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MILOVAN ŽIVKOVIĆ[1]
SVETO RAKIĆ[1]
RADOJKA MALETIĆ[1]
DRAGAN POVRENOVIĆ[2]
MILOŠ NIKOLIĆ[3]
NADA KOSANOVIĆ[4]

[1]Faculty of Agriculture, University of Belgrade, Belgrade, Serbia
[2]Faculty of Technology and Metallurgy, University of Belgrade, Belgrade, Serbia
[3]Faculty of Agriculture, University of Kragujevac, Čačak, Serbia
[4]Institute for Science Application in Agriculture, Belgrade, Serbia

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# EFFECT OF TEMPERATURE ON THE PHYSICAL CHANGES AND DRYING KINETICS IN PLUM (*Prunus domestica* L.) POŽEGAČA VARIETY

*In this study, drying kinetics of autochthonous variety Požegača plum was examined in a laboratory dryer at three temperatures. The whole plum fruits, together with the kernels were subjected to the drying process. The effect of drying has been examined at temperatures of 55, 60 and 75 °C, with a constant air velocity of 1.1 m $s^{-1}$. The corresponding experimental results were tested using six nonlinear regression models. Coefficient of determination ($R^2$), standard regression error ($SS_E$), model correlation coeficient ($V_y$), as well as the maximum absolute error ($\Delta Y$) showed that the logaritmic model was in good agreement with the experimental data obtained. During drying of plums, the effective diffusivity was found to be between $5.6\times10^{-9}$ for 55 °C and $8.9\times10^{-9}$ $m^2$ $s^{-1}$ at 75 °C, respectively. The physical characteristics of fresh (length 39.64 mm and width 29.15 mm) and dried (length 37.52 mm and width 22.85 mm) plum fruit were determined. Finally, by chemical analysis, the contents of micro-and macro-elements (Fe, Mn, Cu, B and N, F, K, Ca, Mg and S) in the skin and flesh of the dried product, prunes, has been established.*

*Key words: convective drying; moisture content; physical characteristics; Požegača plum.*

*Prunus domestica* is the most numerous and diverse group of fruit tree species [1], but the extent of fundamental investigations concerning the prunes production is not appropriate to its importance. However, production of prunes has a long-established tradition in Serbia. The second part of the nineteenth and the begining of the twentieth century are considered to be the golden years for the export of prunes to the world markets. At that time, the plum fruit of the Požegača species were dried in primitive dryers operating on wood fire [2]. At that time, it was traditional that the optimal parameters for the ripeness of plum fruit were estimated on the basis of long term experience of fruit pickers. However, recent investigations show that, for successful prunes production, anthocyanin content, as well as the change in fruit colour in the last plum ripening stage, should be monitored [3].

Correspondening author: S. Rakić, Faculty of Agriculture, University of Belgrade, Belgrade, Serbia.
E-mail: sveto@agrif.bg.ac.rs
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There are numerous studies on the effects of physical properties on fruit drying, namely for apricots [4], strawberries [5], bananas [6], apples [7], carrots [8] and tomatoes [9]. For successful prune production, it is necessary to know the technical and physico-chemical properties of the plum fruit, for it to be subjected to the drying process [10].

Drying is one of the most widely used processing methods in the food industry. It is a well known fact that in prune production, 25% of the total cost is the expenditure for drying [11]. Properly conducted drying of fresh plum fruit gives a product of exceptional nutritional value and long shelf life, if properly packed [12].

Similar investigations are concerned with the problems of drying various fruit species [13]. There are also data on investigations of the models for drying other variety of plums from different geographical areas [14-15]. In many studies related to the drying of different kinds of plums, there was an effect of plum pretreatment methods to the effective moisture diffusivity [16-17]. In the mentioned references, results of investigations for various drying systems and different plum varieties from diferent geographical localities are presented. However, it should be pointed out that there are no published results on the drying of the Požegača variety plums, grown in the South-West Balkan region. For prune production, the beforehand preparation of fresh plum fruit is also very important and various treatments are applied [15-16]. For this variety of plums, there are no data on drying kinetics and the diffusion coefficient values, and therefore it was the main goal of this paper.

