

THIN-LAYER DRYING KINETICS AND COLOR CHANGES OF POTATO SLICES DURING FAR-INFRARED VACUUM DRYING

KINETIKA SUŠENJA I PROMENE BOJE KROMPIRA U TANKOM SLOJU TOKOM INFRACRVENOG VAKUMSKOG SUŠENJA DUGOG SPEKTRA

Vangelce MITREVSKI¹, Cvetanka MITREVSKA², Slobodan BUNDALEVSKI², Borce MITREVSKI³, Milivoj RADOJCIN⁴

¹Faculty of Technical Sciences, Bitola, Makedonska Falanga 33

²Faculty for Safety Engineering, Sveti Nikole

³Center for Energy Efficiency Bobi Turs, Bitola

⁴Faculty of Agriculture Novi Sad, Trg Dositeja Obradovića 8

Correspondence: vangelce.mitreviski@uklo.edu.mk

ABSTRACT

In this study far infrared vacuum drying kinetics and change of color quality parameters of potato slices were analyzed. The experimental data set of drying kinetics was obtained on the experimental set-up designed to imitate an industrial far infrared vacuum dryer. For approximation of the experimental data with regard to the moisture ratio (MR) three well known thin-layers drying models from scientific and engineering literature and model of Mitrevski et al., were used. The performed statistical analyzes show that the model of Mitrevski et al., has the best statistical performance than well-known thin-layer drying models. The estimated values of moisture diffusivity of potato slices obtained from this study are within the range from 5.14×10^{-8} to $5.01 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$. A negative effect on the total color change of far infrared vacuum dried potato slices was observed with increasing of temperature of infrared heaters and vacuum pressure.

Key words: potato slices, thin-layer drying, color changes

REZIME

U ovom radu analizirane su kinetika termoradijacionog vakuumskog sušenja i promene parametara kvaliteta boje kriški krompira. Eksperimentalni podaci o kinetici sušenja dobijeni su na eksperimentalnoj aparaturi projektovanoj tako da simulira industrijsku termoradijacionu vakuum sušaru. Za aproksimaciju eksperimentalnih podataka u odnosu na bezdimenzioni odnos sadržaja vlage primenjena su tri dobro poznata modela sušenja tankog sloja iz naučne i inženjerske literature, kao i model Mitrevski et al. Rezultati sprovedenih statističkih analiza pokazali su da model Mitrevski et al. ima bolje statističke pokazatelje u poređenju sa konvencionalnim modelima sušenja u tankom sloju. Određene vrednosti difuzivnosti vlage kriški krompira u ovom istraživanju kreću se u opsegu od 5.14×10^{-8} do $5.01 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$. Utvrđeno je da povećanje temperature infracrvenih grejača i nivoa vakuum pritiska negativno utiču na ukupnu promenu boje kriški krompira tokom termoradijacionog vakuumskog sušenja.

Ključne reči: kriške krompra, sušenje tankog sloja, promena boje

INTRODUCTION

In the recent decades, increasing consumer demand for high-quality dried food products has driven the development and optimization of drying technologies. Consumers increasingly prefer dried fruits and vegetables that retain their original physicochemical, sensory, and microbiological characteristics. Among the various drying methods, convective drying remains the most widely applied technique in the food industry due to its simplicity, reliability, and cost-effectiveness. The main disadvantages of convective drying are (Kanevce, G., et al. 1998): the material is exposed at high temperature for a long time during the contact with hot air which is the reason for decreases on nutritive values and color change, shrinkage, and low dehydration capacity of the dried material, structure and flavor changes during drying. Far-infrared vacuum drying is an alternative method aimed at overcoming the limitations of conventional drying methods. In the scientific and engineering literature, far-infrared vacuum drying has been extensively investigated by numerous researchers (Kanevce et al., 1998a; Plietić et al., 2003; Bundalevski et al., 2015; Mitrevski et al., 2016; Mitrevski et al., 2016a; Mitrevski et al., 2017; Mitrevski et al., 2019; Mitrevski et al., 2022). These studies have demonstrated its potential to enhance drying efficiency while preserving product quality by reducing thermal degradation and oxidation, as well as reducing energy consump-

tion compared to conventional drying methods. However, few studies have examined the drying kinetics and color parameter changes of materials during far-infrared vacuum drying under high infrared heater temperatures 120–200°C and vacuum pressures 20–80 kPa (Mitrevski et al., 2022). Therefore, the objectives of this study were:

- to evaluate drying kinetics of far infrared vacuum drying potato slices,
- to estimate the moisture diffusivity of potato slices and compared estimated values with the values published in scientific and engineering literature by other authors and
- to investigate of the influence of boundary conditions on the total color changes of dried potato slices.

