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# USING SOME MATHEMATICAL MODELS IN MODELING MUSHROOM DRYING (AGARICUS BISPORUS)

Miroslava Ivanova<sup>1</sup>, Nedyalko Katrandzhiev<sup>2</sup>, Lilko Dospatliev<sup>3</sup> §

<sup>1</sup> Trakia University
 Department of Informatics and Mathematics
 Stara Zagora, 6000, BULGARIA
 <sup>2</sup> University of Food Technology

Department of Computer Systems and Technologies Plovdiv, 4000, BULGARIA

<sup>3</sup> Trakia University
Department of Pharmacology, Animal Physiology
and Physiological Chemistry
Stara Zagora, 6000, BULGARIA

Abstract: In the present study, a thin-layer drying kinetics of Agaricus bisporus mushroom was experimentally investigated in convective dryer. Experiments were performed at air temperatures of 35 °C, 45 °C, and 55 °C and constant air velocity of 2 m s<sup>-1</sup>. In order to select a suitable form of the drying curve, 11 different mathematical models were fitted to experimental data. The high values of coefficient of determination  $(R^2)$  and the low values of reduced chi-square  $(\chi^2)$  and root mean square error (RMSE) indicated that the Modified Henderson and Pabis model could satisfactorily illustrate the drying curve of Agaricus bisporus mushroom. The Modified Henderson and Pabis model had the highest value of  $R^2$  (0.9990), the lowest  $\chi^2$  (0.0001) and RMSE (0.0092). Fick's second law was used to calculate the effective moisture diffusivity. The moisture diffusion coefficient varied between  $1.4970 \times 10^{-8}$  and  $2.7222 \times 10^{-8}$  m<sup>2</sup> s<sup>-1</sup> for the given temperature range and corresponding activation energy was 25.1648 kJ mol<sup>-1</sup>.

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<sup>§</sup>Correspondence author

There is an interest in information regarding the most suitable conditions for the different types mushrooms drying process. All the studies, experiments and analyzes performed by the authors are a basis for creating a Web-based platform with the help of which the most suitable drying model can be offered when specifying the mushrooms type and the drying parameters. The Web-based platform will be able to add new data and analyze it automatically which will allow the platform self-improvement.

AMS Subject Classification: 92B15, 93A30

**Key Words:** mathematical model; diffusivity; activation energy; mushroom *Agaricus bisporus* 

#### 1. Introduction

Auricularia auricularia was the first artificially cultivated mushroom in the world. It was cultivated in 600, followed by other mushrooms like Flammulina velutipes (A.D. 800), Lentinula edodes (A.D. 1000). The global production of cultivated edible mushrooms was 495.127 metric tons in 1961. From 1961 to 2016, mushroom production increased to 10.378.163 metric tons. Agaricus bisporus (white button mushroom) still retains the highest overall world production. The nutritional attributes of edible mushrooms and the health benefiting effects of the bioactive compounds they contain, make mushrooms a health food. Many researchers from different regions of the world confirmed the medicinal importance and nutritional quality of Agaricus bisporus (see [1], [6], [7], [25]).

Mushrooms are highly perishable in nature, with extremely short shelf-life as they contain moisture in the range of 87% to 95% wet basis (w.b.). Quality deterioration takes place if fresh mushrooms are not immediately processed. Therefore, their processing to the forms of more stable products is important.

Drying reduces bulk quantity, thus facilitating transportation, handling and storage. Although sun-drying is economical, mechanical drying speeds up the process, prevents losses, ensures use of safer drying temperatures and produces superior product compared to sun drying.

The drying kinetics of food is a complex phenomenon and requires simple representations to predict the drying behaviour and to optimise the drying parameters.

Thus, layer drying mathematical models were used for drying time prediction and for generalization of drying curves (see [12], [13], [14], [16], [22]).

However, systematic studies on the drying kinetics of Agaricus bisporus mushrooms are lacking. The objectives of the present study were: i) to study the drying kinetics of Agaricus bisporus mushroom in a fluidized bed dryer, ii) to evaluate a suitable thin layer drying mathematical model, and iii) to determine the moisture diffusivity and activation energy during drying of Agaricus bisporus mushroom.

