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AIR DRYING OF BLUEBERRY FRUITS: DRYING KINETICS, MATHEMATICAL MODELING AND PHYSICAL PROPERTIES

KONVEKTIVNO SUŠENJE BOROVNICE: KINETIKA SUŠENJA, MATEMATIČKO MODELOVANJE I FIZIČKE OSOBINE

Ivan PAVKOV[*], Zoran STAMENKOVIĆ*[*], Milivoj RADOJCIN*[*], Kešelj KRSTAN*[*], Siniša BIKIĆ*[**],*
Monika LUTOVSKA[***], Ondrej PONJIČAN*[*]*
[*]Faculty of Agriculture, University of Novi Sad, 21000 Novi Sad, Serbia
[*]Faculty of Technical Science, University of Novi Sad,
Bulevar cara Lazara 6, 21000 Novi Sad, Serbia
[*]Faculty of Technical Sciences, University 'Mother Teresa', 1000 Skopje, North Macedonia,
e-mail:ivan.pavkov@polj.uns.ac.rs

ABSTRACT

The hot air convective drying of blueberries (Vaccinium corymbosum) in a thin layer was performed using a laboratory-scale dryer. The experiments were carried out at drying air temperatures of 60, 70 and 80 ^oC, and drying air velocities of 0.5 and 1.5 m/s. At higher values of the drying air temperature and the drying air velocity, less time was required for the convective drying of blueberries, i.e. the drying time of blueberries decreased with increasing drying air temperatures and velocities. The experimental data obtained during the drying process were fitted to ten different mathematical models. The Midilli et al. model was found to be the most appropriate model for explaining the drying behavior of blueberries during convective drying. Effective moisture diffusion coefficients were calculated using the Fick's diffusion model, ranging from 9.66 x 10^{-12} m^2/s to 9.67 x 10^{-11} m^2/s. These values were found to increase proportionally with the increase in drying air temperatures and velocities. The lowest total color change and shrinkage of dried blueberries were recorded during freeze drying. A water activity less than 0.6 was measured at a blueberry moisture content of 0.235 $kg_w/kg_{d.m}$, a drying air temperature of 26 ^oC and a relative air humidity of 60 %.

***Key words**: blueberries, air drying, mathematical modeling, freeze drying, water activity.*

REZIME

Borovnica (Vaccinium corymbosum) je voće okruglog oblika indigo plave boje koje pripada rodu Vaccinium zajedno sa brusnicom, kupinom i ogrozdom. Sadrži dosta medicinski korisnih substanci i najveći je prirodni antioksidant. Dokazano je da konzumacijom borovnice usporava se process starenja, ojačava imuni sistem, prevenira infarkt i moždani udar, pomaže kod kardiovaskularnih oboloenja i poboljšava vid. Borovnice se prodaju u svežem stanju ili se prerađuju u zamrzavnjem, voćne piree, sokove, sušene i kandirane borovnice.

Od 2016. godine u Srbiji (okolina Bačke Topole) podignuta je plantaža od 100 ha sa planom za dodatnih 30 ha. Vlasnik je strani investitor koji ima plan da izvozi prvu klasu u svežem stanju a drugu klasu u zamrznutom stanju. Treća klasa će služiti za preradu, jedna od mogućih oblika prerade je konvektivno sušenje.

Glavni cilj rada je bio da se istraži uticaj parametara konvektivnog sušenja na kinetiku i da se pronađe matematički model koji će precizno opisati kinetiku sušenja. Takođe, urađeno je poređenje borovnica osušenih sušenjem smrzavanjem i konvektivno sa aspekta promene boje i zapreminskog skupljanja.

Parametri procesa konvetivnog sušenja bili su: temperatura vazduha 60, 70 i 80^oC, a brzina vazduha je 0,5 i 1,5 m / s. Eksperimentalni podaci dobijeni tokom procesa sušenja modelovani su sa deset različitih matematičkih modela. Model Midilli et al. je ocenjen kao najbolji model za opisivanje kinetike konvektivnog sušenja borovnice. Efektivni koeficijenti difuzije vlage izračunati su Ficksovim modelom difuzije i njihove vrednosti variraju od 9,66 x 10^{-12} m^2/s do 9,67 x 10^{-11} m^2/s. Najmanje zapreminsko skupljanje i promenu boje imale su borovnice sušene smrzavanje. Aktivnost vode niža od 0,6 izmerena je pri vlažnosti borovnice od 0,235 $kg_w/kg_{d.m}$ na temperaturi vazduha 26^oC i relativnoj vlažnosti 60%.