## MATERIALS AND METHODS

### Materials

Representative samples in the presented investigations were the whole, ripe plum fruits of the variety *Prunus domestica* L. Požegača. The fruits were picked by hand in September 2009 in the Western Serbia region (23 km southeastern from Bajina Bašta). The sample plum fruit, with stones, of uniform dimensions were selected. The preparation consisted of washing with water at 20 °C. The washed samples were evenly arranged on a drying tray at the density of 16.5 kg $m^{-2}$ and provisionaly dried at room temprature.

### Drying procedure

The drying was conducted in a chamber of dimensions 0.35×0.35×1.00 m, with an installed frame carrier, supplied with two wattles drying tray inclined for 7° towards the hot air flow (Figure 1). The frame carrier was connected with a balance which automatically registered the changes in the mass of the fruit material during the drying process. The electrical air heaters of overall power 16 kW were operated by a sensor for air temperature regulation. Air supply was provided by a fan of 2.2 kW, with an air flow rate of 480 $m^3$ $h^{-1}$ and air velocity of 1.1 m $s^{-1}$ in the drier room. For monitoring the temperature of the air, Fe-Co thermocouple sensors were used. Drying experiments were performed by maintaining fixed starting parameters for the air (temperature, relative humidity) as a continuous drying process at the three inlet temperatures: I - 75, II - 60 and III - 55 °C. Ambient air temperature was measured by a mercury thermometer with a range of 0 to 100 °C, and the precision of ±0.1 °C. The selected temperatures belong to the moderate regimes of drying, in order to preserve the basic characteristics of the finished product. The temperature measurements at the predermined points were achieved by an HP 35731B computer and an aquisition unit HP 3421A. Variation of the moisture in the dried material was continually monitored by the change of the corresponding mass using a digital balance (Sartorius GE 812, Germany, with Stratoconnect software). The drying study showed that the times taken for drying of plums from the initial moisture contents of 81% (w.b.) to final moisture content of around 16% (w.b.). The moisture ratios of samples reduced exponentially with drying time, which is typical for ones for food stuffs. Experiments were performed in five repetitions and mean values were calculated as representative.

### Determination of the physical characteristics, micro-and macroelements

Physical characteristics, namely the size (lenght, width, width at the seam), mass, density and the shape index [18] were determined for the fresh plum fruit samples. Fruit shape index was determined by a mean

