MODELLING CONVECTIVE THIN-LAYER DRYING OF CARROT SLICES AND QUALITY PARAMETERS

by

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The influence of thin layer convective dehydration parameters on drying kinetics parameters, chemical composition, and color parameters of carrot slices were investigated, and corresponding mathematical models were developed. In the carrot slices, convective dehydration process hot air temperature and the sample slice thickness were varied, while measured, calculated, and modeled responses were: time of dehydration, effective moisture diffusivity, the energy of activation, proteins and cellulose contents, lightness, redness, and yellowness. The obtained results showed that varied convective dehydration process parameters statistically significantly affected all investigated responses except activation energy. The most efficient drying model with the minimum thickness (3 mm) and the maximum drying temperature (70 °C) had the shortest drying time (231 minutes). This model had the minimum resistance to mass transfer (the minimum effective moisture diffusivity, $2.04 \cdot 10^{-08} - 7.12 \cdot 10^{-08}$ [m^2s^{-1}]), and the average maximum energy of activation (31.31 kJ/mol). As far as the carrot slices' chemical composition and color parameters were concerned, the model with the maximum thickness (9 mm) and the minimum drying temperature (35 °C) was the optimal one. This model had the longest dehydration time (934 minutes), the maximum resistance to the mass transfer ($8.87 \cdot 10^{-08}$ [m^2s^{-1}]), the minimum total protein content (5.26 %), and the darkest color (49.70). The highest protein content (7.91%) was found for the samples subjected to the highest drying temperatures and the lowest carrot slice thickness. In contrast, the process of convective dehydration had led to the lighter, reddish, and yellowish carrot slices. All developed mathematical models were statistically significant.

Key words*: convective dehydration, thin-layer drying, carrots, drying kinetics, mathematical modelling, carrots quality characteristics*

Introduction

Drying operation in food processing has been successfully used to prevent biochemical, chemical, and physical deterioration of raw biological material. The main goal of drying is reducing the water content. In that way, biological material becomes easier to manipulate and

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less prone to microbial degradation. Removal of the moisture from raw material, or wet food product, enables the shelf life's extension, prolongs the storage time, reduces volume, restrains the microbial growth, and inactivates enzymes [1-3].

Carrots (*Daucus carota L*) are the second most consumed vegetable globally. Due to the abundance of phytochemical constituents such as beta-carotene, vitamin C, carbohydrates, and minerals in its' chemical composition, they have been identified as one of the healthiest vegetables [4].

Drying can prevent the excessive loss of that valuable raw biomaterial by using it as an ingredient in dry mixes for soups, sauces and ready-meals, as well as healthy snacks [5, 6]. Literature describes many different methods of dewatering and drying of carrots and their influence on the quality of the dried products, for example low hot air drying [7].

Hot air drying under forced convection, a stationary layer, is the most prevalent drying technique applied in the fruit and vegetable industries [8].

Heat treatment during carrots' drying disintegrates plant tissue and destroys cellular departments. As a consequence, valuable substances can be brought into contact with other raw material components and may bedecomposed [9]. Particularly, carotenoids in carrots are subjected to rapid decomposition in the presence of oxygen, with concurrent loss of color. Carrots exhibit browning during drying and subsequent storage [10].

Since the drying is a non-linear, dynamic, unsteady, and complex process, it needs to be monitored with care, since the process can lead to different levels of quality loss, depending on various factors. Throughout the entire drying process, product quality monitoring is essential because it will affect the decision-making process of proper drying strategies selection and development. The data is needed to develop non-invasive quality measurements for intelligent drying systems [11, 12].

Mathematical models of the drying processes are used for designing new, improving existing or controling drying processes and systems. Many mathematical models have proposed to describe the carrots' drying process, of them thin-layer drying models have been widely in use. These models can be categorized as theoretical, semi-theoretical, and empirical [13]. Semi-theoretical models are often easy to use and valid within the temperature, relative humidity, air velocity and moisture content range for which they are developed. Drying kinetics and model parameters are generally affected by drying air temperature, velocity and material size [14].

Mathematical modelling of carrots' drying kinetics and quality paramters would provide significant data base that could be of practical use for the drying industry. Hence, this research aims to investigate and develop mathematical models of the thin layer convective dehydration parameters (hot air dehydration temperature and the sample slice thickness) influence on drying kinetics parameters, chemical composition, and color parameters of carrot slices.