***Ključne reči:** borovnice; konvektivno sušenje; matematičko modelovanje, lifilizacija, aktivnost vode.*

INTRODUCTION

Blueberries (*Vaccinium corymbosum*) are round, indigo-colored fruits that belong to genus Vaccinium (alongside cranberries, blueberries and gooseberries). The fruit contains a lot of medicinal substances renowned for their antioxidant effects. It has been proven that the consumption of blueberries slows down the aging process, strengthens the immune system, prevents heart attacks and strokes, facilitates the prevention of cardiovascular diseases and improves visual perception. Blueberries are sold fresh or processed into frozen fruits, purees, juices, and dried and candied berries.

The purpose of this research is to examine the effects of air temperature on the drying behavior of blueberries, to select the best mathematical model for the convective drying curves, and to calculate the effective diffusivity and the activation energy of dried blueberries. Furthermore, convectively and freeze-dried blueberries were compared relative to the total color change and volume shrinkage. The water activity of dried blueberries was also determined at ambient temperature and air humidity.

NOMENCLATURE

a*, b*	- color coordinates,
a_w (-)	- water activity

D_a (m^2/s),	- pre-exponential Arrhenius factor,
D_e (m^2/s),	- moisture diffusivity coefficient,
L^* (-)	- color brightness,
m (g)	- mass,
MR (-)	- moisture ratio,
n (-)	- number of constants in the drying model,
N (-)	- number of observations,
r (m)	- radius of sphere,
R (kJ/molK)	- universal gas constant,
R^2 (-)	- determination of coefficient,
RMSE (-)	- root mean square error,
S (%)	- volumetric shrinkage,
t (h, min)	- drying time,
T (^oC, K)	- temperature,
V (cm^3)	- volume,
X ($kg_w/kg_{d.b.}$)	- moisture content on dry basis,
ΔE (-)	- total color change.

Greek symbols

χ^2(-)	chi – square,
Δ (-)	- parameter value change,
ρ (kg/m^3)	- density.

Subscripts

d.b.	- dry basis,
w.b.	- wet basis,
eq	- equilibrium,
exp	- experimental value,
i	- i sample,
l	- liquid,
o	- initial value,
pre	- predicted value,
r	- rehydrated,
t	- value at the t – time,
w	- water.

MATERIAL AND METHOD

Fresh blueberries (*Vaccinium corymbosum*), purchased at a local street market, were used in the experiment. Each batch of blueberries was carefully selected to obtain fruits of similar size, color and firmness. About 1,800 g of blueberries were used for each drying experiment. On average, blueberries had an initial moisture content of x_o = 4.55 $kg_w/kg_{d.b.}$ (0.82 $kg_w/kg_{w.b.}$), as well as a length of 15.90 mm, a width of 15.47 mm, and a thickness 10.69 mm.

Convective drying experiments were carried out using the laboratory dryer “IVA-2”. The dryer is equipped with an acquisition system which allows for the measurement and observation of drying kinetics (*Pavkov et al., 2010*). Fresh, untreated blueberries were dried in a thin layer at air temperatures of 60, 70 and 80 ^oC, and air velocities of 0.5 and 1 m/s. Blueberries were dried to an average moisture content of 0.26 ± 0.02 $kg_w/kg_{d.b}$, using 6 different drying programs.

The freeze-drying process was carried out using the freeze drier Alpha 2-4 LDplus (Martin Christ, gefriertrocknungsaniagen GmbH, Osterode, Germany). It was conducted at a chamber temperature of 50 ^oC and 0,0010 mbar absolute air pressure during 24 hours. Fresh, untreated blueberries were frozen in a fridge at -20 ^oC. After freezing, there were placed in a freeze dryer and dried to a final moisture content of 0.0508 ± 0.02 $kg_w/g\ k_{d.b.}$ (0.0484 $kg_w/kg_{w.b.}$).

The initial moisture content was measured gravimetrically according to the AOAC methods (925.09, 1990). The moisture content X ($kg_w/kg_{d.b.}$) was determined according to the following equation:

$$X=\frac{m_t-m_0}{m_{d.b.}} \tag{1}$$

The moisture ratio (MR) of the dried blueberry samples at any time was calculated according to the following equation (*Pavkov et al., 2016; Zhengfu et al., 2007*):

$$MR=\frac{X_t-X_{eq}}{X_o-X_{eq}} \tag{2}$$

The convective drying rate was calculated using the following equation (*Hassan-Beygi et al., 2009; Naderinezhad et al., 2016*):

$$\frac{dX_t}{dt}=\frac{X_{t+\Delta t}-X_t}{\Delta t} \tag{3}$$

The drying behavior of blueberries was determined by means of a drying rate vs. time graph.

