Sweet cherry (*Prunus avium* L.) vacuum drying: Kinetics modelling and textural properties

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Abstract

Sweet cherries (*Prunus avium* L.) were vacuum dried at different temperatures in the range between 50 and 70 °C and different pressures between 20 and 200 mbar. Seven mathematical models (Henderson-Pabis, Modified Henderson-Pabis, Simplified Fick's diffusion, Peleg, Logarithmic, Two term and Midilli *et al.*) were used for description of the vacuum drying process and the Midilli *et al.* model was selected as the most suitable with the highest mean value of coefficient of determination (R^2=0.9985) and the lowest mean values of the average absolute relative deviation (AARD=0.90 %), root mean square error (RMSE=0.0061) and the reduced chi-square (χ^2=0.0001). Seven textural properties (shear force, penetration force, hardness, springiness, cohesiveness, gumminess and chewiness) were investigated in all dried sweet cherry samples. The results indicated that the pressure influenced the textural properties of sweet cherries during vacuum drying since the minimum values of all investigated texture properties were obtained in samples dried at the pressure of 200 mbar, while the maximum values were obtained at 20 and 65 mbar. It also was noticed that the temperature influenced the textural properties in the temperature range investigated, but not as significantly as it was the case of the pressure influence.

Keywords: stone fruit; drying technique; mathematical modelling; physical properties.

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1. INTRODUCTION

Sweet cherry (*Prunus avium* L.) belongs to the *Rosaceae* family, *Prunoideae* subfamily, *Prunus genus* and its origin is in the Asian continent [1]. Together with sour cherry (*P. cerasus*), apricot (*P. armeniaca*), plum (*P. domestica*) and peach (*P. persica*) it presents the most prevalent stone fruit in Serbia. Sweet cherries are well known and appreciated by consumers since they possess characteristic sweetness, specific texture and attractive skin colour. This fruit is an excellent source of many nutrients and phytochemicals [2], such as organic acids, phenolic and anthocyanin compounds. Fruits of this species could be consumed fresh, in the form of different products such as jam, jelly, stewed fruit, marmalade, syrup and several types of soft drinks [3] and also as frozen or dried products.

Drying, as a preservation technique, allows sustainability of food by removing water necessary for microorganism growth and for enzymatic activity. The process of heat exchange during a drying process could be conductive and/or convective transfer and/or radiation. Vacuum drying of fruit represents an especially interesting type of drying, since it allows drying at low temperatures in an atmosphere with a reduced oxygen content. This is very important in the case of fruit drying since high temperatures and presence of oxygen negatively affect the quality of the final product, especially its sensory characteristics such as colour, taste and smell.

Drying kinetics is often used to describe the combined macroscopic and microscopic mechanisms of mass transfer during drying [4]. Beside characteristics of the material that is dried and the dryer type, drying kinetics is influenced by drying conditions [5]. The principle of kinetics modelling is based on a set of mathematical equations that can adequately

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characterize the system. Depending on the applied equation, models can be classified as theoretical, semi-empirical, and empirical [6-8]. Theoretical models are based on the Fick's second law of diffusion, while empirical models are more often purely kinetic formulas based on process conditions [9]. Modelling of different drying processes of various fruits and vegetables has been thoroughly investigated by different authors such as vacuum drying kinetics of pumpkin [10], drying of figs described by thin-layer drying models [11] and drying kinetics of kiwi fruit analyzed by the use of exponential, Page's and diffusion models [12].

Among studies of drying kinetics of different fruits by applying different drying techniques, drying of sweet cherries by hot air was described [13]. However, in known and accessible databases, data on kinetics modelling of vacuum drying of sweet cherries are lacking. Thus, the main goal of the present study was application of seven common empirical models i.e. Henderson-Pabis, Modified Henderson-Pabis, Simplified Fick's diffusion, Peleg, Logarithmic, Two term and Midilli *et al*. models for description of this process. Another goal was to investigate textural properties (shear force, penetration force, hardness, springiness, cohesiveness, gumminess and chewiness) of sweet cherries during vacuum drying at different drying temperatures (50-70 °C) and pressures (20-200 mbar) in order to determine optimal process conditions in terms of the textural properties of dried sweet cherry samples.

2. MATERIALS AND METHODS

2. 1. Sample

Raw sweet cherry (variety Sweet Heart) samples were purchased at the Faculty of Agriculture, University of Novi Sad, from the experimental field of the Faculty at Rimski Šančevi (Vojvodina, Serbia). First, stones were carefully moved from each sample and then the samples were frozen and stored at -20 °C until drying.

2. 2. Drying procedure

Vacuum drying was performed in a vacuum dryer prototype, described previously in detail [14]. Vacuum drying was continued until the constant mass (final moisture content in equilibrium). Sample size was kept constant (approx. 150 g) for each experiment and 27 drying processes were performed in total. The conditions of vacuum drying are presented in Table 1.