#### 2. Materials and methods

## 2.1. Samples

Mushroom samples used as raw material in the present study, were obtained from a mushroom maker in Stamboliyski, Bulgaria. 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 (2 mm 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 (Agaricus bisporus) were determined by AOAC standard to 89.8%.

### 2.2. Mathematical modeling

## 2.2.1. Analysis of process and modeling

The moisture ratio of the samples during drying was expressed by the following equation:

$$MR = \frac{M_t - M_e}{M_0 - M_e},$$

where: MR is the dimensionless moisture ratio,  $M_t$  is the moisture content at time t, and  $M_0$  and  $M_e$  are the initial and equilibrium moisture contents, respectively, on dry basis.

As the  $M_e$  is very small compared to  $M_0$  and  $M_t$  values, the  $M_e$  can be neglected and MR can be expressed by (see [2], [8])

$$MR = \frac{M}{M_0}.$$

To select a suitable model for describing the drying process of Agaricus bisporus, drying curves were fitted with eleven thin-layer drying equations (Table 1). Non-linear regression analysis was performed using statistical software R program version 3.5.1. The coefficient of determination  $R^2$  was one of the main criteria for selecting the best equation. In addition to the coefficient of determination, the goodness of fit was determined by other statistical parameters such as sum square error (SSE), total sum of squares (SST), reduced chi-square  $(\chi^2)$ , mean square error (MSE), root mean square error (RMSE) and mean bias error (MBE). For goodness fitting,  $R^2$  value should be higher and  $\chi^2$  and RMSE values should be lower (see [11]). These parameters are calculated as follows:

$$SSE = \sum_{i=1}^{N} (MR - MR_{mod})^{2},$$

where  $MR_{mod}$  is the predicted moisture ratio,

$$SST = \sum_{i=1}^{N} \left( MR - \overline{MR} \right)^{2},$$

where  $\overline{MR}$  is average value of the experimental moisture ratio.

$$R^{2} = 1 - \frac{SSE}{SST},$$

$$\chi^{2} = \frac{SSE}{N - p} = \frac{\sum_{i=1}^{N} (MR - MR_{mod})^{2}}{N - p},$$

$$MSE = \frac{\sum_{i=1}^{N} (MR - MR_{mod})^{2}}{N},$$

$$RMSE = \sqrt{MSE} = \sqrt{\frac{\sum_{i=1}^{N} (MR - MR_{mod})^{2}}{N}},$$

$$MBE = \frac{\sum_{i=1}^{N} (MR_{mod-MR})}{N},$$

where N is the number of observations and p is the number of regression coefficients.

## 2.2.2. Moisture diffusivity

Fick's diffusion equation for the particles spherical in shape was used for the calculation of effective moisture diffusivity (see [19]). Since the Canola seeds

$N_{\overline{0}}$	Model name	Model equation	Ref.
1.	Lewis	$MR = exp\left(-k \cdot t\right)$	see [20]
2.	Henderson and Pabis	$MR = a \cdot exp\left(-k \cdot t\right)$	see [18]
3.	Logarithmic	$MR = a \cdot exp\left(-k \cdot t\right) + c$	see [28], [29]
4.	Two-term exponential	$MR = a \cdot exp(-k_0 \cdot t) +b \cdot exp(-k_1 \cdot t)$	see [3], [21]
5.	Page	$MR = \exp\left(-k \cdot t^n\right)$	see [4]
6.	Modified Page	$MR = a \cdot exp\left(-k \cdot t^n\right)$	see [5]
7.	Wang and Singh	$MR = 1 + a \cdot t + b \cdot t^2$	see [27]
8.	Midilli et al.	$MR = a \cdot exp\left(-k \cdot t^n\right) + b \cdot t$	see [10], [24]
9.	Diffusion approach	$MR = a \cdot exp(-k \cdot t) + (1 - a) \cdot exp(-k \cdot b \cdot t)$	see [31]
10.	Modified Henderson and Pabis	$MR = a \cdot exp(-k \cdot t)$ $+b \cdot exp(-g \cdot t)$ $+c \cdot exp(-h \cdot t)$	see [23]
11.	Verma et al.	$MR = a \cdot exp(-k \cdot t) + (1 - a) \cdot exp(-g \cdot t)$	see [26]