The effective moisture diffusivity (*D_e, m/s^2*), which is generally considered an important kinetics parameter, describes the transport of moisture from the material to the surrounding area in the falling-rate period and can be defined by the Fick’s second law for a sphere (*Bon et al., 2007*). The Fick’s equation assumes the following: uniform initial moisture distribution, negligible external resistance, constant diffusivity, constant temperature and negligible shrinkage. Therefore, the equation for long drying periods is of the following form (*Pavkov et al., 2017; Ratti et al., 2001*):

$$MR=\frac{X_t-X_{eq}}{X_o-X_{eq}}=\frac{6}{\pi^2}\ \exp\left(-\frac{\pi^2\cdot D_e}{r_0^2}t\right) \text{ or}$$

$$\ln(MR)=\ln\left(\frac{6}{\pi^2}\right)\ -\left(\frac{\pi^2\cdot D_e}{r_0^2}t\right) \tag{4}$$

Equilibrium moisture content x_{eq} = 0.015 $g_w/g_{d.m}$.

The temperature dependence of the effective diffusivity may be described by the Arrhenius-type relationship as follows (*Zhengfu et al., 2007*):

$$D_e=D_0\exp\left(\frac{E_a}{RT}\right) \tag{5}$$

The color measuring in this experiment was performed using the three-filter colorimeter Konica Minolta CR-400. The measured color values are presented in the *CIE L*a*b** color range. In this color range, *L** represents the brightness (illumination, lightness), whereas the coordinates *a** and *b** represent color. The negative value *a** is green and the positive *a** is red. Negative *b** is yellow, and the positive *b** is blue. The illuminant combination of the angle observed was C/2^o. The color measurements were conducted before and after convective and freeze drying. The samples were selected randomly. Ten measurements were performed for each sample. The average values of *L*, a** and *b** were used for the total color change calculation of each sample. The color change of the samples during drying is presented by the total color change ΔE. The total color change ΔE is calculated on the basis of the following equation (*Pavkov et al., 2018, Alvarez-Fernandez, et. al., 2003*):

$$\Delta E=\sqrt{(L_0^*-L^*)^2+(a_0^*-a^*)^2+(b_0^*-b^*)^2} \tag{7}$$

For each drying regime, a total of 20 blueberries were measured before and after convective and freeze drying, by immersing the fruits into 96 % ethyl alcohol (*Moshenin, 1986*):

$$V_0=\frac{m_0-m_l}{\rho_l} \tag{8}$$

Table 1. Mathematical models applied to the drying curves

No.	Model	Name of the model	References
1.	MR = exp(−kt)	Newton	*Bon, et al., 2007*
2.	MR = exp(−kt^n)	Page	*Handerson and Pabis, 1961*
3.	MR = aexp(-kt)	Handerson and Pabis	*Handerson and Pabis, 1961*
4.	MR = aexp(−kt) + c	Logarithmic	*Khazaei et al., 2008*
5.	MR = aexp(−kt^n) + bt	Midilli et al.	*Midilli et al., 2002*
6.	MR = aexp(−kt) + (1 − a)exp(−kbt)	Diffusion approach	*Zhegfu et al., 2007;*
7.	MR = aexp(−k$_0$t) + bexp (−k$_1$t) + cexp(−k$_2$t)	Modified Henderson and Pabis	*Roberts et al., 2008*
8.	MR = aexp(−k$_0$t) + bexp(−k$_1$t)	Two term	*Sharaf-Eldeen et al., 1980*
9.	MR = a + bt + ct^2	Wang and Singh	*Wang and Singh, 1978*
10.	MR = exp(− ((t/b)^n)))	Weibull	*Verma et al., 1985*

The volumetric shrinkage of blueberries (S) was determined according to the following equation (Radojčin et al., 2015.):

$$S=\frac{V_0-V}{V_0}\cdot 100 \qquad (9)$$

The water activity was measured using LabSwift-a$_w$, Novisana AG, Switzerland, with a measuring range from 0,001 to 1.00 ±0.01a$_w$. The measurements were conducted at room temperature for four different moisture contents of blueberries.