Materials and methods

Materials

Carrots (*Daucus carota* L.) were collected at the location of the Paracin area (co-ordinates 43°49'57.7"N 21°23'20.3"E, Republic of Serbia), and stored in a refrigerator at 4 °C. The convective drying kinetic was based on mass losses of carrot slices [15, 16].

Methods

Carrot thin layer convective dehydration process

Convective thin layer dehydration of carrot slices (thickness of carrot slices 3 mm, 6 mm, and 9 mm) was conducted in the vertical laboratory dehydrator (Colossus CSS 5330 250W PRC, constant hot airspeed 3 m/s and atmospheric pressure) at 35 °C, 50 °C, and 70 °C with a mass load of 3 kg/m^2 (240 g of carrot slices per single 320 mm diameter tray), to the constant weight. The dehydrated slices were cooled down for 15 minutes and stored in air-glass jars. Before each dehydration process, carrots were taken out of the refrigerator, washed with cold water (10-12 °C), placed at the ambient temperature for a couple of hours to stabilize, and cut into slices [17]. The drying experiment was replicated three times at each dehydration temperature and slice thickness, and average values are reported.

Determination of moisture content

Moisture content on carrot slices was determined according to AOAC [18].

Modelling of carrot thin layer convective dehydration process

The mass transfer during the convective drying process was isothermal. The primary water mass transfer mechanism was diffusional, without considering the material deformations and shrinkage during the drying process [7, 14]. Semi theoretical modelling of carrots' thin-layer dehydration process is characterized by the temperature of dehydration process, relative humidity, (hot) airspeed, moisture content, material thickness, size, and ability to determine moisture diffusivity while the fit of moisture ratio (MR) *vs.* drying time [14]. The water loss (moisture ratio) could be applied and simplified to M_t/M_0 instead of the $MR = (M_t - M_e)/(M_0 - M_e)$, because equilibrium moisture content M_e usually is deficient and can be deleted, without a significant change in MR. The M_t and M_0 are the moisture content achieved after dehydration time t and the initial moisture content.

Determination of effective moisture diffusivity

Moisture transfer from carrot slices was described by applying Fick's diffusion model, and effective moisture diffusivity, D_{eff}, was calculated. The calculation model according to the product geometry (slices) were given [7, 19]:

$$MR = A_1 \sum_{i=1}^{\infty} \frac{1}{J_0^2} \mathrm{e}^{\frac{J_0^2 D_{\mathrm{eff}}}{A_2}} \tag{1}$$

$$A_1 = \frac{8}{\pi^2}, \ A_2 = 4L^2 \tag{2}$$

where D_{eff} [m^{2}s^{-1}] is the effective moisture diffusivity, t [s] – the time, J_0 – the roots of the Bessel function, A_1, A_2 are the geometric constants, and L is the thickness of the potato slice when dehydration process occurred through only one side of carrot slices. For the constant values of D_{eff} and for sufficiently long drying times, the previous equations could be simplified into linear equation $\ln(MR) = \ln(a) - kt$. The function $\ln(MR)$ *vs.* t is linear, and the slope is equal to the constant drying k, and the effective moisture diffusivity could be easily calculated [19]:

$$k = -\frac{\pi^2 D_{\text{eff}}}{A_2} \tag{3}$$

where D_{eff} mainly varies with internal conditions such as the product's temperature, the moisture content, and the structure and external conditions such as drying air velocity, mass load, and the slice thickness [19, 20].

Determination of activation energy

The effect of temperature is one of the strongest factors that affect D_{eff} [19]. An Arrhenius equation, eq. (4), could generally describe this effect:

$$D_{\text{eff}} = D_0 \mathrm{e}^{-\frac{E_a}{\mathrm{R}\,T}} \tag{4}$$

where E_a [kJmol^{-1}] is the activation energy, R [8.3143 Jmol^{-1}K^{-1}] – the universal gas constant, T [K] – the absolute air temperature, and D_0 [m^{2}s^{-1}] – the pre-exponential factor of the Arrhenius equation. The E_a shows the sensibility (the necessary energy required to begin the water diffusion) of the diffusivity against temperature; the greater E_a means more sensibility of D_{eff} to temperature [20-22]. The previous equations could be simplified into linear equation $\ln(D_{\text{eff}}) = \ln(D_0) - 10^{-3}k[1/(T + 273.15)]$. The E_a was calculated from the slope of the Arrhenius equation:

$$k = -\frac{E_a}{\mathrm{R}} \tag{5}$$

Determination of proteins and cellulose

Total proteins, *TP*, and cellulose, *TC*, of fresh and dehydrated carrot slices were determined according to the official methods of AOAC [23, 24].