MATERIAL AND METHODS

Sample preparation

Fresh potato variety Liseta was used as raw material in the experimental part of the research. Prior to processing, the potatoes were stored in a cold chamber at 4 °C and a relative humidity of 75%. Spherical samples with a diameter of $43 \pm 10^{-1} \text{ mm}$ and a thickness of $3 \pm 10^{-1} \text{ mm}$, obtained from the central medulla region where the cell structure is more uniform, were used in the drying experiments. Several measurements were performed using a caliper, and only samples within a $\pm 2\%$ tolerance were

selected for the experimental study. The potato slices were dried in a far-infra red vacuum set-up (Mitreviski et al., 2019). The experimental conditions were selected to ensure that the infrared heater temperatures and vacuum pressures were within ranges applicable to industrial-scale drying operations. The effect of infrared heater temperatures (120, 140, 160, 180, and 200 °C) and vacuum pressures (20, 40, 60, and 80 kPa) on the drying kinetics of potato slices was investigated (Mitreviski et al., 2019). After each experiment, the dried samples were stored in airtight paper packets at room temperature for 24 h prior to analysis. The transient temperatures of drying samples were measured with three micro-thermocouples placed in each of the mid-plane of the drying samples. The measurement of samples mass changes with time was enabled with load cell type OMEGA LCL-040 (Omega, Inc., USA), which was connected to data acquisition system. The temperature and mass changes of dried samples were registered on the personal computer. The initial moisture content of the samples was obtained according to the AOAC method no. 934.06 (AOAC 1995). The experiments were carried out in triplicate and an arithmetic average value was used for data processing. The drying experiments were performed until obtaining the moisture content of dry potato samples of 0.03 kg/kg.

Drying kinetics

The experimental moisture content data obtained at different the infrared heater temperatures and vacuum pressure were converted to the moisture ratio (MR) using the following equation:

$$MR = (u_{\tau} - u_{eq}) / (u_0 - u_{eq}) \tag{1}$$

where (MR) is the dimensionless moisture ratio and u_{τ} , u_0 , and u_{eq} are moisture content at any time, initial moisture content and equilibrium moisture content.

Because of the values of equilibrium moisture content, u_{eq} are relatively small compared to those of moisture content of material, u_{τ} or initial moisture content, u_0 the error involved in the simplification is negligible. Thus, the moisture ratio (MR) was subsequently calculated

$$MR = u_{\tau} / u_0 \tag{2}$$

Moisture diffusivity

The moisture diffusivity of foods is very often considered as an Arrhenius-type temperature function (Kanevce, G., 2007):

$$a_m = a_{m0} \exp[-E_0/(R T)] \tag{3}$$

where a_{m0} is the Arrhenius factor, E_0 - the activation energy for moisture diffusion, R - the ideal gas constant, and T - the absolute temperature. In this study the values of moisture diffusivity were estimated on the basis of an accurate and easy to perform single thermocouple temperature measurement by using an inverse approach (Kanevce, G., 2007):. An arithmetical mean of the readings from the three thermocouples inserted in the mid-palate position separately of each of the three drying slices of potato was used as a transient temperature reading (Kanevce, G., 2007). The estimation methodology is based on the minimization of the ordinary least square norm:

$$E(\mathbf{P}) = [\mathbf{Y} - \mathbf{T}(\mathbf{P})]^T [\mathbf{Y} - \mathbf{T}(\mathbf{P})] \tag{4}$$

where, $\mathbf{Y}^T = [Y_1, Y_2, \dots, Y_{imax}]$ is the vector of measured temperatures, $\mathbf{T}^T = [T_1(\mathbf{P}), T_2(\mathbf{P}), \dots, T_{imax}(\mathbf{P})]$ is the vector of estimated temperatures at time τ_i ($i = 1, 2, \dots, imax$), $\mathbf{P}^T = [P_1, P_2, \dots, P_N]$ is the vector of unknown parameters, $imax$ is the total number of measurements, and N is the total number of unknown parameters

($imax \geq N$). For the minimization of $E(\mathbf{P})$ representing the solution of the present parameter estimation problem the Levenberg-Marquardt method was utilized (Kanevce, G., 2007).