Mathematical modeling

The drying curves (MR – t) were fitted by means of five different moisture ratio models that are widely used in most food and biological materials (Table 1). Those models are generally derived by simplifying the general series solution of the Fick's second law. A non-linear regression analysis was used to estimate the parameters of the models.

The coefficient of determination (R^2), the reduced chi – square (χ^2) and the root mean square error (RMSE) were used as the primary criteria to select the best equation to account for the variation in the drying curves of the dried samples. The reduced χ^2 is used to determine the goodness of fit. The lower the values of the reduced χ^2, the better the goodness of fit. The RMSE indicates the deviation between the predicted and experimental values, and it is required to reach zero. These parameters can be calculated using the following equations (*Serdar et al., 2016; Ertekin et al., 2006, Zhengfu et al., 2007*):

$$\chi^2=\frac{\Sigma_{i=1}^{N}(MR_{\exp(i)}-MR_{pre(i)})^2}{N-n} \qquad (10)$$

$$RMSE=\left[\frac{1}{N}\Sigma_{i=1}^{N}(MR_{pre(i)}-MR_{\exp(i)})^2\right]^{1/2}$$

RESULTS AND DISCUSSION

The drying curves of blueberries at three different air temperatures and two different air velocities are shown in Fig.1. As seen in Figure 1, the drying time decreased with increasing drying air temperatures and velocities. The drying times required to reach the final moisture content were found to be 535, 890 and 2,010 minutes at air temperatures of 80 °C, 70 °C and 60 °C and an air velocity of 0,5 m/s, respectively. At an air velocity of 1.5 m/s and air temperatures of 80 °C, 70 °C and 60 °C, the drying times to reach the final moisture content were found to be 480, 810 and 1,265 minutes, respectively. When the air temperature increased from 60 °C to 80°C, the drying time was reduced by almost threefold. This decrease can be accounted for by growing air temperatures which increase the vapor pressure in the fruit, thus causing a faster removal of moisture from the flesh of blueberries.

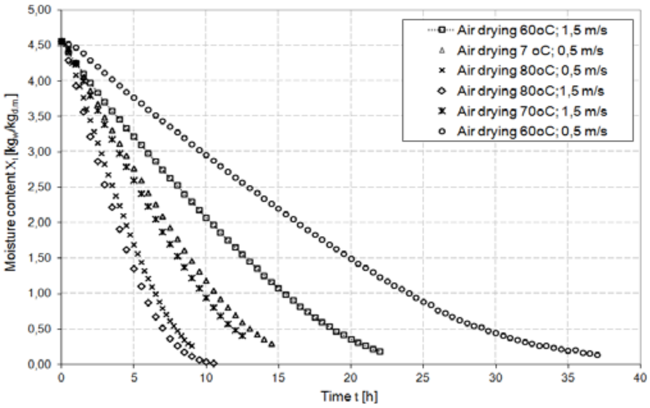

Fig. 1. Air drying kinetics of blueberries at air temperatures of 60 °C, 70 °C and 80 °C, and air velocities of 0.5 and 1.5 m/s

Similar results have been previously reported for raspberries and hawthorn fruits (*Doymaz et al., 2011; Pavkov et al.,2017; Sette et al., 2016)*. As seen in Figures 2 and 3, a constant rate period was not observed in the convective drying of blueberries. Drying rates decreased continuously with the drying time. This can be explained by the movement of the moisture within the fruit as drying is a diffusion controlled process and may be represented by the Fick's second law of diffusion. The results are in agreement with results reported elsewhere in the literature for various products (*Ertekin and menges, 2006; Hassan-Beygi et al., 2009*).

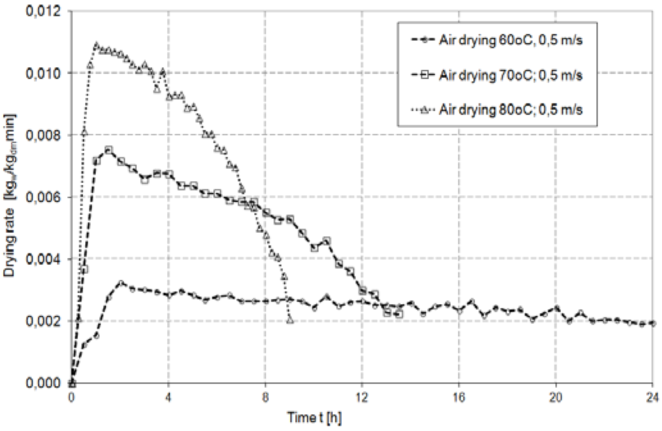

Fig. 2. Kinetics of blueberry drying at air temperatures of 60 °C, 70 °C and 80 °C, and an air velocity of 1.5 m/s

The values obtained for the effective moisture diffusivity of dried blueberries ranged from 9.67 x 10^{-12} m^2/s to 9.67 x 10^{-11} m^2/s (Table 2).