Table 1. Conditions of vacuum drying – temperature, pressure and drying time at reaching the equilibrium

Sample	Temperature, °C	Pressure, mbar	Drying time*, h
1	50	20	7.5
2	50	65	13.4
3	50	110	11.0
4	50	155	13.2
5	50	200	10.5
6	55	20	9.5
7	55	65	14.0
8	55	110	16.5
9	55	155	16.5
10	55	200	14.0
11	60	20	7.8
12	60	20	7.8
13	60	20	7.8
14	60	65	10.5
15	60	110	11.3
16	60	155	12.8
17	60	200	15.2
18	65	20	8.5

Sample	Temperature, °C	Pressure, mbar	Drying time*, h
19	65	65	9.2
20	65	110	12.5
21	65	155	13.2
22	65	200	12.2
23	70	20	7.7
24	70	65	9.7
25	70	110	11.8
26	70	155	13.2
27	70	200	11.8

*The time of vacuum drying was recorded in the moment at which the constant mass was achieved (final moisture content in equilibrium).

2. 3. Mathematical modelling

Dimensionless moisture ratio (MR) for each experimental run could be calculated according to the following equation:

$$\mathrm{MR} = \frac{M_\mathrm{t} - M_\mathrm{e}}{M_0 - M_\mathrm{e}} \tag{1}$$

where M_t, M_0 and M_e are the moisture content at any drying time, initial moisture content and equilibrium moisture content, respectively. However, it is often difficult to determine the equilibrium moisture content in plant materials, since it is too low and often negligible. Therefore, the dimensionless moisture ratio could be simplified as the ratio of moisture content at any drying time and the initial moisture content [15]:

$$\mathrm{MR} = \frac{M_\mathrm{t}}{M_0} \tag{2}$$

The sample weight during drying was measured on line by a programmable logic controller PLC (Unitronics, Israel) which records the sample mass at 10 min intervals. Based on these recorded data the moisture ratio (MR) for each drying point (in 10 min intervals) was calculated.

Statistical parameters used to describe goodness of the fit were the coefficient of determination (R^2), average absolute relative deviation (AARD), root mean square error (RMSE) and the reduced chi-square (χ^2). The AARD, RMSE and χ^2 were calculated according to the following equations [25]:

$$\mathrm{AARD} = \frac{100}{N}\sum_{i=1}^{N}\frac{\left|\mathrm{MR}_{\mathrm{pre,i}} - \mathrm{MR}_{\mathrm{exp,i}}\right|}{\mathrm{MR}_{\mathrm{exp,i}}} \tag{3}$$

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{pre,i}} - \mathrm{MR}_{\mathrm{exp,i}})^2\right]^{\frac{1}{2}} \tag{4}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{pre,i}} - \mathrm{MR}_{\mathrm{exp,i}})^2}{N - z} \tag{5}$$

where, $\mathrm{MR}_{\mathrm{exp,i}}$ is the i$^{\mathrm{th}}$ experimentally observed moisture content, $\mathrm{MR}_{\mathrm{pre,i}}$ is the i_{th} predicted moisture content, N is the number of observations and z is the number of adjustable parameters in the model equation. The model was considered best when AARD, RMSE and χ^2 were minimal, while R^2 was at the maximum value.

For mathematical modelling of experimental data, seven commonly known empirical models (Henderson-Pabis, Modified Henderson-Pabis, Simplified Fick's diffusion, Peleg, Logarithmic, Two term and Midilli *et al.)* were applied and the model equations are presented in Table 2.

Table 2. Empirical models used for mathematical description of the sweet cherry vacuum dying process

Model	Equation	Reference
Henderson-Pabis	$\mathrm{MR} = ae^{-kt}$	Henderson and Pabis [17]
Modified Henderson-Pabis	$\mathrm{MR} = ae^{-kt} + be^{-gt} + ce^{-ht}$	Karathanos [18]
Simplified Fick's diffusion	$\mathrm{MR} = ae^{\left(-c\frac{t}{L^2}\right)}$	Diamante and Munro [19]
Peleg	$\mathrm{MR} = \mathrm{MR}_0 - \frac{t}{k_1 + k_2 t}$	Mercali *et al.* [20]
Logarithmic	$\mathrm{MR} = ae^{-kt} + b$	Yagcioglu *et al.* [21]
Two term	$\mathrm{MR} = ae^{-k_1 t} + be^{-k_2 t}$	Henderson [22]
Midilli *et al.*	$\mathrm{MR} = ae^{-kt^n} + bt$	Midilli *et al.* [23]

2. 4. Texture analysis

Instrumental texture measurements were performed using a Texture Analyser (TE32, Stable Micro Systems, UK). In the framework of texture analyses, the shearing test, penetration test and texture profile analysis (TPA) were performed.

Shearing Test

The shear force was measured using a Craft Knife Adapter while the settings for shear force analyses were: load cell – 5 kg; test speed – 1.0 mm/s. The shear force has been expressed as force (kg) required for sample cutting.

Penetration test

The penetration test was carried out by using 2 mm stainless Cylinder probes and settings for the penetration force were: load cell – 5 kg; test speed – 2.0 mm/s. The penetration force has been expressed as force (kg) required for penetration through the samples.