Color analysis

The fresh and the dehydrated color of carrot slices were optimized using a tri-stimulus color meter type CR-400 (Konica, Minolta, Tokyo, Japan) with D65 illuminant. The color parameters were expressed as per the CIELab system in terms of co-ordinates: L^* is the lightness (0 – black to 100 – white), a^* – the redness ($-a^*$ – green to $+a^*$ – red), and b^* – the yellowness ($-b^*$ – blue to $+b^*$ – yellow). The experimental analysis was implemented under constant lighting conditions, at 28 °C, using a color attribute of white control plate, $L^* = 98.76$, $a* = -0.04$, and $b^* = 2.01$ [25].

Statistical analysis of carrot thin layer convective dehydration process

Analysis of variance (ANOVA) and response surface methodology (RSM) were used to model the process variables (dehydration temperature and carrot slice thickness) on the carrot thin-layer convective dehydration process [25]. The independent variables were dehydration temperature of 35 °C, 50 °C, 70 °C and carrot slices, 3 mm, 6 mm, and 9 mm thickness, for dehydration process ($X_{1\text{-}2}$). The dependent variables were dehydration time (t, $Y_{1\text{-}3}$), activation energy (E_a, $Y_{4\text{-}6}$), and coefficient of diffusion (D_{eff}, $Y_{7\text{-}9}$). The following second-order polynomial (SOP) model was embedded into experimental models:

$$Y_k = \beta_{k0} + \sum_{i=1}^{2} \beta_{ki} X_i \sum_{i=1}^{2} \beta_{kii} X_i^2 + \beta_{kij} X_i X_j, \;\; k = 1\text{-}7 \tag{6}$$

where β_{kij} is the constant regression coefficients. The evaluations of ANOVA (Tukey HSD Test) and RSM analyses of experimental results were accomplished using STATISTICA 12.0 [26] software to estimate any statistically significant difference at a confidence level of 95% ($p < 0.05$).

Results and discussion

The effects of hot air dehydration temperature and the carrot slice thickness on the drying kinetics during thin layer convective drying in the range 35-70 °C were investigated.

The initial moisture content of carrots was about 86.11-86.61 %, tab. 1.

The dominant mechanism in the falling dehydration rate (moisture removal) from vegetables and fruits is diffusion. The diffusion rate is directly proportional to the concentration gradient and surface/geometric area. It depends on the moisture content and the nature of the dehydrated material, including the dehydration parameters (temperature, airspeed, the thickness of materials, mass load*, etc.*) [20, 27, 28]. The shortest dehydration time of carrot slices had the model with the 3 mm of thickness, dehydrated on the temperature of 70 °C (231 ±18 minutes), unlike the longest dehydration time of carrot slices with the 9 mm thickness, dehydrated on temperature 35 °C (934 minutes). Aghbashlo *et al.* [27] showed that one of the main factors influencing the dehydration process of carrots is the air temperature.

Table 1. Thin layer convective dehydration parameters of carrot slices

d [mm]	T [°C]	M_0 [%]	t [minute]	D_{eff} [m^{2}s^{-1}]	E_a [kJmol^{-1}]
3	35	86.11 ±0.94^{a}	645 ±47^{c,d}	$2.04 \cdot 10^{-08}$ ±$4.69 \cdot 10^{-09d}$	31.31 ±4.55^{a}
	50	86.61 ±1.84^{a}	442 ±31^{b}	$4.78 \cdot 10^{-08}$ ±$4.14 \cdot 10^{-09a}$	
	70	86.60 ±1.23^{a}	231 ±18^{a}	$7.12 \cdot 10^{-08}$ ±$3.80 \cdot 10^{-09b}$	
6	35	86.11 ±0.94^{a}	813 ±61^{e,f}	$4.24 \cdot 10^{-08}$ ±$7.91 \cdot 10^{-09a}$	29.02 ±3.55^{a}
	50	86.61 ±1.84^{a}	542 ±44^{b,c}	$1.02 \cdot 10^{-07}$ ±$6.66 \cdot 10^{-09c}$	
	70	86.60 ±1.23^{a}	427 ±26^{b}	$1.36 \cdot 10^{-07}$ ±$5.92 \cdot 10^{-09e}$	
9	35	86.11 ±0.94^{a}	934 ±80^{f}	$8.87 \cdot 10^{-08}$ ±$9.59 \cdot 10^{-09b,c}$	28.51 ±1.94^{a}
	50	86.61 ±1.84^{a}	726 ±67^{d,e}	$2.37 \cdot 10^{-07}$ ±$8.53 \cdot 10^{-09f}$	
	70	86.60 ±1.23^{a}	613 ±34^{c,d}	$2.83 \cdot 10^{-07}$ ±$7.48 \cdot 10^{-09g}$	