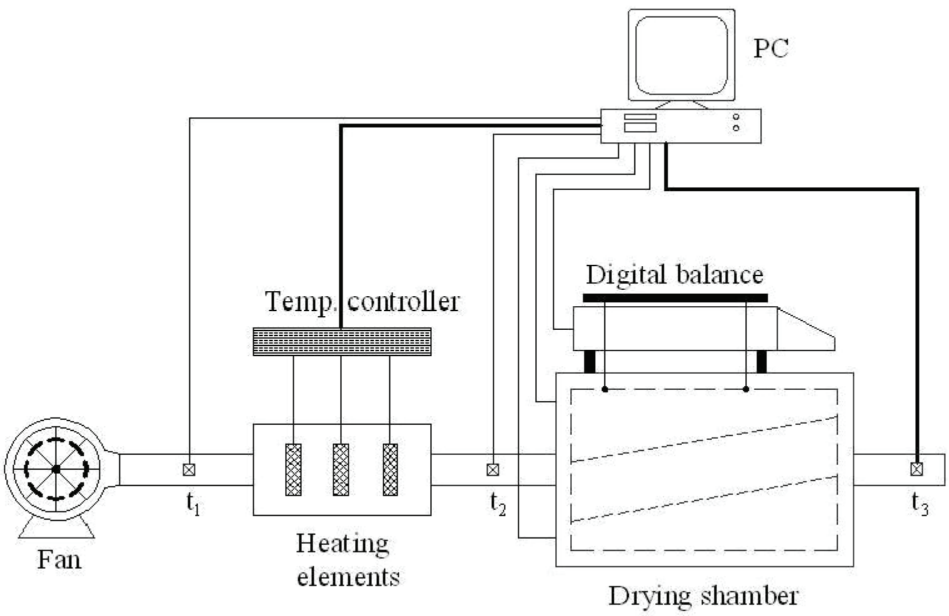


*Figure 1. Schematic of the drying unit.*

width and length of randomly selected fresh and dried fruits, in batches of 30 samples, calculated by the following equation [19-20]:

$$R_a = W/L \quad (1)$$

where: $R_a$ is shape index, $L$ is the average length of the fruit (mm), and $W$ the average width of the fruit (mm).

For the determination of micro-and macro elements, samples were washed, dried and chopped up into small pieces. Preparatory chemical analysis was perfomed by the method of "dry burning" at 500-550 °C, after which the samples were transfered to an acidic solution (HCl) and filtered. Two times 5 ml of a 6 mol $L^{-1}$ HCl were added and subsequently evaporated, the residue was washed with another 5 ml of a 0.5 mol $L^{-1}$ HCl and quantitavely transferred to a 50 ml measuring flask. The results were calculated on the basis of dry matter [21].

### Data and the statistical analysis

The obtained experimental data were processed using appropriate mathematical and statistical methods. The evaluation of the regression parameters was performed by the software Statistica 7.1 for Windows [22].

## RESULTS AND DISCUSSION

### Physical characteristics of the fresh plum fruit

For the purpose of the present investigation, healthy looking plum fruit of uniform size and ripeness were selected. The results of the corresponding physical characteristics are given in Table 1. The fresh plume fruit of the Požegača variety are non-uniform egg shaped dark blue colored specimens, covered by a greyish wax layer. Average lenght of the fresh fruit is 30.64 mm and the width 29.15 mm. The dried prune product has an average lenght of 37.52 mm and width 22.85 mm. On the basis of the shape index it could be concluded that drying diminished the sphericity of the product. On the other hand, the density was increased by 10.02%.

### Mathematical modeling of drying kinetics

Variations of the moisture content in the plums subjected to the drying processes at three selected temperatures are presented in Figure 2. Analysis of the drying curves shows that there is no constant rate period, but that the period of gradual reducing of rate was present, the same as in previous studies in drying of grapes [23-24]. Comparison of the three drying curves in the figure showed that the results were as ex-

*Table 1. Basic physical charasteristics of the fresh plum fruit and prunes obtained from the same material Prunus domestica L. Požegača variety*

| Fruit | Size, mm | | | | Mass, g | Density, g $cm^{-3}$ |
|---|---|---|---|---|---|---|
| | Lenght | Width | Seam width | Shape index | | |
| Fresh plums | 38.9-44.4 | 28.5-34.8 | 27.9-29.3 | 1.27-1.36 | 17.051-19.002 | 1.065-1.074 |
| Prunes | 35.0-40.5 | 21.2-24.5 | 20.6-20.8 | 1.50-1.64 | 5.801-9.403 | 1.161-1.205 |