Table 1: Mathematical models for the drying curves

have spherical geometry, the equation is expressed as:

$$MR = \frac{8}{\pi^2} \cdot \left(\frac{-\pi^2 \cdot Deff \cdot t}{L^2}\right),\tag{1}$$

where Deff is the effective diffusivity in  $m^2$  s<sup>-1</sup>, t is the time of drying in seconds, and L is the slab thickness in meters. Equation (1) can be further simplified to only the first term of the series and expressed in a logarithmic form for long drying periods:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 \cdot Deff}{L^2}\right) \cdot t. \tag{2}$$

The effective moisture diffusivity was calculated from the slope (K) of a straight line, plotting experimental drying data in terms of  $\ln(MR)$  versus time

according to (2) (see [9]) 
$$K = \frac{\pi^2 \cdot Deff}{L^2}.$$
 Then, 
$$Deff = \frac{K \cdot L^2}{\pi^2}.$$

The relationship between effective moisture diffusivity and air temperature is assumed to be an Arrhenius-type equation (see [9], [23]):

$$Deff = D_0 \cdot \exp\left(\frac{E_a}{R \cdot (T + 273.15)}\right).$$

Here  $D_0$  is the pre-exponential factor (m<sup>2</sup> s<sup>-1</sup>),  $E_a$  is the activation energy (kJ mol<sup>-1</sup>), R is the universal gas constant (8.314 × 10<sup>-3</sup> kJ mol<sup>-1</sup> K<sup>-1</sup>), and T is temperature (°C). The equation can be linearized by taking natural logarithm on both sides:

$$\ln\left(Deff\right) = \ln\left(D_0\right) \cdot \left(-\frac{E_a}{R}\right) \cdot \left(\frac{1}{T + 273.15}\right).$$

#### 3. Results and discussion

The time taken for drying of mushroom slices at different temperatures is given in Table 2. It is evident that drying air temperature has an important effect on drying. When the temperature was increased, the drying time reduced. The results are similar with the earlier observations on drying of garlic slices, onion slices, egg plants, peach slices (see [15]) and plum slices (see [11]).

Drying temperature (°C)	Drying time (min)
35	170
45	150
55	120

Table 2: Drying time of Agaricus bisporus mushroom

The changes in the moisture content of mushroom slices with drying time for 35 °C, 45 °C and 55 °C air temperatures are given Figures 1 and 2. As seen from the figures, the moisture content decreases continuously with the drying

time. Drying of mushroom slices takes about 2-3 h in the dryer. As seen from Figures 1 and 2, one of the main factors influencing the drying kinetics of the mushroom slices is the air temperature. An increase in air temperature results in a decrease in drying time.

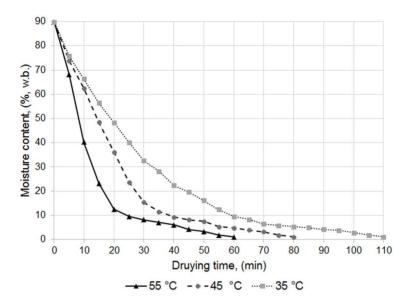


Figure 1: Variation of moisture content with drying time during for  $Agaricus\ bisporus\ mushroom$ 

The average moisture ratio of Agaricus bisporus mushroom dried at different temperatures was test verified with eleven different drying models to find out their suitability to describe the drying process. The correlation coefficient and results of statistical analysis obtained from nonlinear regression analysis using R 3.5.1 software package are summarized in Table 3. The best model to describe the drying behavior of Agaricus bisporus mushroom was selected on the basis of high  $R^2$  and low reduced  $\chi^2$ . MBE and RMSE values must be low too.