$^{a\text{-}g}$ Different numbers in superscript in the same table column indicate on the statistically significant difference between values, at a significance level of $p < 0.05$

A mechanism of diffusion controls the dehydration process. The experimental values of effective moisture diffusivity, D_{eff}, are presented in tab. 1. By increasing the dehydration temperature and the carrot slice thickness, the values for D_{eff} were statistically significantly ($p < 0.05$) increased. Similar results were presented in Botelho *et al.* [29]. In the research of Doymaz [7], as the thickness of carrot cube slices was increased, the diffusion path was increased. Carrot slices of 9 mm thickness dehydrated on the temperature of 70 °C had the highest resistance to mass transfer (the maximum $D_{\text{eff}} = 2.83 \cdot 10^{-07}$ m^2/s). Aghbaslo *et al.* [27] also showed that the highest D_{eff} ($8.98 \cdot 10^{-7}$ m^2/s) had the experimental models of carrot convective thin layer dehydration model, dehydrated on 70 °C and the hot air speed 1.5 m/s. The D_{eff} values are not exclusively a function of the dehydration parameters but also of the carrot variety [10]. Larger effective diffusivities were obtained at higher material thicknesses and high airspeed [30].

High activation energy, E_a, values are related to materials in which water is more strongly bound to the structure, and the samples' structure carries out water removal [31]. In different researches the activation energy of carrot thin layer convective dehydration was about: 28.26 kJ/mol [14] and 29.09 kJ/mol [29]. Increasing the carrot slice thickness and the dehydration temperature, the E_a was decreased without statistical significance ($p < 0.05$). The highest E_a had the experimental models of carrot slices with 3 mm thickness (E_a: 31.31 kJ/mol). Gomez-Daza and Ochoa-Martínez [30] reported the value of E_a (35.50 kJ/mol) because of using different equipment and different processing conditions. The carrot pomace had a lower E_a (17.96-23.05 kJ/mol) [32], while Aghbashlo *et al.* [27] showed that increasing the airspeed from 0.5-1.5 m/s, varied E_a values from 23.02-28.10 kJ/mol.

The TP and TC and color parameters of different dehydrated carrot slices are given in tab. 2. The TP and TC of the fresh carrot slices were: 8.02 and 6.76% dry basis, db, respectively.

An increase in the temperature of the thermal treatment and the warm air-flow speed can more intensively disrupt the cell membrane and increase the protein content [33]. The TP of carrot slices treated with different dehydration parameters were statistically significantly different ($p < 0.05$), tab. 2. The highest protein content (7.91% db) was found for the carrot slices subjected to the highest dehydration temperatures of 70 °C and the lowest carrot slice thickness of 3 mm. The lowest protein content (5.26% db) was found for the carrot slices dehydrated at the lowest temperature (35 °C) and the highest carrot slice thickness of 9 mm. Increasing the dehydration temperature, the TP was statistically significantly increased and increasing the carrot slice thickness, TP was statistically significantly decreased, probably due to statistically significantly longer drying duration. Similar experimental results were found in Teferra *et al.* [33] research, unlike the TP was lower because of the lower TP in fresh carrot slices. However, TP recorded for the fresh carrot was generally higher than the dehydrated. The loss could be due to the washing of carrots before the cutting process and variation in sensitivity of specific protein components to the dehydration parameters.