Texture Profile Analysis (TPA)

Texture profile analysis (TPA) was performed as described by Bourne [24]. By using a cylindrical plate of 36 mm in diameter, dried samples were compressed twice to 40 % of their original height at a constant speed of 1 mm/s. By using the TPA test, hardness, springiness, cohesiveness, gumminess and chewiness were obtained. Hardness was expressed as the force (kg) required to compress the sample during the first compression cycle, chewiness (kg) was expressed as energy required to chew a solid food into a state ready for swallowing calculated by multiplying the values of hardness, cohesiveness and springiness, while springiness, cohesiveness and gumminess are dimensionless values.

2.5. Statistical analysis

Non-linear least squares model estimation (regression) was applied in order to determine model parameters and coefficients of determination (R^2) using Statistica 10.0 (StatSoft Inc., Tulsa, OK, USA). The model was considered best when R^2 was maximal, while AARD, RMSE and χ^2 were at minimum values [25].

All texture analyses were performed seven times for statistical purpose and all texture data were analysed by univariate analysis of variance (ANOVA, $p<0.05$) in order to differentiate the samples by using the Tukey's Multiple Comparison Test and an $\alpha = 0.05$ criterion. Statistica 10.0 [26] was used for the ANOVA.

3. RESULTS AND DISCUSSION

3. 1. Kinetics models of vacuum drying

The results obtained for moisture contents for all sweet cherry vacuum dried samples at each drying point were fitted to seven empirical models: Henderson-Pabis, Modified Henderson-Pabis, Simplified Fick's diffusion, Peleg, Logarithmic, Two term and Midilli *et al*. Calculated average values of: coefficients of determination (R^2); average absolute relative deviations (AARD); root mean square errors (RMSE) and reduced chi-squares (χ^2) for each condition and for each model are presented in Table 3. Calculated model parameters and statistical parameters for six investigated models (Henderson-Pabis, Modified Henderson-Pabis, Simplified Fick's diffusion, Peleg, Logarithmic and Two term) separately, are given in Supplementary material (Table 1S-6S, respectively) while these results for the Midilli *et al*. model are presented in Table 4.

Table 3. Average values of statistical parameters for all investigated models.

Model	R^2	AARD, %	RMSE	χ^2
Henderson-Pabis [17]	0.9758	4.75	0.0261	0.0004
Modified Henderson-Pabis [18]	0.9762	4.73	0.0261	0.0005
Simplified Fick's diffusion [19]	0.9753	4.78	0.0262	0.0005
Peleg's [20]	0.9961	1.27	0.0090	0.0002
Logarithmic [21]	0.9948	1.75	0.0115	0.0005
Two-term [22]	0.9764	4.33	0.0244	0.0005
Midilli *et al.* [23]	0.9985	0.90	0.0061	0.0001

Table 4. Calculated model parameters and statistical parameters for the Midilli et al. model

T / °C	p / mbar	Adjustable coefficients				R^2	AARD, %	RMSE	χ^2
		a	k / h^{-n}	n	b / h^{-1}				
50	20	1.02	0.0004	3.32	-0.0768	0.9994	0.95	0.0061	0.000145
	65	1.01	0.0020	1.86	-0.0333	0.9992	0.75	0.0057	0.000074
	110	1.00	0.0093	1.50	-0.0066	0.9996	0.22	0.0022	0.000035
	155	1.01	0.0165	1.45	0.0009	0.9994	0.41	0.0038	0.000050
	200	1.01	0.0437	1.13	0.0284	0.9971	0.26	0.0029	0.000048
55	20	0.99	0.0144	1.79	-0.0273	0.9991	1.38	0.0075	0.000139
	65	1.02	0.0351	0.84	-0.0158	0.9982	0.65	0.0060	0.000074
	110	1.01	0.0252	0.81	-0.0118	0.9990	0.36	0.0037	0.000038
	155	0.99	0.0000	10.68	-0.0096	0.9956	0.30	0.0033	0.000035
	200	1.00	0.0129	0.75	-0.0033	0.9981	0.14	0.0017	0.000021
60	20	1.00	0.0046	1.97	-0.0738	0.9991	1.22	0.0071	0.000162
	20	1.00	0.0017	2.48	-0.0627	0.9992	0.91	0.0061	0.000139
	20	1.00	0.0124	1.83	-0.0468	0.9983	1.71	0.0099	0.000225
	65	1.01	0.0099	0.74	-0.0589	0.9988	0.84	0.0067	0.000112
	110	1.01	0.0520	1.04	-0.0018	0.9983	0.69	0.0062	0.000096
	155	1.01	0.0387	0.63	-0.0167	0.9979	0.46	0.0050	0.000067
	200	1.01	0.0210	0.78	-0.0125	0.9987	0.35	0.0037	0.000042
65	20	0.99	0.0402	1.53	-0.0283	0.9978	3.30	0.0131	0.000272
	65	1.02	0.0524	0.76	-0.0361	0.9964	1.22	0.0100	0.000192
	110	1.01	0.0148	0.80	-0.0378	0.9991	0.62	0.0052	0.000072
	155	1.01	0.0405	0.88	-0.0156	0.9990	0.53	0.0048	0.000063
	200	1.01	0.0406	0.89	-0.0006	0.9979	0.39	0.0042	0.000061
70	20	0.99	0.0274	1.77	-0.0318	0.9985	2.45	0.0106	0.000246
	65	1.00	0.0323	1.37	-0.0278	0.9990	1.37	0.0077	0.000140
	110	1.01	0.0188	0.97	-0.0418	0.9991	0.85	0.0062	0.00009
	155	1.01	0.0317	1.32	0.0067	0.9968	0.95	0.0093	0.000122
	200	1.02	0.0568	0.92	-0.0095	0.9986	0.66	0.0060	0.000088