Since the models are different number of coefficients is correct to look for models with maximum adjusted  $R^2$  and minimal reduced  $\chi^2$ . It is observed from Table 3 that for 35 °C, 45 °C and 55 °C the best model is Modified Henderson and Pabis (model 10, Table 1). It gave comparatively the highest  $R^2$  values of in all the drying temperatures, where as the  $\chi^2$ , MBE and RMSE values were also found to be the lowest.

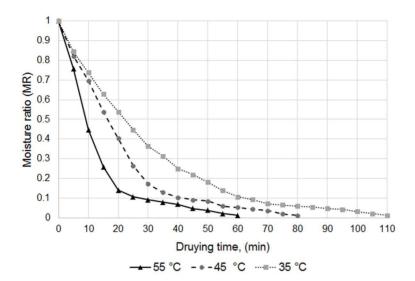


Figure 2: Moisture ratio with drying time for  $Agaricus\ bisporus$  mushroom

Table 3: Statistical results of 11 mathematical models for ID hot-air drying model

$\mathcal{N}_{\overline{0}}$	T(°C)	Constants	SSE	$R^2$	$\chi^2$	RMSE	MBE
1.	$35^{\circ}\mathrm{C}$	k = 0.034	0.005	0.997	0.000	0.015	0.002
	$45^{\circ}\mathrm{C}$	k = 0.049	0.022	0.986	0.001	0.360	0.000
	$55^{\circ}\mathrm{C}$	k = 0.081	0.016	0.986	0.001	0.035	-0.007
2.	35°C	a = 1.020 $k = 0.035$	0.004	0.998	0.000	0.013	0.003
	45°C	a = 1.050 $k = 0.051$	0.018	0.989	0.001	0.032	0.003
	55°C	a = 1.033 $k = 0.084$	0.015	0.987	0.001	0.034	-0.005
3.	35°C	a = 1.030 k = 0.032 c = -0.018	0.004	0.998	0.000	0.012	0.005
	45°C	c = -0.018 a = 1.060 k = 0.049	0.017	0.989	0.001	0.031	0.000

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Table 3 – Continued from previous page

Nº	T(°C)	Constants	SSE	$\frac{R^2}{R^2}$	$\frac{\chi^2}{\chi^2}$	RMSE	MBE
		c = -0.016					
	$55^{\circ}\mathrm{C}$	a = 1.024	0.014	0.000	0.001	0.022	0.000
		k = 0.088 c = 0.015	0.014	0.988	0.001	0.033	0.000
4.	$35^{\circ}\mathrm{C}$	a = 0.013 $a = 1.041$					
	00 0	$k_0 = 0.035$	0.000	0.000	0.000	0.010	0.000
		b = -0.041	0.003	0.998	0.000	0.012	0.002
		$k_1 = 4.153$					
	$45^{\circ}\mathrm{C}$	a = 1.141					
		$k_0 = 0.056$	0.011	0.993	0.001	0.025	-0.000
		b = -0.141 $k_1 = 4.153$					
	$55^{\circ}\mathrm{C}$	a = 1.213					
		$k_0 = 0.098$	0.000	0.002	0.001	0.005	0.011
		b = -0.213	0.008	0.993	0.001	0.025	-0.011
		$k_1 = 4.153$					
5.	$35^{\circ}\mathrm{C}$	k = 0.025	0.003	0.999	0.000	0.010	0.006
	45°C	n = 1.082 $k = 0.024$					
	40 0	n = 0.024 n = 1.213	0.010	0.994	0.001	0.024	0.002
	$55^{\circ}\mathrm{C}$	k = 0.054	0.019	0.000	0.001	0.021	0.019
		n = 1.155	0.013	0.989	0.001	0.031	-0.013
6.	$35^{\circ}\mathrm{C}$	a = 0.982					
		k = 0.024	0.002	0.999	0.000	0.009	-0.003
	45°C	n = 1.094 a = 1.001					
	40 C	a = 1.001 k = 0.024	0.008	0.995	0.001	0.022	-0.005
		n = 1.224	0.000	0.000	0.001	0.022	0.000
	$55^{\circ}\mathrm{C}$	a = 1.016					
		k = 0.058	0.012	0.990	0.001	0.031	-0.011
_	2500	n = 1.135					
7.	$35^{\circ}\mathrm{C}$	a = -0.024	0.037	0.980	0.002	0.040	0.009
	45°C	b = 0.000 a = -0.033					
	40 0	a = -0.033 b = 0.000	0.039	0.975	0.003	0.048	0.006