Table 2. Thin layer convective dehydration parameters of chemical composition and color parameters

d [mm]	T [°C]	TP [% db]	TC [% db]	L^*	$+a^*$	$+b^*$
3	35	$7.78 \pm 0.15^{b,c}$	6.08 ± 0.12^{a}	$56.29 \pm 0.73^{d,e}$	29.27 ± 0.35^{a}	42.24 ± 0.49^{c}
	50	$7.82 \pm 0.15^{b,c}$	6.14 ± 0.12^{a}	59.88 ± 0.84^{f}	$33.55 \pm 0.62^{c,d}$	44.37 ± 0.55^{d}
	70	7.91 ± 0.13^{c}	$6.53 \pm 0.13^{a,b}$	61.10 ± 0.88^{g}	32.82 ± 0.68^{c}	45.28 ± 0.59^{f}
6	35	6.41 ± 0.13^{d}	6.18 ± 0.15^{a}	52.41 ± 0.43^{c}	$30.45 \pm 0.45^{a,b}$	40.11 ± 0.45^{b}
	50	6.87 ± 0.12^{e}	$6.28 \pm 0.15^{a,b}$	55.00 ± 0.75^{d}	35.97 ± 0.69^{e}	42.11 ± 0.50^{c}
	70	7.43 ± 0.17^{b}	$6.66 \pm 0.16^{a,b}$	57.65 ± 0.74^{e}	$34.96 \pm 0.93^{d,e}$	44.22 ± 0.54^{d}
9	35	5.26 ± 0.11^{a}	6.21 ± 0.18^{a}	49.70 ± 0.55^{a}	$31.72 \pm 0.46^{b,c}$	38.47 ± 0.40^{a}
	50	6.32 ± 0.12^{d}	$6.32 \pm 0.19^{a,b}$	$50.12 \pm 0.50^{a,b}$	36.42 ± 0.76^{e}	40.63 ± 0.37^{b}
	70	6.98 ± 0.13^{e}	6.72 ± 0.20^{b}	$51.14 \pm 0.56^{a,b,c}$	$35.25 \pm 0.84^{d,e}$	42.87 ± 0.32^{c}

$^{a-f}$ Different numbers in superscript in the same table column indicate on the statistically significant difference between values, at a significance level of $p < 0.05$

The TC of different thickness of carrot slice subjected to different dehydration temperatures had no statistically significant variation in results ($p < 0.05$, tab. 2). The experimental results showed that the dehydration parameters did not rapidly degrade the cell membranes of carrot slices and increased the TC as the TP was increased.

Thermal dehydration affects food quality, such as color, and is generally observed. Due to the larger exposed surface, a slab-shaped carrot slice exhibits a high accuracy as far as color measurement is concerned [34]. The acceptability of dehydrated fruits and vegetables by consumers largely depends on their color. The color values (L^*, $+a^*$, and $+b^*$) of the fresh carrot slices were 49.57, 20.41, and 26.97, respectively, and for the dehydrated slices with different dehydration parameters, there were statistically significant differences in values ($p < 0.05$), tab. 2. Increasing the dehydration temperature, at the constant carrot slice thickness, the dehydrated carrot slices were lighter, more reddish, and yellowish. Unlike the thickness growth, the dehydrated carrot slices were darker, more reddish, and less yellowish at the constant dehydration temperature. The lightest and the darkest pattern were the dehydrated models of carrot slices of 3 mm thickness, with the dehydration temperature of 70 °C ($L^*_{max} = 61.10$), and 9 mm thickness with the dehydration temperature of 35 °C ($L^*_{max} = 49.70$), respectively. These experimental results could be related to oxidative reactions during the dehydration process, which was reinforced by dehydration hot air temperature and/or the dehydration duration [7].

As shown in tab. 2, in the slice thickness of 3, 6, and 9 mm, the experimental models showed a continuous trend of statistically significant L^* growth with temperature growth, the same as in the experimental models of Aversa *et al.* [34] and Krokida *et al.* [35]. An increase of $+a^*$ and a variation of $+b^*$ in analyzed experimental models were due to the presence of carotenoids, especially β-carotene, as Sumnu *et al.* [36] confirmed. Also, it may be due to the degradation of carotenoid pigments, non-enzymatic Maillard browning, and the formation of brown pigments [37]. The hot air could increase the color reactions and degradation and accelerate the Maillard browning reactions if the material has been exposed to heat treatment long enough [7]. All the color parameters were significantly affected by the variation during the dehydration process [10].

