INFLUENCE OF VARIABLE TEMPERATURE DRYING ON RED BEETROOT CHIPS DRYING KINETIC PARAMETERS AND SPECIFIC ENERGY CONSUMPTION

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In this work, the influence of variable temperature drying, mass of the samples, and the blanching pretreatment were varied to determine the influence of these parameters on the kinetics and specific energy consumption of red beetroot chips during convective drying. Beetroot samples used for the analysis were fresh and blanched slices of 5mm thickness. Three different temperature regimes were used during drying experiments: first regime (I) was drying at a constant temperature of 70°C, second regime (II) was performed with two-stage drying at temperatures of 80°C and 55°C, and third regime (III) was conducted with three-stage drying at temperatures of 80°C, 60°C, and 55°C, respectively. Results obtained from the experiments were analyzed from the aspects of equilibrium moisture content, drying time, specific energy consumption and drying kinetics including determination of effective moisture coefficient. It was concluded that stage drying strongly affects equilibrium moisture content, while blanching pretreatment increases initial moisture content. The drying time was strongly dependent on the initial mass of the samples, while the energy consumption was depended, besides on the mass, also on drying regime, and it was found to be smallest for two-stage drying. Visually, beetroot had the typical red color for all samples at the beginning, with notable shrinkage effect at the end of the drying process.

Key words: drying kinetics, beetroot chips, variable temperature drying, moisture content

1. Introduction

Nutrition habits of modern man impose new criteria in food production and preservation. In order to reduce the use of fast food, more and more natural and organic products can be found on the market labeled healthy food or "functional food" [1]. One of such products, which is increasingly attracting the attention of consumers, are healthy snacks in the form of chips from dried fruits and vegetables. This type of product has an advantage primarily because it doesn't involve standard methods of heat treatment such as frying, cooking and baking and compared with standard snacks has lower caloric value and total fat content.

Many researchers have studied the kinetics of drying and evaluated the quality of fruit and vegetable chips. Most research works are related to apple and potato chips drying and characterization. However, beetroot is one of the recognized functional foods known for its antioxidant properties, high content of beta-carotene, calcium and iron, and other essential components such as vitamins, minerals, phenolics, carotenoids, nitrate, ascorbic acids and betalains that are beneficial for human health [1,2].

1.1. Beetroot drying

Convective drying in hot air at constant temperature is still the most popular method used to reduce the moisture content of fruit and vegetable chips [3], [4], including beetroot. However, this method requires relatively long times and high air temperatures, which causes degradation of important nutritional substances, as well as color alteration [5]. Also, during convective drying there is a pronounced shrinkage of the material, which is a result of tissue collapse caused by volume reduction due to the loss of moisture.

Regarding the methods used for the beetroot drying, several investigations have been performed recently, including convective drying [6-9], natural convection drying [10], vacuum drying [11,12], microwave drying [13,14], ultrasound drying [15], freeze and heat pump drying [11], as well as hybrid drying by combining different drying methods: ultrasound- and microwave-assisted convective drying [15-17] and microwave-vacuum drying [12-14].

The pretreatment methods used prior to drying process of the beetroot comprise the effect of the pulsed electric field (PEF) [18], ultrasound and osmotic dehydration [19] and blanching [9]. Blanching as a pretreatment is used to reduce drying time and increase shelf life by inactivating the enzymes that deteriorate the material during storage [20]. Moreover, blanching removes air from the intercellular spaces and also modifies the mechanical properties [9].

1.2. Two- and three- stages drying

Drying in two or more stages, also known as Variable Temperature Drying (VTD) [21] is the drying process during which the temperature of the drying medium (commonly hot air) is changed. The temperature is changed either at specific time intervals [22], after a certain amount of the moisture has been removed, or according to some other criteria, such as sample temperature or sample's area ratio [23]. This type of drying could potentially reduce the drying time and energy consumption, thus positively impacting overall energy efficiency of the process [24]. For convective drying with the hot air as a medium, there are several publications available in the literature dealing with VTD of fruit and vegetable. In [24], slices of mangoes 5mm thick were dried in two stages, the first stage at temperature 95 or 80^{o}C for 40 min, and the second stage at 60 or 70^{o}C until the samples' final moisture content of about 8,68%. In [25] cantaloupe slices of 5 mm thickness were dried convectively in two-stage process at 80^{o}C in the first stage until the reduction of a moisture content by 50%, and then at 50, 60 or 70^{o}C until the end of the measurements. In [23] ginseng root was dried in three stages: first stage at 38^{o}C until samples' area ratio (AR) was reduced to 0.70, second stage at 50^{o}C until AR reached 0.5, and then third stage again at 38^{o}C until the end of the measurements. In [26], a three-stages drying of osmotically pretreated green peas was performed in convective tray dryer at air temperatures of 70^{o}C for 180 min in the first stage, then at 60^{o}C for next 120 min, and finally, the third stage at 50^{o}C until the moisture content of the samples fell to 10%$_{wb}$. In [27] two-stage drying of onions was performed with the first stage being drying at 85°C until the breakpoint (defined by sample temperature) and then the second stage at 75, 65 or 55°C till reaching the final moisture content of 7%.