Color measurement and kinetics on color changes

In order to investigate the effect of infrared heater temperatures and vacuum pressure on the color changes of dried potato, a three-filter colorimeter Konica Minolta CR-400 (Konica Minolta Sensing Americas, Inc., USA) was used. This instrument shows the quantitative parameters of color change in different systems. The measured values of the color parameters are represented in the CIE, L^* , a^* , b^* color space. In this color space, L^* values are used as an indicator of lightness/darkness (ranges from 0 to 100), co-ordinate a^* to indicate chromaticity on a green (-) to red (+) axis (ranges from -120 to 120), and co-ordinate b^* to indicate chromaticity on a blue (-) to yellow (+) axis (ranges from -120 to 120). The color measurements were conducted before and after far infrared vacuum drying of potato slices. Five measurements were performed for each sample which is selected randomly. The values used for total color change calculations encompassed the average values of L^* , a^* and b^* of each sample.

The total color change, ΔE is calculated on the basis of the equation (Radojčin, et al., 2010):

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \tag{5}$$

where: L_0^* , a_0^* and b_0^* are initial values for lightness, redness, and yellowness.

In order to determine the rate of color changes during drying of far infrared vacuum drying, the kinetics of the parameters of lightness, L^* , redness, a^* and yellowness, b^* were investigated. For approximation of the total color changes, ΔE data during far infrared vacuum drying process the model of Mitreviski et al., (Mitreviski et al., 2022) were used:

$$\Delta E = A + B/t_h + C \cdot p^2 \tag{6}$$

where A , B , C , are parameters, t_h , - temperature of infrared heaters, and p - vacuum pressure. In this study multiple regression relationship between dependent variable, ΔE and independent variables, temperature of infrared heaters and vacuum pressure were used.

RESULTS AND DISCUSSIONS

Fitting of drying curves

For approximation of experimental data on the drying kinetics of potato slices four thin-layer mathematical models from scientific literature were used, tab. 1.

Table 1. Thin-layer drying models

Num. model	Name of model	Model	References
M1	Aghbashlo	$MR = \exp(-k_1 \tau / (1 + k_2 \tau))$	Aghbashlo et al., 2009
M2	Parabolic	$MR = A + B\tau + C\tau^2$	Doymaz, 2011
M3	Jena and Das	$MR = A \exp(-k_1 \square + B \square^{0.5}) + C$	Jena et al., 2017
M4	Mitreviski	$MR = A \exp(-k_1 \square) / ((1/p^C)(1/t_h^D) + (1-A) \exp(-k_1 B \square))^{**} (1/p^E 1/t_h^F)$	Mitreviski et al., 2022

$MR = M/M_0$ moisture ratio, A, B, C, D, E, F - the parameters, k_1, k_2 [min^{-1}] - drying rate constant, τ [min] - drying time, t_h [°C] - temperature of infrared heaters, and p [kPa] - vacuum pressure

The method of multiple indirect non-linear regression and estimation methods of: Quasi-Newton, Simplex, Simplex and quasi-Newton, Hooke-Jeeves pattern moves, HookeJeeves pattern moves and quasi-Newton, Rosenbrock pattern search, Rosenbrock pattern search and quasi-Newton, Gauss-Newton and Levenberg-Marquardt from computer program StatSoft Statistica (Statsoft Inc., Tulsa, OK, <http://www.statsoft.com>), were used to calculate the statistical parameters and estimate the parameters in the given models. Because the regression method, estimation method, the initial step size, starting values of parameters, convergence criterion and form of the function have a significant influence on the accuracy of estimated parameters (Mitreviski et al., 2015), a large number of numerical experiments were performed. On the basis of thin-layer data and each model from, tab. 1, the values of: coefficient of determination, R^2 , root mean squared error, RMSE, and mean relative deviation, MRD, were calculated. When the value for coefficient of determination obtained from different estimation methods was different, the greatest value was accepted as relevant. In order to estimate and select the best thin-layer drying model the value of performance index, ϕ , and chi-squared, $\chi^2_{0.005}$ were calculated:

$$\phi = \frac{R^2}{RMSE \cdot MRD} \tag{7}$$

$$\chi^2 = z_1^2 + z_2^2 \tag{8}$$

where z_1 and z_2 are individual statistics for testing of the population of skewness and kurtosis (Sheskin, D.J., 2011). The most appropriate model describing the thin-layer drying characteristics of potato slices was selected based on its statistical performance. The selection criteria included the highest performance index (ϕ) and a chi-square (χ^2) value lower than the critical value at $p = 0.05$ ($\chi^2_{0.005} = 5.99$) for 2 degrees of freedom, tab. 2.