The RSM was chosen to develop mathematical models of dehydration parameters, chemical composition, and color parameters of carrot slices during convective drying at varying process parameters of dehydration temperature and carrot slice thickness.

Table 3 shows the results of response surface models ANOVA.

Table 3. The ANOVA of dehydration parameters, chemical composition, and color parameters

<table>
<tr><th colspan="2" rowspan="2">Termq</th><th rowspan="2">df^1</th><th rowspan="2">t</th><th rowspan="2">D_{eff}</th><th colspan="5">Sum of squares</th></tr>
<tr><th>TP</th><th>TC</th><th>L^*</th><th>$+a^*$</th><th>$+b^*$</th></tr>
<tr><td rowspan="2">Temperature</td><td>Linear</td><td>1</td><td>209440.2*</td><td>$1.91 \cdot 10^{-14*}$</td><td>4.08*</td><td>0.04</td><td>18.76*</td><td>22.39*</td><td>22.23*</td></tr>
<tr><td>Quadratic</td><td>1</td><td>8968.1*</td><td>$1.77 \cdot 10^{-15}$</td><td>0.10</td><td>0.01</td><td>0.08</td><td>20.06*</td><td>0.40</td></tr>
<tr><td rowspan="2">Thickness</td><td>Linear</td><td>1</td><td>153704.1*</td><td>$3.80 \cdot 10^{-14*}$</td><td>1.48*</td><td>0.22*</td><td>100.48*</td><td>9.97*</td><td>16.02*</td></tr>
<tr><td>Quadratic</td><td>1</td><td>40.5</td><td>$1.96 \cdot 10^{-15}$</td><td>0.01</td><td>0.02</td><td>0.00</td><td>0.77</td><td>0.05</td></tr>
<tr><td colspan="2">Cross product</td><td>1</td><td>2380.1</td><td>$4.76 \cdot 10^{-15}$</td><td>0.62*</td><td>0.01</td><td>3.40</td><td>0.00</td><td>0.50</td></tr>
<tr><td rowspan="2">Error</td><td>Residual variance</td><td>3</td><td>2186.5</td><td>$1.52 \cdot 10^{-15}$</td><td>0.04</td><td>0.04</td><td>4.75</td><td>0.51</td><td>0.20</td></tr>
<tr><td>Total sum of squares</td><td>8</td><td>369332.0</td><td>$6.48 \cdot 10^{-14}$</td><td>6.14</td><td>0.33</td><td>126.01</td><td>50.52</td><td>39.45</td></tr>
<tr><td colspan="3">R^2</td><td>0.994</td><td>0.977</td><td>0.993</td><td>0.975</td><td>0.962</td><td>0.990</td><td>0.995</td></tr>
</table>

* Statistically significant at level of significance of $p < 0.05$; [1] df – degrees of freedom

Models were developed based on experimental results of dehydration parameters: *t*, D_{eff}; chemical composition parameters: TP, TC and color parameters L^*, $+a^*$, $+b^*$. Based on these results, statistically significant independent variables (dehydration temperature and carrot slice thickness) and their interactions on mathematical model responses were analyzed.

The SOP in the form of eq. (6) for seven responses in RSM is used.

Based on ANOVA testing of analyzed responses presented in tab. 3, it can be seen that values of dehydration parameters, (*t* and D_{eff}), were both statistically significantly influenced by both independent variables, where the more dominant factor was the temperature of hot air. In both dehydration parameters of both linear terms and quadratic term for temperature statistically significantly contributed to the model forming. Together with a high coefficient of correlation, R^2, minor residual variance indicated the excellent fitting of the developed model to the experimental results. Trends of the effects of both independent variables on dehydration parameters can be visualized on graphical presentations of developed mathematical models presented on figs. 1(a) and 1(b).