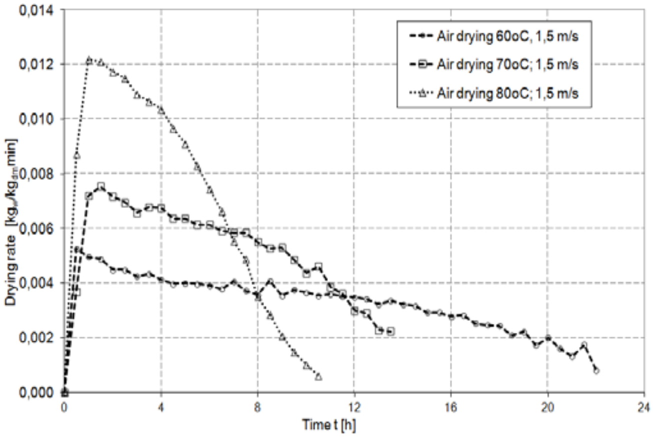

Fig. 3. Kinetics of blueberry drying at air temperatures of 60 °C, 70 °C and 80 °C, and an air velocity of 0.5 m/s

The results obtained show that the D_e value increased significantly with increased heating energy, which in turn increased the kinetic energy of water molecules and moisture diffusivity. The D_e values obtained in this study are within the general diffusivity range reported in the literature, i.e. 10^{-12} – 10^{-9} m^2/s for fruits and vegetables (*Kowalski et al., 2016; Pavkov et al., 2016*).

Table 2. Effective moisture diffusion coefficients of dried blueberries

Air temperature (°C)	Air velocity (m/s)	D_e (m^2/s)	R^2
60	0.5	9.67×10^{-12}	0.997
	1.5	1.45×10^{-11}	0.996
70	0.5	3.38×10^{-11}	0.998
	1.5	3.87×10^{-11}	0.998
80	0.5	4.83×10^{-11}	0.998
	1.5	9.67×10^{-11}	0.998

The ln D_e values versus 1/T were plotted for activation energies according to the linearized Arrhenius equation. The activation energy values obtained were 92.78 kJ/mol and 79.11 kJ/mol for air velocities of 1.5 m/s and 0.5 m/s, respectively. The values obtained are within the general range determined for fruits and vegetables (*Sette et al., 2016; Zhengfu et al., 2007*).

The five thin-layer drying models (Table 1) were evaluated relative to the three statistical parameters: R^2, χ^2 and RMSE (Table 3).

In all the cases studied, the R^2 values obtained for the models were greater than 0.95n (ranging between 0.952 and 0.999), which indicated a good fit. Furthermore, the χ^2 values obtained varied between 0.0287 and 9.08E-06, whereas the RMSE values ranged between 0.0153 and 2,26E-05. On balance, the Midilli et al. model showed higher R^2 values and lover χ^2 and RMSE values. Accordingly, this model was selected to represent the thin-layer convective drying characteristics of blueberries. When the Midilli et al. model was analyzed relative to different drying air temperatures and velocities, the individual constants of the blueberry convective drying were obtained (Table 4.)

Figures 4 and 5 compare the experimental and predicted results using the Midilli et al. model for the convective drying of blueberries at air temperatures of 60 °C, 70 °C, 80°C, and air velocities of 0.5 and1.5 m/s. It has been reported that the Midilli et al. model gives better results than other models for apples, apple pomace and hawthorn fruits (*Roberts et al., 2008; Zhegfu et al., 2007*).

According to the results shown in Fig. 6, significant changes in the total color are observable. The values of the total color changes ranged between 0.88 and 6.80. There was a noticeable difference in the sample brightness (ΔE*) between freeze- and air-dried blueberries. However, the effect of different air temperatures on the color of air-dried blueberries was indistinguishable. This can be accounted for by the fact that hot air convective drying intensifies the oxidation process.