Table 2. Statistic summary of regression analysis

Model	R^2	RMSE	MRD	ϕ	χ^2	Rank
M1	0.9997	0.0056	0.2017	885.07	1.3324	2
M2	0.9981	0.0153	0.8575	76.076	1.3468	3
M3	0.9979	0.0155	0.9739	66.106	2.1483	4
M4	0.9998	0.0047	0.1981	1073.8	1.1490	1

From tab. 2 it is evident that model M4, has the highest value of performance index, $\phi = 1073.8$, (Rank 1) in comparison with the other models. Furthermore, all evaluated models exhibited chi-square (χ^2) values lower than the critical chi-square value at $p = 0.05$, indicating that each model provides an acceptable fit to the experimental data. In accordance with the statistical criteria, the model proposed by Mitreviski et al. accurately correlates the experimental drying kinetics of potato slices, with a root mean squared error (RMSE) of 4.7%

The estimated values of parameters in model of Mitreviski et al., are presented in tab. 3.

Table 3. The values of estimated parameters

A	K_1	B	C	D	E	F
-0.0004	0.0051	0.0049	-0.0844	1.3234	0.0243	-1.2891

The analysis of variance (ANOVA) results indicated that the temperature of heaters ($p \leq 0.001$), vacuum pressure ($p \leq 0.05$), and the interaction of the temperature of heaters and vacuum pressure ($p \leq 0.05$) significantly affected the drying time of potato slices.

Fig. 1 illustrates the experimental and predicted moisture ratio (MR) of potato slices as a function of drying time at infrared heater temperatures of 120, 140, 160, 180, and 200 °C and vacu-

um pressures of 20, 40, and 60 kPa. The predicted values from the Mitreviski et al. model show good agreement with the experimental data, demonstrating that the model accurately captures the drying kinetics of potato slices under all drying conditions.

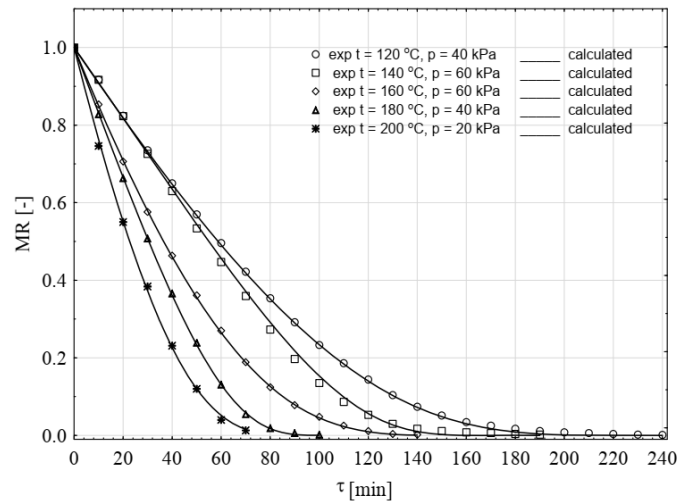


Fig. 1 Comparison of experimental and predicted moisture ratio (MR) values using the Mitreviski et al. model at different infrared heater temperatures and vacuum pressures

Moisture diffusivity

The values of the parameters of effective moisture diffusivity, a_{m0} , and activation energy E_0 are determined by application of inverse approach. The estimated values of moisture diffusivity of potato obtained from this study are within the range from 5.14×10^{-8} to $5.01 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$. These values are comparable with values for other dried food materials which values generally were reported in scientific literature, from 10^{-13} to $10^{-6} \text{ m}^2 \text{ s}^{-1}$ (Panagiotou, et al., 2004).