As the main criteria for choosing the best model describing the sweet cherry vacuum drying process the maximum value of R^2 and minimum values of AARD, RMSE and χ^2 were adopted. These values for models in all experiments were in the range between 0.9753 and 0.9985 (R^2); 0.90 % and 4.78 % (AARD); 0.0061 and 0.0262 (RMSE); 0.0001 and 0.0005 (χ^2). The highest mean value of R^2 (0.9985) and the lowest mean values of AARD (0.90 %), RMSE (0.0061) and χ^2 (0.0001) were obtained for the Midilli *et al*. model, which was selected as the most suitable model for representing the sweet cherries vacuum drying. The lowest value of R^2 (0.9753) and also the highest values of AARD (4.78 %), RMSE (0.0262) and χ^2 (0.0005) were obtained for the Simplified Fick's diffusion model indicating lower suitability of this model for describing the investigated process.

In the previous research [16], the Midilli *et al*. model was also selected as the most suitable model for representing vacuum drying of cornelian cherries. On the other hand, in a study of thin-layer drying characteristics of sweet cherries the Page model was selected as the best [13] while the Logarithmic model was shown to fit the best the experimental drying data of thin layer drying characteristics of organic apple slices [27].

Since the Midilli *et al*. model agreed best with the experimental data obtained for the Sample 3 (50 °C, 110 mbar; the highest R^2 = 0.9996) the experimental *vs.* predicted values for this sample at the pressure of 110 mbar and the five investigated temperatures and at the temperature of 50 °C and the five investigated pressures are presented in Figures 1 and 2, respectively. The experimentally obtained data and predicted values for the moisture ratio values of these samples in each detected point during drying are presented in Tables 7S and 8S (Supplementary material).