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Table 3 – Continued from previous page

	Table 3 – Continuea from previous page						
$N_{\overline{0}}$	T(°C)	Constants	SSE	$R^2$	$\chi^2$	RMSE	MBE
	$55^{\circ}\mathrm{C}$	a = -0.049	0.092	0.921	0.009	0.084	0.015
		b = 0.001	0.092	0.921	0.009	0.064	0.015
8.	$35^{\circ}\mathrm{C}$	a = 0.978					
		k = 0.022	0.004	0.998	0.000	0.012	0.007
		n = 1.112	0.001	0.000	0.000	0.012	0.001
		b = 0.000					
	$45^{\circ}\mathrm{C}$	a = 0.990					
		k = 0.018	0.005	0.997	0.000	0.018	-0.000
		n = 1.333					
	55°C	b = 0.000					
	35°C	a = 1.010 $k = 0.042$					
		n = 0.042 $n = 1.280$	0.006	0.995	0.001	0.022	-0.002
		h = 1.200 b = 0.001					
9.	$35^{\circ}\mathrm{C}$	a = 15.000					
		k = 0.047	0.030	0.999	0.000	0.011	-0.007
		b = 1.025					
	$45^{\circ}\mathrm{C}$	a = 0.438	0.022	0.986	0.002	0.036	0.000
		k = 0.049					
		b = 1.000					
	$55^{\circ}\mathrm{C}$	a = 0.444					
		k = 0.081	0.016	0.986	0.002	0.035	-0.007
		b = 1.000					
10.	$35^{\circ}\mathrm{C}$	a = 1.199					
		k = -0.268					
		b = -1.516	0.002	0.999	0.000	0.009	-0.009
		g = 0.368 c = 0.307					
		c = 0.307 h = -0.441					
	45°C	a = -0.441 a = 0.820					
	40 C	a = 0.820 $k = -0.423$					
		b = -1.020					
		g = 0.553	0.003	0.998	0.000	0.014	0.014
		h = -0.507					
		h = -0.507					

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$N_{\overline{0}}$	T(°C)	Constants	SSE	$R^2$	$\chi^2$	RMSE	MBE
-	55°C	a = 0.786					
		k = -0.639					
		b = -0.360	0.006	0.995	0.001	0.021	-0.014
		g = -0.152	0.000	0.555	0.001	0.021	-0.014
		c = -0.430					
	2500	h = 1.302					
11.	$35^{\circ}\mathrm{C}$	a = 6.469		0.000		0.011	
		k = 0.047	0.003	0.999	0.000	0.011	0.005
	45°C	g = 0.050	0.000	0.005	0.001	0.000	0.006
	45 C	a = 15.033 k = 0.084	0.008	0.995	0.001	0.022	-0.006
		g = 0.084					
	$55^{\circ}\mathrm{C}$	a = 1.213					
	33 0	k = 0.098	0.008	0.993	0.001	0.025	-0.011
		g = 3.975	2 300	- 300	- 30-		- 3

Table 3 – Continued from previous page

The effective moisture diffusivity, Deff was calculated using the method of slopes (2). Figures 3, 4 and 5 depict the relationship between  $\ln(MR)$  and drying time for  $Agaricus\ bisporus$  dried at different temperature. From these figures, using the slope of the best fit linear equations, the moisture diffusivity values were calculated using (1) and (2). The best-fit regression equations for different temperatures during initial and later stages of drying with coefficient of correlation and effective moisture diffusivity Deff are given in Table 4.