Table 3. Statistical results obtained for the ten models under different drying conditions

No.	Name of the model	Air veloc. (m/s)	Drying air temperature								
			60°C			70°C			80°C		
			R^2	χ^2	RMSE	R^2	χ^2	RMSE	R^2	χ^2	RMSE
1.	Newton	0.5	0.952	0.00188	0.005225	0.953	0.00426	0.0115	0.946	0.00503	0.0115
		1.5	0.962	0.00153	0.005544	0.954	0.00419	0.0120	0.957	0.00423	0.0153
2.	Page	0.5	0.998	0.0000251	0.000598	0.996	0.000349	0.00324	0.997	0.000219	0.00236
		1.5	0.992	0.000389	0.002938	0.996	0.000333	0.003325	0.998	0.000581	0.005496
3.	Henderson and Pabis	0.5	0.970	0.001119	0.003996	0.969	0.02876	0.009316	0.968	0.00304	0.00882
		1.5	0.971	0.001106	0.004951	0.970	0.00282	0.009677	0.970	0.00173	0.00948
4.	Logarithmic	0.5	0.998	3.36E-05	0.000687	0.998	0.000152	0.002105	0.997	0.000204	0.00225
		1.5	0.999	1.74E-05	0.000614	0.998	0.00135	0.002075	0.998	0.00297	0.01201
5.	**Midilli et al.**	**0.5**	**0.999**	**9.08E-06**	**0.000354**	**0.999**	**4.1E-05**	**0.001074**	**0.9997**	**2.20107E-05**	**0.00072840**
		1.5	**0.999**	**2.26E-05**	**0.00069**	**0.999**	**3.29E-05**	**0.001003**	**0.999**	**0.00353**	**0.012602**
6.	Diffusion approach	0.5	0.9936	0.000161	0.001506	0.9974	0.00025	0.002697	0.9464	0.005182202	0.01151037
		1.5	0.992	0.000343	0.002725	0.9946	0.000533	0.004124	0.9572	0.000623512	0.005496
7.	Modified Henderson and Pabis	0.5	0.9706	0.001191	0.003996	0.96994	0.003336	0.009316	0.9959	0.003440141	0.00882606
		1.5	0.9719	0.001225	0.004951	0.9705	0.003337	0.009677	0.9959	0.000589329	0.004736
8.	Two term	0.5	0.9706	0.001154	0.003996	0.9699	0.003089	0.009316	0.9685	0.003231647	0.00882606
		1.5	0.971972	0.001162	0.004952	0.9705	0.003059	0.009677	0.995	0.000497447	0.00473
9.	Wang and Singh	0.5	0.9993	2.45E-05	0.000587	0.999	9.46E-05	0.00166	0.9985	0.000141867	0.0018770
		1.5	0.999	1.13E-05	0.000493	0.999	8.49E-05	0.001645	0.9988	0.000128372	0.002494
10.	Weibull	0.5	0.995	0.000156	0.00149	0.9963	0.000349	0.003243	0.9977	0.000219375	0.0023682
		1.5	0.992	0.000389	0.002938	0.996	0.000333	0.003325	0.9973	0.000275796	0.003783

Table 4. Statistical results of the Midilli et al. model and its constants and coefficients under different drying conditions

Name of .the model	Air veloc. (m/s)	Drying air temperature																				
		60°C							70°C							80°C						
		k_0	k_1	k_2	a	b	c	n	k_0	k_1	k_2	a	b	c	n	k_0	k_1	k_2	a	b	c	n
Newton	0.5	0.055979			-	-	-	-	0.125718							0.204251						
	1.5	0.088594			-	-	-	-	0.137265							0.236092						
Page	0.5	0.022567						1.2940	0.048490						1.459536	0.090561						1.518166
	1.5	0.036951						1.3619	0.055763						1.455862	0.136294						1.353767
Henderson and Pabis	0.5	0.063004			1.112494				0.140219			1.104429				0.232549			1.124499			
	1.5	0.096320			1.076910											0.260010			1.092771			
Logarithm.	0.5	0.024996			1.780773		-0.749168		0.056534			1.761559		-0.731712		0.090934			1.831773		-0.78541	
	1.5	0.036353			1.809649		-0.808408		0.060841			1.785982		-0.756255		0.109450			1.712757		-0.68447	
Midilli et al.	0.5	-0.053302			1	-0.079042	-	0.8318	0.056566			1	-0.009186		1.266339	0.094989			1	-0.011632		1.366609
	1.5	0.049115			1	-0.011937		1.0618	0.063416			1	-0.010367	-	1.263571	0.126450			1	-0.014185		1.288564
Diffusion approach	0.5	0.1155			-78.1042	0.9887			0.0237			-28.2004	1.0956			0.204251			0.586920	1.000002		
	1.5	0.1723			-63.0087	0.9876			0.2843			-78.0896	0.9887			0.236096			0.658441	1.000002		
Modified Henderson and Pabis	0.5	0.063007	0.063009	0.062999	0.370154	0.369789	0.372557		0.140228	0.140221	0.140208	0.373575	0.364070	0.366782		0.232566	0.232565	0.23251	0.413238	0.448247	0.263021	
	1.5	0.096325	0.096322	0.096314	0.344883	0.360956	0.371075		0.153000	0.152979	0.152987	0.379654	0.367773	0.355349		0.4767	0.4767	0.5068	7.8612	7.8606	-14.7381	
Two term	0.5	0.063005	0.063005		0.564070	0.548426			0.140225	0.140217		0.498288	0.606144			0.232529	0.232586		0.414535	0.709961		
	1.5	0.096320	0.096321		0.538432	0.538483			0.152989	0.152990		0.533025	0.569758									
Wang and Singh	0.5				1.028438	-0.042742	0.000386					1.027411	-0.095813	0.001960					1.044536	-0.161005	0.00538	
	1.5				0.998082	-0.063341	0.000845					1.027383	-0.104712	0.002323					1.026361	-0.180288	0.00709	
Weibull	0.5					17.81953		1.45407					7.952878		1.459531					4.864643		1.518163
	1.5					11.26525		1.36191					7.262873		1.455857					4.243470		1.456509

