different models, including the drying model coefficients and the comparison criteria used to evaluate goodness of fit, namely, R^2, χ^2 and RSME, are listed in Table 2.

In all cases, R^2 values were higher than 0.918, and χ^2 and RMSE values were lower than 0.9742 and 0.0882, respectively.

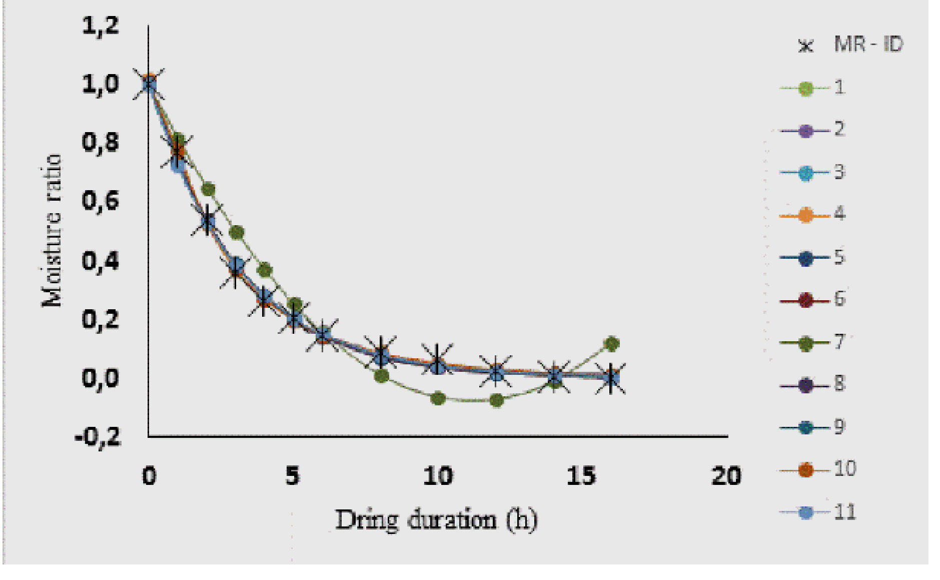

Figure 1. Comparison between values of eleven selected models and experimental data of mushroom at 105°C

To further explain the drying process, 11 different thin layer drying models were compared according to their R^2, chi-square (χ^2) and RMSE. In the experiment, Modified Henderson & Pabis model was most appropriate for fitting $MR - t$ curve of ID of hot-air drying, its correlation coefficients for R^2 are above 0.999; for χ^2 are below 0.0075; for RMSE are below 0.0077. And its regression curve is remarkable. From these results, the empirical models chosen in this work proved to be quite good to describe the drying behavior of different hot-air drying methods. Thus, the knowledge of drying kinetics and their models are important to design, simulate and optimize drying process. Also, the best described modeling can be applied to estimate optimum drying.

Table 2. Statistical results of 11 mathematical models for ID hot-air drying model

№	Constants						R^2	χ2	RMSE
1.	k = 0.3149						0.9970	0.0362	0.0170
2.	k = 0.3198	a = 1.0146					0.9972	0.0333	0.0163
3.	k = 0.3257	a = 1.0102	c = 0.0066				0.9973	0.0319	0.0160
4.	k_0 = 0.3318	k_1 = 0.0890	a = 0.9920	b = 0.0256			0.9974	0.0316	0.0159
5.	k = 0.3009	n = 1.0366					0.9972	0.0333	0.0163
6.	k = 0.3086	a = 1.0101	n = 1.0249				0.9973	0.0321	0.0160
7.	a = -0.1914	b = 0.0085					0.9188	0.9742	0.0882
8.	k = 0.3026	a = 1.0085	b = 0.0008	n = 1.0508			0.9976	0.0288	0.0152

9.	k = 0.3149	a = 4.9592	b = 1.0000				0.9970	0.0362	0.0170
10.	k = 0.2447	a = 0.5974	b = -0.1729	c = 0.5755	g = 7.6392	h = 0.6321	0.9994	0.0075	0.0077
11.	k = 0.3196	a = 0.9919	g = 0.0428				0.9970	0.0356	0.0169

Conclusions

From obtained results, the semi-theoretical models chosen in this work proved to be quite good to describe the drying behavior of isothermal drying. In the experiment, Modified Henderson and Pabis model was most appropriate for fitting $MR - t$ curve of ID of hot-air drying, its correlation coefficients for R^2 is above 0.999; for χ^2 is below 0.0075; for RMSE is below 0.0077.

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