T (00)	falling rate of drying						
1 (10)	Equation	$R^2$	Deff	$\ln(Deff)$			
35 °C	y = -0.037x + 0.078	0.989	$1.497 \times 10^{-8}$	-18.017			
$45~^{\circ}\mathrm{C}$	y = -0.052x + 0.025	0.984	$2.106 \times 10^{-8}$	-17.676			
55 °C	y = -0.067x - 0.207	0.969	$2.722 \times 10^{-8}$	-17.419			

Table 4: Moisture diffusivity equations, coefficient of correlation and effective moisture diffusivity Deff (m<sup>2</sup> s<sup>-1</sup>) at different temperatures for drying of  $Agaricus\ bisporus\ mushroom$ 

The effective moisture diffusivity (Deff) values of Agaricus bisporus mush-

room slices dried at 35 °C, 45 °C and 55 °C were  $1.4970 \times 10^{-8}$ ,  $2.1056 \times 10^{-8}$  and  $2.7222 \times 10^{-8}$  m<sup>2</sup> s<sup>-1</sup> respectively (Table 4). Deff value is a physical property indicating how the moisture is transferred from the center to the surface of mushroom in falling-rate drying period. These values are within the general range of  $10^{-12}$  -  $10^{-8}$  m<sup>2</sup> s<sup>-1</sup> for drying of food materials (see [17]). The drying temperature greatly affected the Deff values of  $Agaricus\ bisporus\ mushroom$ .

The activation energy  $(E_a)$  value calculated using the Arrhenius equation indicates the lowest energy level to be overcome in order to realize the moisture diffusion within the product. In this study,  $E_a$  value was 25.1648 kJ mol<sup>-1</sup>. The values of activation energy lie within the general range of 12.7 - 110 kJ mol<sup>-1</sup> for food materials (see [30]).

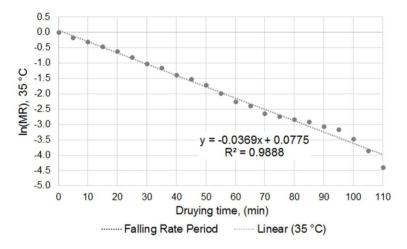


Figure 3: Relationship between  $\ln(MR)$  and drying time for Agaricus bisporus mushroom dried at 35 °C

#### 4. Conclusion

The moisture ratio of Agaricus bisporus mushroom slices during the drying process was found to be exponentially decreasing with increased drying times. The moisture diffusion coefficient varied between  $1.4970\times10^{-8}$  and  $2.7222\times10^{-8}$  m<sup>2</sup> s<sup>-1</sup> for the given temperature range (of 35 °C, 45 °C, and 55 °C) and corresponding activation energy was 25.1648 kJ mol<sup>-1</sup>, and drying kinetic parameters were best defined by the Modified Henderson and Pabis model.

The authors have researched also other types of mushrooms. An analysis of the available scientific literature had shown that there were many publications

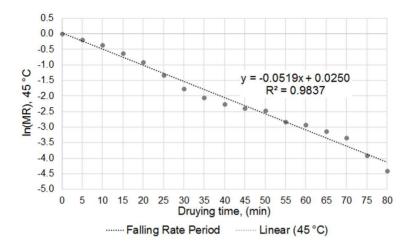


Figure 4: Relationship between  $\ln(MR)$  and drying time for Agaricus bisporus mushroom dried at 45 °C

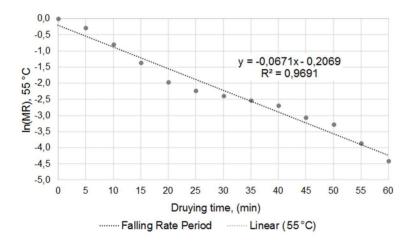


Figure 5: Relationship between  $\ln(MR)$  and drying time for Agaricus bisporus mushroom dried at 55 °C

in this field and that there was a huge interest in choosing the best drying model depending on the type of sponge, size of sliced mushrooms, drying temperature, type of drying and so on.

All the studies, experiments and analyzes performed by the authors are a basis for creating a Web-based platform with the help of which the most suitable drying model can be offered when specifying the mushrooms type and the drying parameters. The Web-based platform will be able to add new data and analyze it automatically which will allow the platform self-improvement.

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