As it can be seen from the literature review, drying process with variable temperature regimes of several fruits and vegetables have been investigated, however none of the articles have analyzed the drying of the beetroot chips. In this work, the influence of blanching pretreatment with two- and three-stage drying of beetroot thin slices (chips) was examined in order to determine the influence of variable temperature drying on drying kinetics of the beetroot. The novelty of this paper lies in VTD of beet root chips, which is common in commercial industrial drying, but in scientific papers, according to the authors' best knowledge, has not been investigated. Application of VTD and blanching pretreatment might reduce the chemical, physical, and biological changes that occur during long-lasting convective drying. Also, VTD could potentially reduce the energy consumption of the drying process.

2. Material and methods

2.1. Material

The beetroot (Detroit 2 cultivar) used in this study were obtained from an orchard in region Vojvodina, Serbia. Initially, samples are stored in a refrigerator at 5°C, and after a stabilization period at room temperature, samples of uniformed sizes were selected, peeled and cut to 5 mm thickness disc-shaped slices. The initial mass of the samples ranged from 61.62 g to 140.94 g, and on average, it was greater for the blanched samples. The initial moisture content of the beetroot samples was determined gravimetrically by standardized method of drying at 105°C for 12h.

All samples were divided into two groups. The first group comprised fresh samples without pretreatment and the second group consisted of blanched samples. Blanching pretreatment involved immersing the samples in hot water at about 95°C for 2 minutes and cooling them to a room temperature.

2.2. Drying equipment

For the purposes of the experiments, the experimental dryer shown was used. The experiments were carried out in drying chamber, shown in Figure 1. The hot air temperature is measured and regulated by the PID thermoregulator, and the temperature sensor was positioned just before the hot air reaches the material. The material was placed on the tray, and the mass was measured every 5 min.

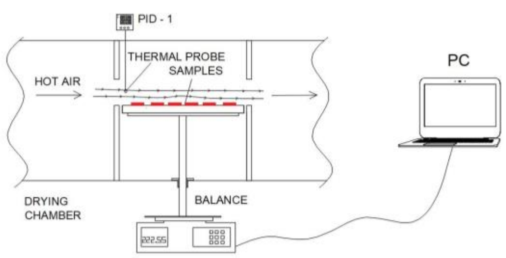

Figure 1. Schematic drawing of drying chamber

2.3. Experimental methods

Beetroot slices of 5 mm thickness (both with and without pretreatment) were dried by hot air (convective drying). The mass change of the material was recorded at intervals of 5 min with the balance placed beneath the drying chamber. The balance used was KERN & Sohn, KB 3600-2N with the accuracy of ±0.01 g. Hot air temperature was measured and regulated by the PID thermo-regulator (REX C-100) of accuracy ± 0.1 ^{o}C, thermocouple accuracy ± 0.1 ^{o}C. The air velocity was adjusted with frequency regulator attached to a fan and it was set to 2.5 m/s for all experiments. The velocity of the air was verified by the hot wire anemometer Airflow^{TM} TA35 with the accuracy of ±0.05 m/s.

Temperatures of the hot air during drying process were between 55 and 80 ^{o}C. The experiments were performed in two groups, the first one being without pretreatment, and the other with blanching pretreatment prior to drying. In each group of the experiments, three series of experiments were performed, including single-, two- and three-stage drying, which lead to the final number of 6 experiments. Single-stage continuous drying was performed at constant temperature of 70^{o}C throughout the drying process. Two-stage drying was performed at air temperature of 80^{o}C for the first 30 min and then at 55^{o}C till the end of the experiment. Three-stage drying was performed at air temperature of 80^{o}C for the first 30 min, then at 65 ^{o}C for the next 30 min and finally at 55 ^{o}C till the end of the experiment. Experiments were considered finished when the sample's mass did not change anymore. The experiments are numbered as presented in Table 1.

Table 1. Performed drying experiments

	Untreated samples			Blanched samples		
Drying regime (temperatures)	70	80-55	80-65-55	B-70	B-80-55	B-80-65-55
Experiment number	E1	E2	E3	E4	E5	E6

Based on the drying time, mass of the samples and knowing the characteristics of the experimental dryer (determined in [28]) the specific energy consumption for the each experiment was calculated. For the experiments with blanching (E4, E5 and E6) the specific energy consumption of the blanching pretreatment was negligible compared to energy required for drying, and thus was not included in the calculations.

3. Mathematical modeling of drying curves

Mathematical models, commonly used for fruit and vegetable drying, were used to describe the drying kinetics of red beetroot slices. Theoretical models imply set of differential equations taking into account internal moisture movement mechanisms, external conditions, and material properties and are thus challenging to solve. Therefore, drying curves were fitted to the simi-empirical models (Table 2). These models are derived either from the Fick's Second law of diffusion or Newton's law of cooling and the correlating parameters in the models take into account external conditions, such as hot air velocity, temperature, relative humidity, as well as internal mechanisms of moisture transport through the material.