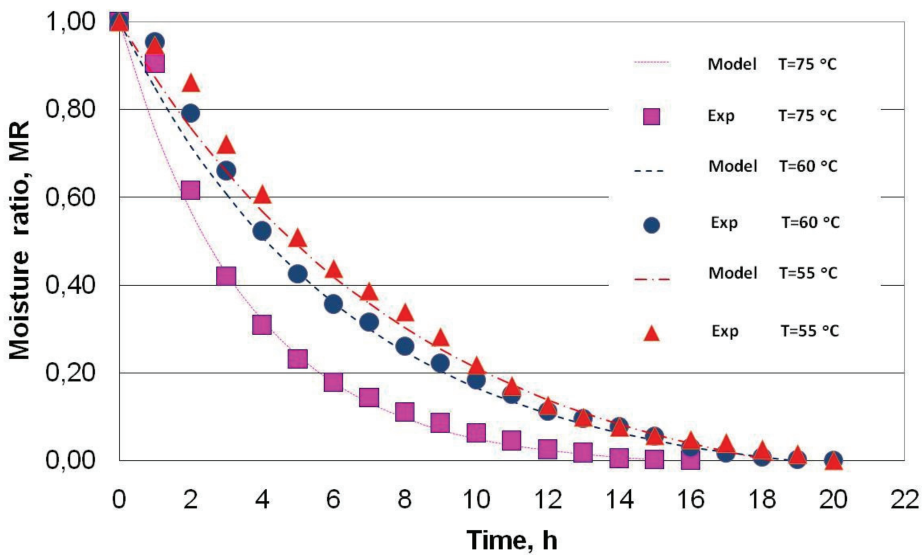


*Figure 2. Experimental data and predicted moisture ratio variations as the function of time for the drying of Požegača plum variety at three temperatures.*

pected, but that the dominant factor affecting the kinetics of drying was the inlet air temperature.

For the postulation of a matematical model for describing the drying process of the Požegača variety of plums, the obtained experimental data were tested by the use of six nonlinear models shown in Table 2.

*Table 2. Mathematical models applied to the drying curves*

| Model name | Equation | Reference |
|---|---|---|
| Newton model | $y = \exp(-kt)$ | [34] |
| Henderson and Pabis | $y = a\exp(-kt)$ | [29,30] |
| Logarithmic | $y = a\exp(-kt) + c$ | [32] |
| Two-term | $y = a\exp(-k_0 t) + b\exp(-k_1 t)$ | [35] |
| Wang and Singh | $y = 1 + at + bt^2$ | [33] |
| Parabolic | $y = c + at + bt^2$ | [31] |

These models are applied to the variation in the ratio of the moisture content in the course of drying to the starting moisture as a function of time ($t$). In Eq. (2) the variation of the moisture ratio, $MR$, is given by the expression:

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{2}$$

where: $MR$ - moisture ratio, $M$ - moisture at a given time during the drying procedure, kg water/kg dry solid, $M_e$ - moisture of the dry materal in equilibrium of the ambient air moisture, kg water/kg dry solid, and $M_0$ - initial moisture of the material, kg water/kg dry solid.

In the mathematical models used, the coefficient of determination ($R^2$) is a criteria for estimating the best nonlinear model which follows the moisture variations in observed samples. Other than the correlation coefficient $R^2$, standard regression error ($SS_E$), model correlation coeficient ($V_y$), as well as the maximum absolute error ($\Delta Y$) of the chosen model, were also used in the calculation. The highest value of the coefficient $R^2$ and the lowest values of $SS_E$, $V_y$, and $\Delta Y$, were selected as criteria for selection of the model best adapted to experimental data.

These parameters were calculated according to the following expressions:

$$SS_E = \left( \frac{\sum_{i=1}^{N} (MR_{\exp_i} - \hat{MR}_{\mathrm{pre}_i})^2}{N} \right)^{1/2} \tag{3}$$

$$V_{\hat{y}} = \frac{SS_E}{\bar{MR}} \tag{4}$$

$$R^2 = 1 - \frac{\text{Residual}}{\text{Corrected total}} \tag{5}$$

$$\max \Delta Y = \left| MR_i - \hat{MR}_i \right| \tag{6}$$

where $MR_{\exp i}$ is experimentally determined moisture at time $i$, $MR_{\mathrm{pre}i}$ is moisture value calculated from the model, and N is the number of observations [25].

Statistical indicators for the investigated models, calculated in the above manner, together with those from the study of the drying experiments are presented in Table 3. All the examined models satisfactorily describe the variation of the moisture index (moisture ratio) MR and the differences in the proposed statistical indicators are rather small, as it can be seen in Table 3.