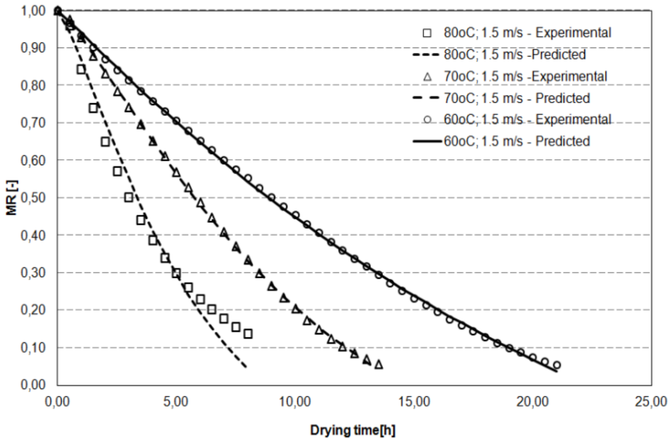

Fig. 4. Experimental and predicted moisture ratio changes (MR) relative to the drying time at air temperatures of 60 °C, 70 °C and 80°C, and an air velocity of 1.5 m/s

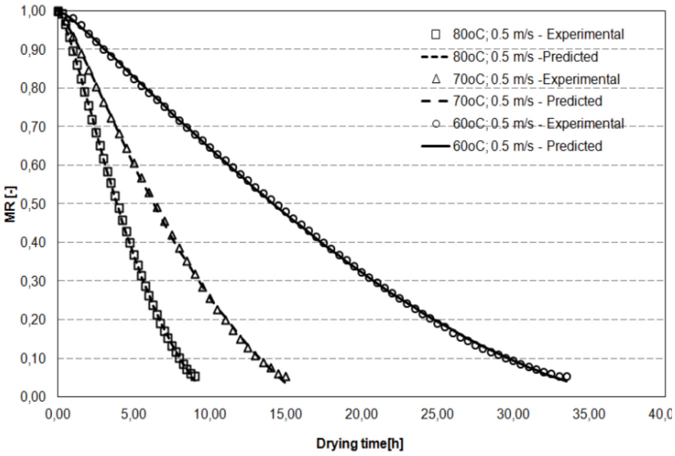

Fig. 5. Experimental and predicted moisture ratio changes (MR) relative to the drying time at air temperatures of 60 °C, 70 °C and 80 °C, and an air velocity of 1.5 m/s