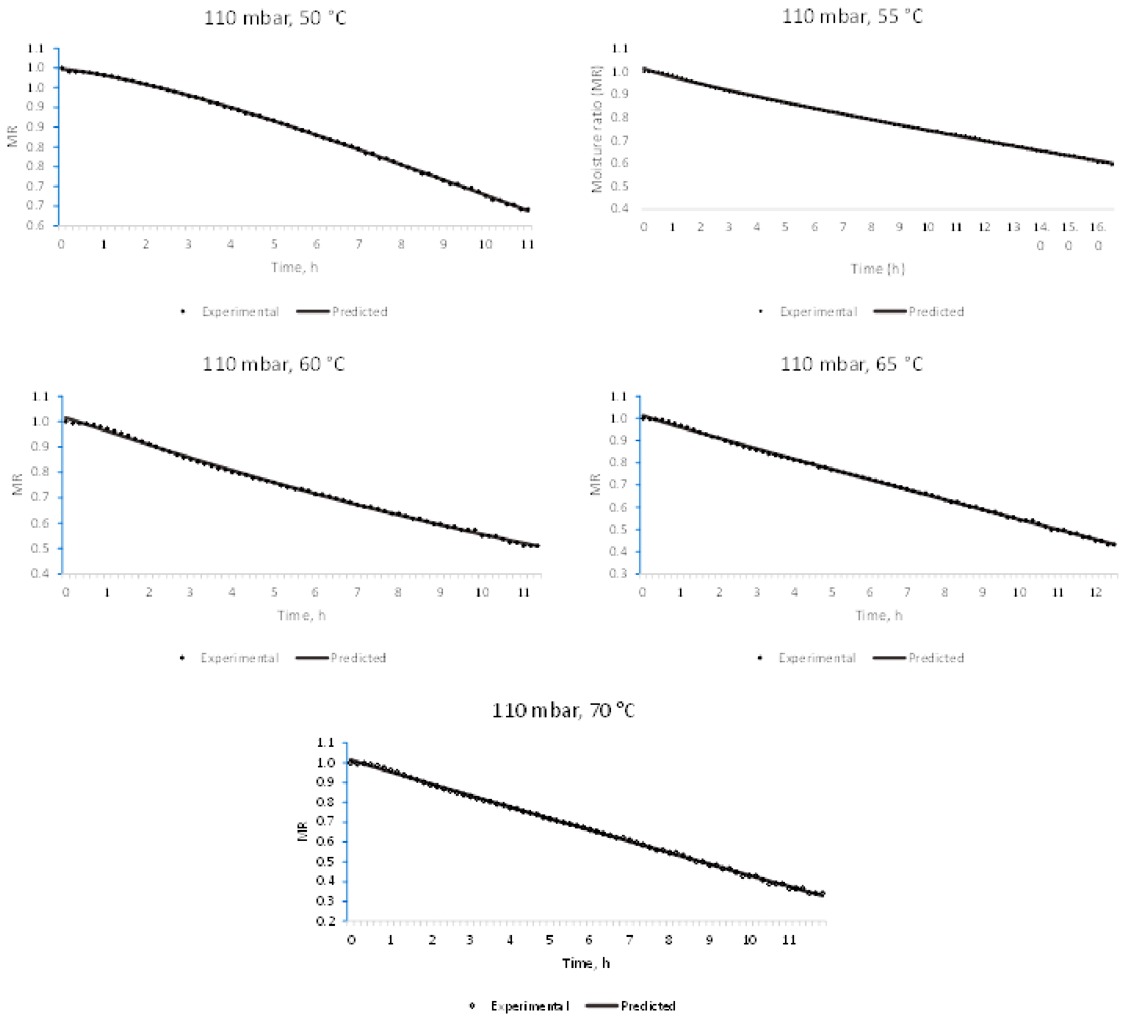

Figure 1. Experimental vs. predicted values for the Midilli et al. model for samples dried at 110 mbar.

However, the lowest values of AARD (0.14 %), RMSE (0.0017) and χ^2 (0.000021), were obtained for the Sample 10 (55 °C, 200 mbar, Table 4). According to the literature, Henríquez *et al*. [28] obtained that the Two-terms model had the best goodness of fit at 110 °C; the Page model at 120 °C while the Midilli–Kucuk model had the best goodness of fit at 130 °C, but with very similar statistical fitting values compared to those reported by the Two-terms model.

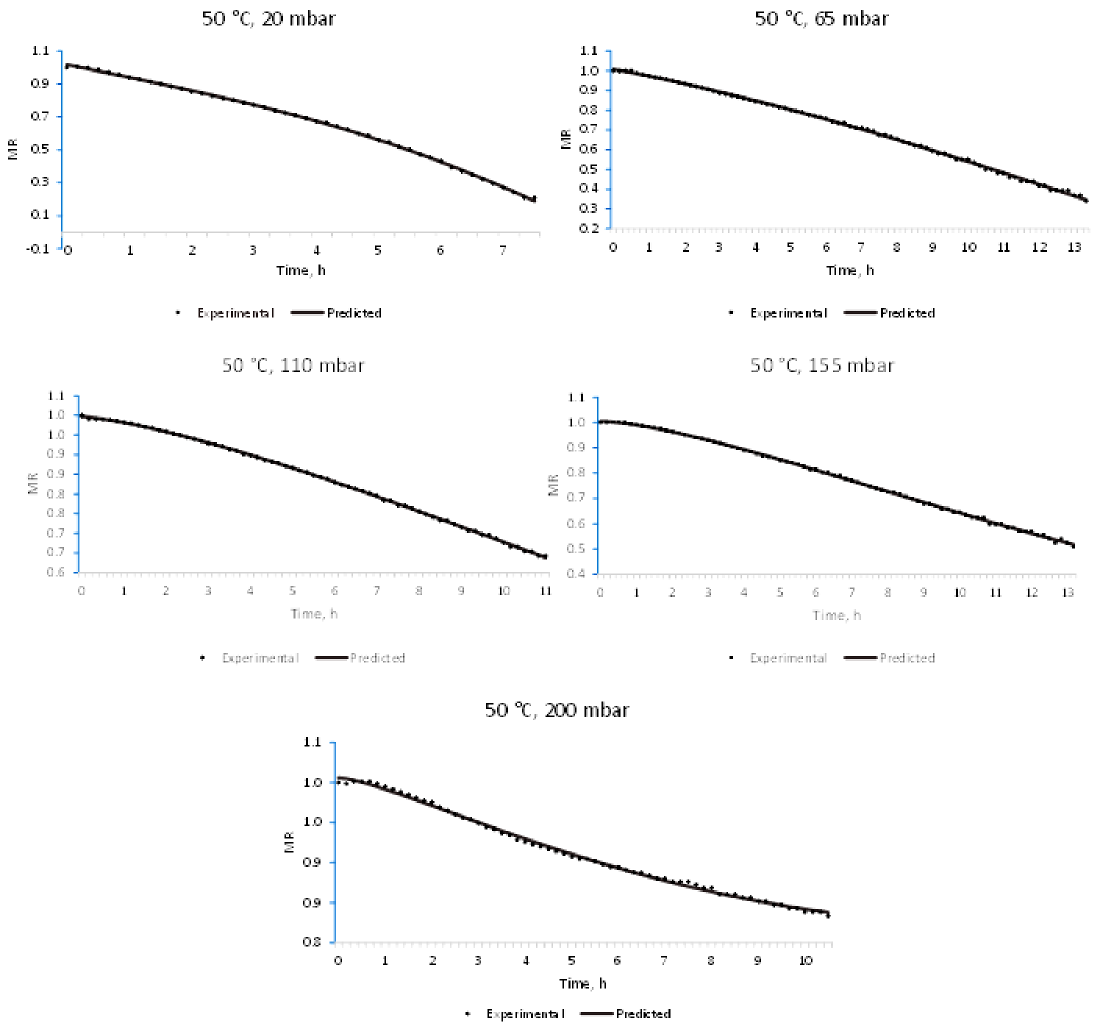

Figure 2. Experimental vs. predicted values for the Midilli et al. model for samples dried at 50 °C.