However, the logaritmic model is outstanding, as it better describes the experimental drying procedures. This is evident from the analysis of the values of $R^2$ (0.9886 for the first temperature regime, 0.9950 for the second, and 0.9972 for the third), as well as $SS_E$ (0.0352, 0.0236, 0.0186), $V_y$ (0.1440, 0.0794, 0.0561) and $\Delta Y$ (0.0580, 0.1058 and 0.0567).

Exceptionaly good agreement of the Logarithmic model curves with experimental results for the drying the Požegača variety of plums at the three applied temperaratures are presented in Figure 2.

It can be seen from the figure that the drying process occurs only in the falling rate period. Fick's second law of diffusion, symbolized as a mass-diffusion equation for drying of agricultural products drying in a falling rate period, is shown in the following equation:

$$\frac{\partial M}{\partial t} = D_{\mathrm{eff}} \nabla^2 M \tag{7}$$

The analytical solutions of Fick's second law (Eq. (6)) for spherical geometry is described by Eq. (8):

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left( -n^2 \pi^2 \frac{D_{\mathrm{eff}} t}{R^2} \right) \tag{8}$$

where, $D_{\mathrm{eff}}$ is the effective moisture diffusivity in m$^2$ s$^{-1}$, $t$ is the time (s), $n$ is a positive integer, $R$ is the radius of samples (m), respectively. For long drying periods, Eq. (8) can be further simplified to only the first term of the series. Thus, Eq. (8) is written in a logarithmic form as follow [26]:

$$\ln MR = \ln\left( \frac{6}{\pi^2} \right) - \pi^2 \frac{D_{\mathrm{eff}}}{R^2} t \tag{9}$$

The effective moisture diffusivity was calculated from a slope of a straight line by plotting data in terms of ln $MR$ *versus* drying time, which gives a straight line with a slope $S$, in which:

*Table 3. Statistical data of the tested models for the three drying procedures*

| Model name | Equation | $R^2$ | $SS_E$ | $V_{\hat{y}}$ / % | Max ($\Delta Y$) |
|---|---|---|---|---|---|
| | Model $T$ = 75 °C | | | | |
| Newton model | $y = \exp(-kt)$; $k$ = 0.2726 | 0.9843 | 0.0394 | 0.1612 | 0.1432 |
| Henderson and Pabis | $y = a\exp(-kt)$; $a$ = 1.0649; $k$ = 0.2891 | 0.9882 | 0.0353 | 0.1444 | 0.1071 |
| Logarithmic | $y = a\exp(-kt) + c$; $a$ = 1.0723; $k$ = 0.2782; $c$ = -0.0723 | 0.9886 | 0.0352 | 0.1440 | 0.1058 |
| Two-term | $y = a\exp(-k_0t) + b\exp(-k_1t)$; a = 0.5339; $k_0$ = 0.2891; $b$ = 0.5310; $k_1$ = 0.2891 | 0.9882 | 0.0378 | 0.1547 | 0.1071 |
| Wang and Singh | $y = 1 + at + bt^2$; $a$ = -0.1740; $b$ = 0.0073 | 0.9524 | 0.0709 | 0.2901 | 0.1244 |
| Parabolic | $y = c + at + bt^2$; $c$ = 0.9385; $a$ = -0.1591; $b$ = 0.0066 | 0.9580 | 0.0689 | 0.2819 | 0.1187 |
| | Model $T$ = 60 °C | | | | |
| Newton model | $y = \exp(-kt)$; $y = \exp(-0.1678t)$ | 0.9848 | 0.0389 | 0.1310 | 0.1079 |
| Henderson and Pabis | $y = a\exp(-kt)$; $y$ = 1.0704 exp(-0.1803$t$) | 0.9911 | 0.0306 | 0.1030 | 0.0784 |
| Logarithmic | $y = a\exp(-kt) + c$; $y$ = 1.1123exp(-0.1556t) - 0.1123 | 0.9950 | 0.0236 | 0.0794 | 0.0580 |
| Two-term | $y = a\exp(-k_0t) + b\exp(-k_1t)$; $y$ = 0.7090exp(-0.1803$t$) + 0.3694exp(-0.1803$t$) | 0.9912 | 0.0323 | 0.1087 | 0.0784 |
| Wang and Singh | $y = 1 + at + bt^2$; $y = 1 - 0.1187t + 0.0036t^2$ | 0.9862 | 0.0382 | 0.1286 | 0.0706 |
| Parabolic | $y = c + at + bt^2$; $y = 0.9869 - 0.1162t + 0.0034t^2$ | 0.9864 | 0.0389 | 0.1310 | 0.0792 |
| | Model $T$ = 55 °C | | | | |
| Newton model | $y = \exp(-kt)$; $k$ = 0.1462 | 0.9744 | 0.0522 | 0.1574 | 0.1152 |
| Henderson and Pabis | $y = a\exp(-kt)$; $a$ = 1.0977; $k$ = 0.1596 | 0.9845 | 0.0417 | 0.1258 | 0.1191 |
| Logarithmic | $y = a\exp(-kt) + c$; $a$ = 1.1821; $k$ = 0.1215; $c$ = -0.1821 | 0.9972 | 0.0186 | 0.0561 | 0.0567 |
| Two-term | $y = a\exp(-k_0t) + b\exp(-k_1t)$; $a$ = 9.2699; $k_0$ = 0.2644; $b$ = -8.2616; $k_1$ = 0.2898 | 0.9948 | 0.0252 | 0.0760 | 0.0519 |
| Wang and Singh | $y = 1 + at + bt^2$; $a$ = -0.1066; $b$ = 0.0029 | 0.9952 | 0.0727 | 0.2192 | 0.0634 |
| Parabolic | $y = c + at + bt^2$; $c$ = 1.0243; $a$ = -0.1114; $b$ = 0.0031 | 0.9960 | 0.0216 | 0.0651 | 0.0478 |