Color change

In tab. 4 the average value changes in lightness, L^* , redness, a^* , yellowness, b^* and total color changes, ΔE , of potato slices for different value of temperature of infrared heaters and vacuum pressure are presented. From tab. 4 it is evident that, the L^* value of dried potato slices decreased during drying. The, L^* decreased from initial $L_0^* = 82.09$ to final value $L^* = 62.78$, when potato slices are dried at 200 °C and 80 kPa. The changes in L^* parameter value were less at lower temperature of infrared heaters and lower vacuum pressure. As temperature of infrared heaters increased from 120-200°C and vacuum pressure changes from 20-80 kPa the lightness of potato slices decreased from 80.71 to 62.78. The decrease in L^* value was in correlation with nonenzymatic browning reactions which accelerates at high temperatures (Mariscal et al., 2009). The reduction in L^* value may be attributed to intense browning reaction and increase crust formation due to exposure to high temperature (Mariscal et al., 2009). Because the lightness is a very important color quality parameter, lower temperature of infrared heaters and lower vacuum pressure are preferable to preserve of dried potato slices. The temperature of infrared heaters and vacuum pressure also have an effect on the redness parameter, a^* . From instance, a^* value increased from initial value $a_0^* = -6.01$ to $a^* = 6.49$ at the end point when potato slices were dried at 200 °C and 80 kPa. As shown in tab. 4 the yellowness of dried slices increased during drying from 2.29 to 6.49. The values of yellowness, b^* increased from initial value $b_0^* = 21.01$ to $b^* = 25.23$ when potato slices were dried at 200 °C and 80 kPa. As the temperature of

infrared heaters increased from 120-200 °C and value of vacuum pressure varied between 20 to 80 kPa the yellowness of potato slices increased from 22.01 to 25.23. Similar effects on the drying kinetics on changes of color parameters were reported for banana (Swasdisevi, et al., 2007) and apple (Mitrevski et al., 2022).

Table 4. The effect on drying conditions on changes of color parameters

t_h	p	a^*	b^*	L^*	ΔE
120	20	2.29±3.79	22.01±9.33	80.71±2.00	8.47
140	20	2.88±3.81	22.79±9.73	72.98±3.20	12.85
160	20	4.04±3.59	22.89±10.61	71.11±3.04	15.00
180	20	4.58±3.80	23.01±19.38	69.11±3.21	16.78
200	20	5.36±4.10	23.15±11.31	68.01±3.11	18.22
120	40	2.76±3.71	22.06±9.36	79.89±3.22	9.10
140	40	3.37±3.58	23.00±10.31	70.44±3.34	15.09
160	40	4.52±3.80	23.11±10.72	69.89±3.51	16.25
180	40	5.21±3.89	24.21±11.30	68.88±3.26	17.62
200	40	5.88±4.58	24.00±11.51	67.02±3.19	19.43
120	60	3.03±3.88	22.11±10.36	77.42±3.17	10.23
140	60	3.66±3.80	23.13±11.36	69.03±3.14	16.39
160	60	4.74±3.57	23.19±11.30	67.77±3.33	18.04
180	60	5.23±4.80	24.12±11.37	66.84±3.41	19.20
200	60	6.25±3.70	25.02±11.60	65.91±4.01	20.69
120	80	3.33±3.61	23.01±10.36	72.94±3.16	13.23
140	80	4.04±3.58	23.11±11.30	65.97±3.15	19.11
160	80	5.01±3.80	24.03±12.37	64.89±3.23	20.65
180	80	6.00±4.11	25.01±13.39	64.09±3.25	22.01
200	80	6.49±4.57	25.23±13.52	62.78±4.33	23.39

t_h - heaters temperature, p - vacuum pressure, a^* - redness, b^* - yellowness, L^* - lightness, ΔE - total color change, mean ± standard deviation

Tab. 4 clearly shows that ΔE values, increased during the drying of potato slices and color changes intensity is more intense at higher temperature of infrared heaters and higher vacuum pressure. The total color change, ΔE values increased from 8.47 to 23.39, when potato slices were dried at temperature of heaters from 120-200°C and vacuum pressure from 20-80 kPa. Similar results were reported for far infrared vacuum drying of peach (Alaei et al., 2015).

For estimation of the statistical parameters in the model of total color change, eq. (6), the method of multiple indirect non-linear regression and estimation method of QuasiNewton, from computer program StatSoft Statistica (Statsoft Inc., Tulsa, OK, <http://www.statsoft.com>), were used. In tab. 5 the estimated values of parameters from the mathematical model with eq. (6) are presented.