Regarding the values of k / h^{-n} (constant of drying velocity) obtained for the Midilli *et al*. model (Table 4) higher average values over the investigated pressure range were obtained for the higher applied temperatures 65 and 70 °C, although it should be noted that due to different exponent, n, values, k had different units for each sample type. This result is in accordance with literature data of mathematical modelling of the moisture content in apple slices during drying which predicted higher average values of k at higher drying temperatures [29]. Mathematical modelling of thin-layer heat pump drying of yacon slices resulted in higher values of k for the Midilli *et al*. model at higher investigated temperatures [30]. In both mentioned studies, the Midilli *et al*. model was found to be the most suitable for describing drying curves of apples and the thin-layer drying behaviour of yacon, respectively. The obtained average value of k, observed in the present study at a constant pressure and different temperatures was the highest for the pressure of 200 mbar, while the lowest average k value was obtained at the pressure of 20 mbar.

In order to interpret the effects of drying parameters, temperature and pressure, on the coefficients for the Midilli *et al*. model, regression analysis was performed. Thus, relations between the model coefficients (a, k, n and b) and the drying parameters were obtained, Eqs (6) to (12). The relation between model coefficient k and pressure as drying parameter was obtained non satisfactory (R^2=0.5760) and thus has been omitted from the list of the equations.

$$a = - 0.0008\, T^3 + 0.0104\, T^2 - 0.0388\, T + 1.05 \qquad R^2=0.8214 \tag{6}$$

$$k = 0.0012\, T^3 - 0.0071\, T^2 + 0.0163\, T - 0.0104 \qquad R^2=0.9923 \tag{7}$$

$$n = - 0.1142\, T^3 + 1.2125\, T^2 - 4.2833\, T + 6.502 \qquad R^2=0.9998 \tag{8}$$

$$b = 0.0031\, T^3 - 0.0313\, T^2 + 0.1188\, T - 0.168 \qquad R^2=0.9961 \tag{9}$$

$$a = -0.3952\, p^3 + 4.2739\, p^2 - 14.434\, p + 96.83 \qquad R^2=0.9918 \tag{10}$$
$$n = -0.0485\, p^3 + 0.5032\, p^2 - 1.731\, p + 2.74 \qquad R^2=0.7642 \tag{11}$$
$$b = 0.1084\, p^3 + 1.23\, p^2 + 3.314\, p - 2.9242 \qquad R^2=0.7887 \tag{12}$$

3. 2. Texture analysis

Texture presents a significant quality indicator of dried fruits since it is related to the other properties of dried product as well as to the pleasantness of the fruit intake. Thermal treatment, during processing of plant tissue causes irreversible changes in the tissue structure [31]. The outcome is lower elasticity of dried products as compared to raw materials. Based on texture results obtained in the present study (Table 5) it could be noticed that the minimum values of all investigated texture properties *i.e.* shear force, penetration force, hardness, springiness, cohesiveness, gumminess and chewiness, were obtained in samples dried at the pressure of 200 mbar, *i.e.* in Sample 27 (70 °C, 200 mbar); Sample 5 (50 °C, 200 mbar); Sample 22 (65 °C, 200 mbar); Sample 10 (55 °C, 200 mbar); Sample 5 (50 °C, 200 mbar) and Sample 22 (65 °C, 200 mbar), respectively.

Table 5. Textural properties, shear force, penetration force, hardness, springiness, cohesiveness, gumminess and chewiness, of vacuum dried sweet cherries