$$S = \frac{\pi^2 D_{\mathrm{eff}}}{R^2} \qquad (10)$$

The effective diffusivity, $D_{\mathrm{eff}}$, was calculated for the different drying conditions. During the drying of plums, the effective diffusivity was found to be between 5.6×10$^{-9}$ for 55 °C and 8.9×10$^{-9}$ m$^2$ s$^{-1}$ for 75 °C, and it is clear that, increasing the drying air temperature resulted in increasing effective diffusivities [13,28]. These values are higher than the reported diffusivities for plums [5], but within the general range of 10$^{-13}$-10$^{-6}$ m$^2$ s$^{-1}$ for food materials.

## Macro- and micro-elements contents of dried prunes

The content of the macro- and micro-elements in the final product of the drying process, prunes, depends primarily on the sort of the starting plum material, but also on other factors, like physical and chemical properties of the soil, climate, and also metabolic and physiological conditions of the plant [21]. The content of the macro-and micro elements in the dried product originating from the *Prunus domestica* L. variety Požegača is presented in Table 4.

Content of macro- and micro-elements in the prune skin and flesh is considerably different, their relative contribution is larger in the skin than in the flesh, except for K. The differences between the skin and the flesh are mostly in the contribution of N, Fe, Cu and B and less in the contribution of S and Mn. Mg is the least and K is the most abundant macroelement in the analysed samples. The content of Fe (36 mg kg$^{-1}$) in the skin of the obtained prunes product is considerably larger than that for other analysed micro-elements, namely B (18 mg kg$^{-1}$), Mn (8 mg kg$^{-1}$) and Cu (4.2 mg kg$^{-1}$). There is also a considerably larger content of Fe in the flesh of prune samples than of the other micro-elements. Similar results on the content of macro- and micro-elements has been reported in previous studies relating to the prunes obtained from other plum species [18].