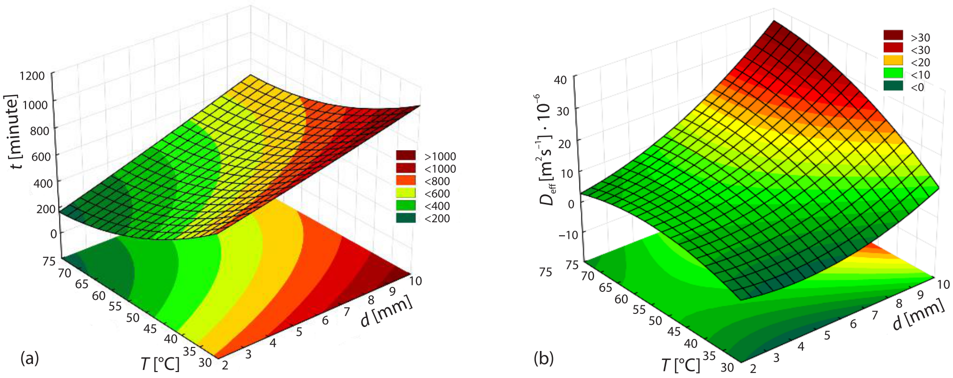


Figure 1. Graphical presentation of modeled dependence of; (a) dehydration time and (b) effective moisture diffusivity from dehydration temperature and carrot slice thickness

The ANOVA test showed that TP values were statistically significantly affected by both independent variables, while in the case of TC, only carrot slice thickness statistically significantly influenced the mathematical model. Together with the cross-product term, both linear terms were statistically significant in the case of the TP model. In contrast, in the TC model, the only linear term for carrot slice thickness was statistically significant. In both chemical composition parameters, the residual variance was statistically insignificant, and R^2 was high. Trends of the effects of dehydration temperature and carrot slice thickness on chemical composition can be visualized on graphical presentations of developed mathematical models presented on figs. 2(a) and 2(b).

The ANOVA testing of color parameters showed that both independent variables statistically significantly influenced developed mathematical models in cases of all three responses. Both linear terms for all three-color responses were statistically significant, while in the case of $+a^*$, the quadratic term for temperature was also statistically significant. As in previous cases, residual variances were statistically insignificant for all developed models, and R^2 values were high. Effects of both independent variables on color parameters can be followed on graphical presentations of developed mathematical models presented on figs. 3(a) to 3(c).

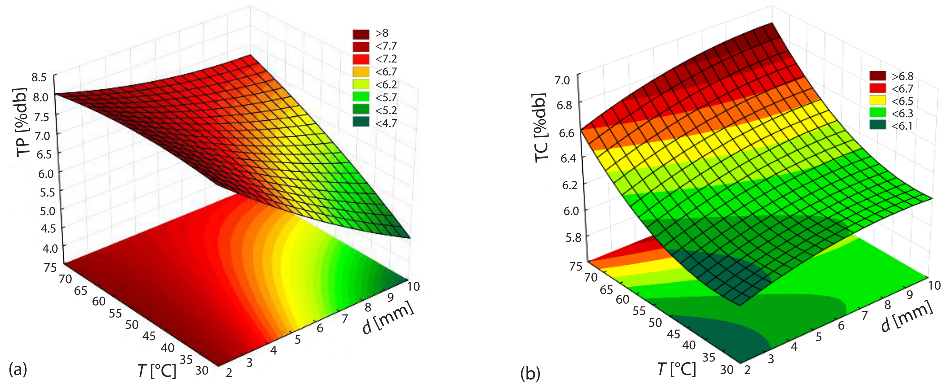
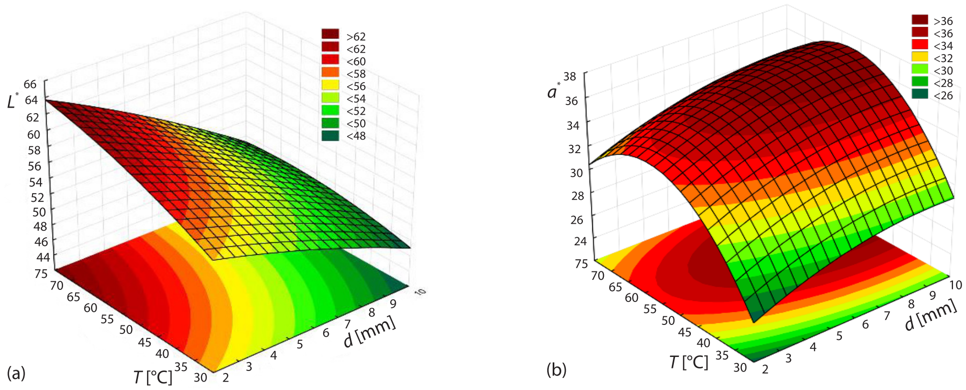


Figure 2. Graphical presentation of modeled dependence of; (a) total protein content and (b) total cellulose content from dehydration temperature and carrot slice thickness