Sample	Shear force, kg	Penetration force, kg	Hardness, kg	Springiness	Cohesiveness	Gumminess	Chewiness, kg
1	3.45±0.47^{b}	0.41±0.10^{b}	0.75±0.19^{e}	0.93±0.12^{b}	0.81±0.07^{ab}	596.81±148^{c}	0.56±0.18^{b}
2	0.92±0.15^{ghij}	0.14±0.03^{ghi}	0.37±0.12^{e}	4.42±4.69^{a}	0.87±0.07^{a}	318.03±91^{c}	1.25±1.27^{ab}
3	1.49±0.12^{defgh}	0.07±0.01^{ij}	0.59±0.26^{e}	0.75±0.08^{b}	0.67±0.04^{cdef}	385.00±150^{c}	0.29±0.12^{b}
4	1.52±0.29^{defgh}	0.06±0.006^{ij}	1.13±0.12^{de}	0.86±0.10^{b}	0.72±0.05^{bcdef}	811.99±116^{c}	0.70±0.17^{b}
5	1.44±0.12^{defgh}	0.03±0.008^{j}	0.78±0.04^{e}	0.65±0.02^{b}	0.61±0.06^{f}	474.90±60^{c}	0.31±0.04^{b}
6	4.36±0.23^{a}	0.3±0.08^{cd}	3.40±0.27^{b}	0.77±0.11^{b}	0.68±0.08^{bcdef}	2321.05±291^{b}	1.80±0.32^{ab}
7	1.57±0.16^{def}	0.05±0.008^{j}	0.71±0.22^{e}	0.66±0.05^{b}	0.64±0.03^{def}	459.44±150^{c}	0.30±0.08^{b}
8	1.72±0.32^{cd}	0.06±0.01^{ij}	0.50±0.21^{e}	0.74±0.14^{b}	0.67±0.04^{def}	340.49±153^{c}	0.27±0.17^{b}
9	1.83±0.21^{cde}	0.07±0.009^{hij}	0.66±0.13^{e}	0.75±0.15^{b}	0.63±0.04^{ef}	420.20±101^{c}	0.32±0.14^{b}
10	1.08±0.20^{fghij}	0.05±0.003^{ij}	0.97±0.13^{e}	0.62±0.03^{b}	0.64±0.02^{def}	620.34±71^{c}	0.38±0.06^{b}
11	3.12±0.39^{b}	0.26±0.05^{cde}	2.78±1.58^{bc}	0.81±0.11^{b}	0.68±0.07^{bcdef}	1864.25±1043^{b}	1.46±0.70^{ab}
12	2.00±0.31^{cd}	0.23±0.03^{def}	0.95±0.37^{e}	0.95±0.05^{b}	0.81±0.02^{ab}	763.97±283^{c}	0.73±0.29^{b}
13	2.29±0.18^{c}	0.19±0.03^{efg}	1.00±0.61^{e}	1.44±1.48^{ab}	0.75±0.07^{abcde}	752.92±488^{c}	0.83±0.54^{b}
14	0.75±0.06^{ij}	0.09±0.02^{hij}	0.88±0.50^{e}	0.86±0.17^{b}	0.70±0.05^{bcdef}	622.48±354^{c}	0.55±0.33^{b}
15	1.39±0.23^{defgh}	0.08±0.02^{hij}	0.42±0.14^{e}	0.85±0.09^{b}	0.71±0.02^{bcdef}	294.31±111^{c}	0.25±0.10^{b}
16	1.05±0.17^{fghij}	0.05±0.009^{ij}	0.40±0.10^{e}	0.80±0.20^{b}	0.65±0.03^{def}	257.83±60^{c}	0.20±0.03^{b}
17	1.07±0.21^{fghij}	0.07±0.005^{ij}	0.65±0.13^{e}	0.79±0.03^{b}	0.68±0.02^{bcdef}	442.98±96^{c}	0.35±0.08^{b}
18	1.54±0.18^{defg}	0.39±0.08^{b}	4.60±1.21^{a}	0.85±0.03^{b}	0.70±0.08^{bcdef}	3253.48±1020^{a}	2.79±0.94^{a}
19	1.30±0.18^{efghi}	0.06±0.006^{ij}	0.48±0.25^{e}	0.84±0.16^{b}	0.67±0.07^{cdef}	326.28±189^{c}	0.29±0.22^{b}
20	1.07±0.04^{fghij}	0.07±0.01^{ij}	0.43±0.14^{e}	0.92±0.27^{b}	0.72±0.09^{bcdef}	309.09±85^{c}	0.28±0.11^{b}
21	1.52±0.19^{defgh}	0.04±0.005^{j}	0.74±0.08^{e}	2.89±4.50^{ab}	0.72±0.09^{bcdef}	538.17±105^{c}	1.92±3.32^{ab}
22	1.43±0.40^{defg}	0.09±0.03^{hij}	0.31±0.05^{e}	0.69±0.12^{b}	0.63±0.06^{ef}	195.85±46^{c}	0.14±0.05^{b}
23	4.17±0.68^{a}	0.32±0.03^{bc}	2.2±0.86^{cd}	0.89±0.09^{b}	0.80±0.04^{abc}	1775.88±666^{b}	1.58±0.63^{ab}
24	1.56±0.30^{def}	0.56±0.05^{a}	0.75±0.42^{e}	0.87±0.08^{b}	0.77±0.08^{abcd}	559.93±281^{c}	0.48±0.23^{b}
25	0.91±0.15^{hij}	0.16±0.04^{fgh}	0.68±0.14^{e}	1.38±1.11^{ab}	0.67±0.04^{bcdef}	458.66±95^{c}	0.68±0.66^{b}
26	1.37±0.13^{defghi}	0.05±0.006^{j}	0.36±0.11^{e}	0.83±0.06^{b}	0.67±0.04^{cdef}	243.53±52^{c}	0.19±0.05^{b}
27	0.61±0.07^{j}	0.06±0.009^{ij}	0.31±0.09^{e}	0.83±0.11^{b}	0.69±0.02^{bcdef}	207.82±53^{c}	0.18±0.03^{b}