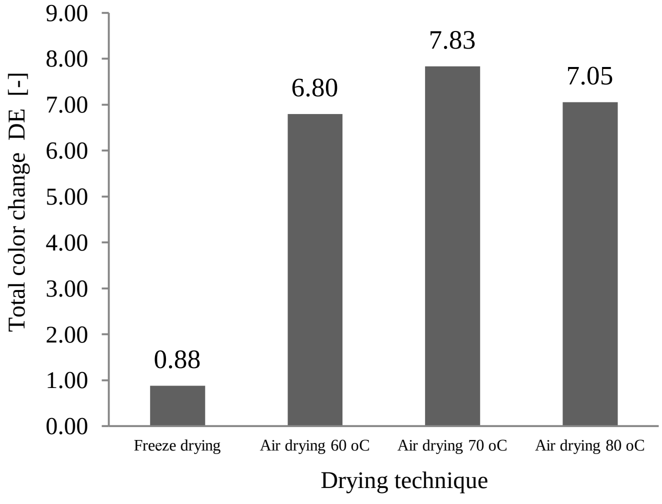

Fig. 6. Total color change of dried blueberries

As shown in Fig. 7, the smallest shrinkage of blueberries was recorded during freeze drying. Of the air temperatures under consideration, the best results were obtained at a temperature of 70 °C. At higher drying temperatures, the drying rate is high and leads to a mechanical stabilization of the surface, thus limiting the degree of shrinkage. Similar results have been reported in the literature for potato, pomegranate and onion.

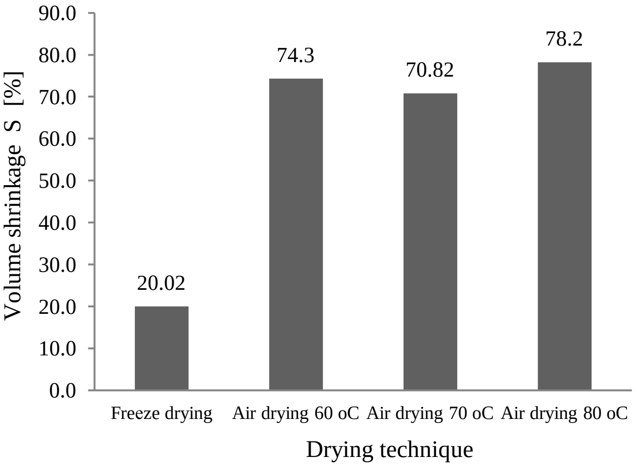

Fig. 7. Blueberry volume shrinkage during freeze drying and convective drying (at different air temperatures)

The results of water activity measurements are shown in Figure 8 relative to different moisture contents of blueberries, a storage air temperature of 25 °C, and a relative air humidity of 60 %. For safe storage, the value of water activity should be les then 0.6. Accordingly, dried blueberries with a moisture content of 0.235 $kg_w/kg_{d.m.}$ (0.1905 $kg_w/kg_{w.m.}$) are safe for storage at 25 °C and a relative air humidity of 60 %.

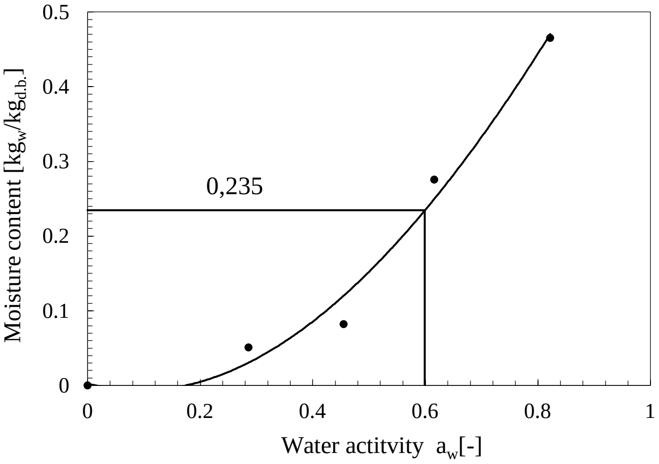

Fig. 8. Water activity at different moisture contents of blueberries, a storage air temperature of 25 °C, and a relative air humidity of 60 %

CONCLUSION

The effects of different air temperatures and velocities on the drying characteristics of blueberries were examined using a convective dryer. Increased air temperatures and velocities shortened the drying time. The process of blueberry drying occurred in the falling-rate period. The experimental data was fitted to ten thin-layer models and the *Midilli et al.* model was found to be the best for describing the characteristic of blueberries under all the experimental conditions. The effective moisture diffusivity values ranged between 9.67 x 10^{-12} m^2/s to 9.67 x 10^{-11} m^2/s. The D_e values increased with increasing air temperatures and velocities. The smallest total color change of dried blueberries was recorded during freeze drying (0.88). The smallest shrinkage of blueberries was also recorded during freeze drying, whereas the best results of hot air convective drying were obtained at an air temperature of 70 ^{o}C. Dried blueberries with a moisture content of 0.235 kg$_{w}$/kg$_{d.m.}$ are safe for storage at 25 ^{o}C and a relative air humidity of 60 %.

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