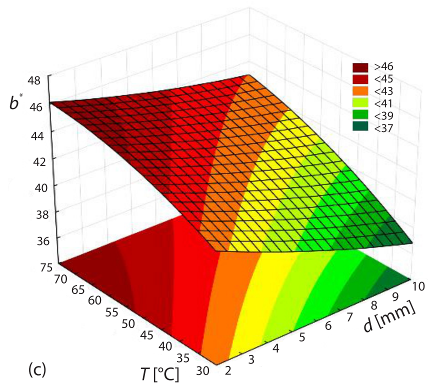


Figure 3. Graphical presentation of modeled dependence of; (a) lightness, (b) redness, and (c) yellowness from dehydration temperature and carrot slice thickness

Table 4 shows regression coefficients of seven-second order polynomial models of dehydration parameters, chemical composition, and color parameters of carrot slices during the process of convective drying. Statistical significance of individual coefficients is also shown.

Regression coefficients can be used for completing quadratic equations, which describe mathematical models of selected responses of carrot slices during the process of convective drying.

Table 4. Regression coefficients of SOP of dehydration time, the effective moisture diffusivity, activation energy, chemical composition, and color parameters of thin layer convective dehydration of carrot slices

	t	D_{eff}	TP	TC	L^*	$+a^*$	$+b^*$
β_0	1559, 938*	$-1.5484 \cdot 10^{-07}$	12.5564*	6.5593*	50.35503*	–4.0788	38.7115*
β_1	–36.971*	$9.7432 \cdot 10^{-09}$	–0.1712*	–0.0146	0.28644	1.2243*	0.2260*
β_{11}	0.224*	$-9.9549 \cdot 10^{-11}$	0.0008	0.0002	–0.00068	–0.1006*	–0.0015
β_2	23,131	$-4.9561 \cdot 10^{-08}$	–0.1713	–0.0916	–0.39426	1.2743	–1.1164*
β_{22}	0.500	$3.4790 \cdot 10^{-09}$	–0.0046	0.0111	0.00204	–0.0691	0.0182
β_{12}	0.463	$6.5492 \cdot 10^{-10}$	0.0075*	0.0004	–0.01898	–0.0003	0.0067

* Statistically significant at $p < 0.05$ level

Solving these equations with input values of independent variables (dehydration temperature and carrot slice thickness), values of desired responses can be calculated. In that way values of dehydration parameters, chemical composition, and color parameters can be predicted in the ranges of values of independent variables for which mathematical models were developed. Perspective in terms of future research work could be an increase the efficiency of the process of drying, *e.g.*, by the implementation of the other drying methods, such as osmotic dehydration and/or microwave drying, and lyophilization), which may affect the color of the dried carrot slices and chemical composition simultaneously.

Conclusion

The drying parameters (the thickness and the temperature) statistically significantly ($p < 0.05$) affect the thin-layer convective drying of carrot slices. Carrot slices with thicknesses of 3 mm, 6 mm, and 9 mm were dehydrated as monolayers at different drying temperatures (35 °C, 50 °C, 70 °C). Experimental results could be applied in both industrial and domestic drying conditions. The most efficient drying model, in terms of shorter drying time (231 minutes), was a model with the minimum thickness (3 mm) and the maximum drying temperature (70 °C), which will have the minimum resistance to mass transfer (the minimum effective moisture diffusivity, $2.04 \cdot 10^{-08}$-$7.12 \cdot 10^{-08}$ m^2/s), and the average maximum energy demand to initiate start the water diffusion from the internal areas to the surface of the dehydrated material (31.31 kJ/mol). Unlike the efficiency of the drying process, the most optimal drying model in terms of chemical composition and color parameters of carrot slices was the model with the maximum thickness (9 mm) and the minimum drying temperature (35 °C); this model had the longest dehydration time (934 min), the maximum resistance to the mass transfer ($8.87 \cdot 10^{-08}$ m^2/s), the minimum total protein content (5.26 %), and the darkest color (49.70). The predicted and observed responses had a good correlation, allowing good prediction of the quality responses based on the drying temperature and the carrot slice thickness. The obtained experimental results could be used to increase the efficiency of the process of drying, *e.g.*, by the implementation of the other drying methods, such as osmotic dehydration and/or microwave drying), which may at the same time affect the color of the dried carrot slices and chemical composition.

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