*Means that do not share a same letter in a same column are significantly different, according to Tukey's HSD test (p<0.05)

The smallest difference between the minimum and maximum values of shear force was obtained in the sample dried at 65 °C and 110 mbar; for penetration force in the sample dried at 55 °C and 200 mbar; for both hardness and springiness in the same sample dried at 50 °C and 200 mbar; for cohesiveness in the sample dried at 70 °C and 200 mbar; for gumminess in the sample dried at 65 °C and 200 mbar and for chewiness in the sample dried at 60 °C and 155 mbar. Also, it could be seen that the maximum values of all investigated texture properties were obtained at 20 and 65 mbar, which are at the same time the lowest applied values of the pressure. This indicates that the drying pressure influenced significantly the textural properties of sweet cherries during vacuum drying. In terms of the temperature influence, it was noticed that both minimum and maximum values of all investigated textural parameters were obtained in samples dried at temperatures 50, 55, 60 and 70 °C. These results indicate that temperature also influenced textural properties in the temperature range investigated in this research but not as significantly as it was the case of the influence of pressure. Influence of the pressure and temperature on the firmness of sour cherries during vacuum drying was investigated in the previous authors research [14] where the experimental data were fitted with a quadratic polynomial model and it was concluded that the linear terms of drying temperature and pressure, and quadratic term of pressure with p<0.0001 significantly influenced firmness of dried sour cherries. Influence of vacuum application of, among other parameters, on the texture profile could be also found in literature [32], where it was obtained that the values of hardness, chewiness and gumminess of berries processed by hot air convective drying were several times higher in comparison to those of berries produced by microwave vacuum drying or by combination of these two techniques. Also, microwave vacuum drying of cranberries resulted in a better quality product, in terms of texture and colour, as compared to conventional hot air dried samples [33].

4. CONCLUSION

Based on the results obtained in this research for the kinetics modelling of vacuum drying of sweet cherries it can be concluded that the highest mean value of R^2 (0.9985) and the lowest mean values of AARD (0.94 %), RMSE (0.5230) and χ^2 (0.0091) were obtained by application of the model proposed by Midilli *et al.*, and therefore this model was selected as the most suitable for representing this process. Furthermore, the minimum values of all investigated texture properties (shear force, penetration force, hardness, springiness, cohesiveness, gumminess and chewiness) were obtained in samples dried at the pressure of 200 mbar, while the maximum values of all investigated texture properties were obtained at lower pressures, 20 and 65 mbar, which indicates that the drying pressure influenced significantly the textural properties of sweet cherries during vacuum drying. Regarding the influence of temperature, it was noticed that this parameter did not have such a high influence on textural properties in the temperature range investigated in this research, as compared to the influence of the drying pressure.

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SAŽETAK

Sušenje trešnje (*Prunus avium* L.) u vakuumu: kinetika sušenja i teksturalne karakteristike

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(Naučni rad)

U okviru ovog istraživanja, trešnje (*Prunus avium* L.) su osušene tehnikom vakuum sušenja na različitim temperaturama u opsegu od 50 do 70 °C i različitim pritiscima u opsegu od 20 do 200 mbar. Sedam matematičkih modela primenjeno je za opis procesa vakuum sušenja i to Henderson-Pabisov (Henderson-Pabis) model, modifikovan Henderson-Pabisov model, pojednostavljen Fikov model difuzije, Pelegov (Peleg) model, logaritamski model, dvočlani model i model Midilija i saradnika (Midilli *et al.*). Kao model koji najbolje opisuje proces vakuum sušenja trešnje izabran je model Midilija i saradnika koji je dao nabolje slaganje sa eksperimentalnim rezultatima na osnovu najveće vrednosti koeficijenta determinacije (R^2=0.9985), kao i najmanjih vrednosti prosečne apsolutne relativne devijacije (engl. average *absolute relative deviation*, AARD=0.90 %), korena srednje kvadratne greške (engl. *root mean square error*, RMSE=0.0061) i redukovanog hi-kvadrata (engl. *the reduced chi-square,* χ^2=0.0001). Takođe, sedam teksturalnih karakteristika (sila presecanja, sila probijanja, tvrdoća, elastičnost, kohezivnost, gumljivost i žvakljivost) ispitane su u svim vakuum osušenim uzorcima. Rezultati su ukazali na uticaj pritiska na teksturalne osobine trešnje tokom vakuum sušenja s obzirom da su minimalne vrednosti svih ispitanih teksturalnih karakteristika zabeležene u uzorcima osušenim na 200 mbar, dok su maksimalne vrednosti zabeležene u uzorcima trešnje osušenim pri 20 mbar i 65 mbar. Takođe, zabeleženo je i da je temperatura imala uticaj na teksturalne karakteristike u opsegu temperatura ispitivanom u ovom istraživanju ali ne tako značajan kao u slučaju uticaja pritiska.

Ključne reči: koštičavo voće; tehnika sušenja; matematičko modelovanje; fizičke osobine