*Table 4. Content of the macro- and micro-elements in the product of drying the Prunus domestica L. Požegača variety*

| Sample | Content of macro-elements, % | | | | | | Content of micro-elements, mg kg$^{-1}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | N | P | K | Ca | Mg | S | Fe | Mn | Cu | B |
| Skin | 0.54 | 0.100 | 0.79 | 0.087 | 0.044 | 0.20 | 36 | 8 | 4.2 | 18 |
| Flesh | 0.37 | 0.088 | 0.82 | 0.063 | 0.036 | 0.19 | 21 | 7 | 1.4 | 15 |

## CONCLUSIONS

The aim of the present investigation is to study the drying process of the autochthonous sort Požegača plums at three selected temperatures 75, 60, and 55 °C. Examination of the physical characteristics of the corresponding fruit, showed that the plum specimens of this sort are small (17-19 g), of irregular egg shape, dark blue coloured and covered by a thin gray waxy layer. The average lenght of the fruit is 39.64 mm and width 29.15 mm. According to the analysis of the experimentaly obtained data on the moisture ratio MR as a function of time, employing six non-linear regression models, it was established that the Logaritmic model, could adequately describe the drying behaviour of Požegača plums. The effective moisture diffusivity values were estimated as $5.6\times10^{-9}$ at 55 °C and $8.9\times10^{-9}$ $m^2 s^{-1}$ at 75 °C, respectively. The content of macro- and micro-elements differs in the skin and the flesh of the dried product prunes, their relative contribution being larger in the skin than in the flesh.

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MILOVAN ŽIVKOVIĆ[1]
SVETO RAKIĆ[1]
RADOJKA MALETIĆ[1]
DRAGAN POVRENOVIĆ[2]
MILOŠ NIKOLIĆ[3]
NADA KOSANOVIĆ[4]

[1]Poljoprivredni fakultet, Univerzitet u Beogradu, Beograd, Srbija
[2]Tehnološko-metalurški fakultet, Univerzitet u Beogradu, Beograd, Srbija
[3]Agronomski fakultet, Čačak, Univerzitet u Kragujevcu, Srbija
[4]Institut za primenu nauke u poljoprivredi, Beograd, Srbija

NAUČNI RAD

# UTICAJ TEMPERATURE NA FIZIČKE PROMENE I KINETIKU SUŠENJA ŠLJIVE (*Prunus domestica* L.) SORTE POŽEGAČA

*Predmet ispitivanja ove studije je kinetika sušenja šljive autohtone sorte Požegača u laboratorijskoj sušari na tri temperaturna režima. Tretirani su celi plodovi šljiva, zajedno sa košticom. Ispitivan je efekat sušenja pri različitim temperaturama 55; 60 i 75 °C, praćenjem promene vlažnosti materijala u funkciji vremena sušenja pri stalnoj brzini vazduha od 1,1 m $s^{-1}$. Eksperimentalni rezultati ovih ispitivanja sušenja testirani su na šest nelinearnih regresionih modela. Koeficijent determinacije ($R^2$), standardna greška regresije ($SS_E$), koeficijent varijacije modela ($V_y$), kao i maksimalna apsolutna greška ocenjenog modela ($\Delta Y$), su pokazali da je Logarithmic model najbolje prilagođen eksperimentalnim podacima. Tokom sušenja plodova šljiva, utvrđen je koeficient difuzije čija se vrednost kretala između $5,6\times10^{-9}$ za 55 °C i $8,9\times10^{-9}$ $m^2$ $s^{-1}$ za 75 °C, respektivno. Određene su fizičke karakteristike svežih (dužina 39,64 mm i širine 29,15 mm) i sušenih (dužina 37,52 mm i širine 22,85 mm) plodova šljive. Hemijskom analizom određen je sadržaj mikro-i makroelemenata (Fe, Mn, Cu, B i N, C, K, Ca, Mg i S) u koži i mesu kod sušenih plodova šljive.*

*Ključne reči: konvektivno sušenje; sadržaj vlage; fizičke karakteristike; šljiva Požegača.*