Table 5. The values of estimated parameters (eq.6)

A	B	C
31.144	-2.538.1	0.0008

Figure 2 illustrates the variation in total color change (ΔE) of potato slices as a function of infrared heater temperature at different vacuum pressures during the far-infrared vacuum drying process. The results indicate that both infrared heater temperature and vacuum pressure significantly influence the color characteristics of the dried potato slices.

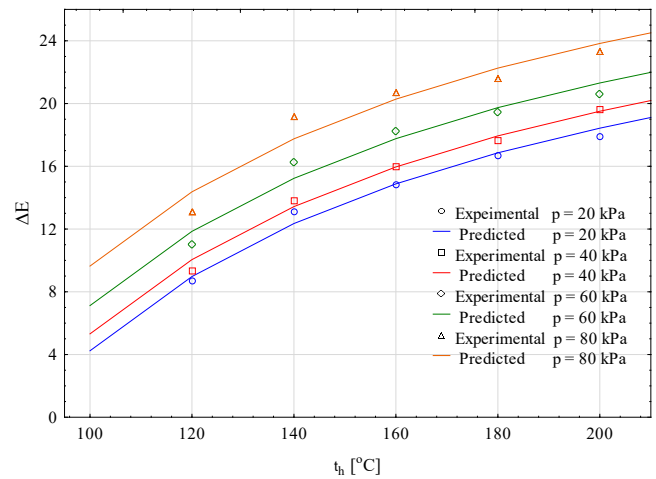


Fig 2. Effect of infrared heater temperatures on total color change on potato slices at different vacuum pressure

The high coefficient of determination ($R^2 = 0.9884$) together with the low root mean squared error (RMSE = 0.054) demonstrates the excellent agreement between the experimental data and the predicted values obtained from the model proposed by Mitrevski et al. (Mitrevski et al., 2022). These statistical indicators confirm that the Mitrevski et al. model adequately describes the changes in total color during the far-infra red vacuum drying process.

Furthermore, the increase in infrared heater temperature combined with higher vacuum pressure resulted in greater total color change (ΔE), indicating a deterioration in the visual quality of the dried potato slices. This behavior may be attributed to intensified thermal degradation reactions and pigment changes occurring at elevated drying temperatures.

Figure 3 presents the color changes of potato slices dried under different heater temperatures and vacuum pressures.

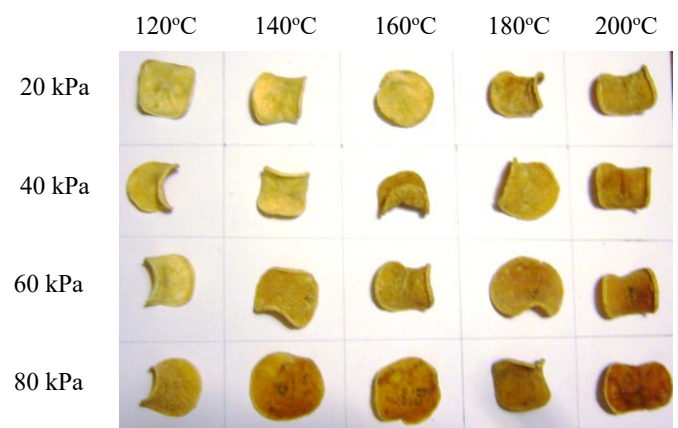


Fig. 3 Effect of different far-infrared vacuum drying regimes on the color of potato slices

CONCLUSIONS

In the present study, the effects of the temperature of infrared heaters and vacuum pressure on the drying kinetics and color quality of potato slices were examined. The experimental drying data, expressed in terms of the moisture ratio (MR), were fitted using three thin-layer drying models from the scientific literature, including the model proposed by Mitrevski et al. According to the statistical evaluation, the Mitrevski et al. model showed

better statistical performance compared to the other thin-layer drying models.

The study also confirmed that the boundary conditions on the surface of the potato slices, specifically the temperature of the infrared heaters and the vacuum pressure have a significant influence on the changes in color parameters (L^* , a^* , b^* , and ΔE).

Higher infrared heater temperatures and higher vacuum pressure values were found to negatively affect the total color change of the dried potato slices.

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Received: 8. 3. 2026.

Accepted: 31. 3. 2026.