Table 2. Drying models

Model	Equation	Ref.
Page	$MR = \exp\left(-kt^n\right)$	[29]
Wang and Sing	$MR = a \cdot t^2 + b \cdot t + c$	[30]
Modified Page Equation	$MR = \exp\left(-(kt)^n\right)$	[31]
Logarithmic	$MR = a \cdot \exp(-kt) + c$	[32]
Henderson and Pabis	$MR = a \cdot \exp(-kt)$	[33]

Moisture ratio (MR) values for beet root slices during the drying were calculated using Eq. 1:

$$MR = \frac{M_\tau - M_e}{M_o - M_e} \quad (1)$$

Where, MR, M_τ, M_e and M_o are the moisture ratio (dimensionless), the moisture content at any given time (kg water/kg dry matter), the equilibrium moisture content (kg water/kg dry matter) and the initial moisture content (kg water/kg dry matter), respectively.

The equilibrium moisture content (Me) presents the final moisture content a sample has at the end of the drying process. It depends on the type of material being dried and drying conditions, mainly air temperature and relative humidity. Therefore, it is of great importance to investigate the exact equilibrium moisture for each drying regime.

For experimental curve fitting, two different criteria were used for evaluation of the goodness of the fit: correlation coefficient - R^2 and chi-squared - χ^2. The most suitable model for describing drying characteristics of red beet root slices is a model with highest R^2 and lowest χ^2 values. The expressions for R^2 and χ^2 are given by the Eq. 2 and 3, respectively:

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - \overline{MR_{\exp,i}}\right)\left(MR_{pre,i} - \overline{MR_{pre,i}}\right)}{\sqrt{\sum_{i=1}^{N}\left(MR_{\exp,i} - \overline{MR_{\exp,i}}\right)^2 \sum_{i=1}^{N}\left(MR_{pre,i} - \overline{MR_{pre,i}}\right)^2}} \quad (2)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N - m} \quad (3)$$

$MR_{\exp,i}$, $MR_{pre,i}$, N and m in Eq. 2 and Eq. 3 present the experimental moisture ratio, predicted moisture ratio, the number of observation and the number of model constants, respectively.

The drying rate (DR) of beet root slices was calculated by equation (4):

$$DR = \frac{M_{\tau+d\tau} - M_\tau}{d\tau} \quad (4)$$

, where ($M\tau + d\tau$) is moisture content at time ($\tau + d\tau$) (kg water/ kg dry matter), $M\tau$ is moisture content at time τ (kg water/ kg dry matter) and τ is drying time (s).

3.1. Moisture diffusion coefficient

The drying of fruits and vegetables takes place in the falling rate period and therefore, it is widely accepted that diffusion is the main mechanism of moisture transport through material. In this case, the formulation of the second Fick's law can be used to describe the drying of agricultural products [34].

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} \tau}{4\delta^2} \right) \quad (5)$$

In order to determine the effective diffusivity coefficient D_{eff}, the experimental drying data of MR are plotted against time, i.e. in $ln(MR) - \tau$ diagram. The slope of the line can be expressed as:

$$k_0 = -\frac{\pi^2 D_{eff}}{4\delta^2} \quad (6)$$

Where δ represents the thickness of the sample.

Experimental data in $ln(MR)$-τ diagram can be approximated with a straight line using regression analysis tools. From the slope of the fitted straight line, the D_{eff} can be calculated from the Eq. 6. The D_{eff} was determined for each experiment, and for experiments with more than one drying stage, D_{eff} was determined for each stage.

4. Results and discussion

4.1. Initial and equilibrium moisture content

The initial moisture content (M_0) was 6.90 ± 0.01 kg water per kg dry matter (87.34 % wb) and 8.13 ± 0.01 kg water per kg dry matter (89.05 % wb) for the fresh and blanched beetroot slices, respectively. The equilibrium moisture content (Me) depended both on the drying regime and pretreatment, as shown in Table 3. The equilibrium moisture content (Me) ranged from 0.02 to 0.39 kg water per kg dry matter.

Table 3. Drying parameters

	Non-treated samples			Blanched samples		
	E1 (70)	E2 (80-55)	E3 (80-65-55)	E4 (B-70)	E5 (B-80-55)	E6 (B-80-65-55)
Average temperature [^{o}C]	70	59	62.2	70	58.3	59.2
Sample mass [g]	61.62	96.85	82.18	122.18	140.94	137.53
Initial moisture content (kg_w / kg_{dm})	6.90			8.13		
Equilibrium moisture content (kg_w / kg_{dm})	0.16	0.09	0.02	0.39	0.31	0.39

The equilibrium moisture content (Me) was significantly lower for non-treated samples in comparison to blanched samples. The value of Me of non-treated samples lied between 0.02 and 0.16

kg_w / kg_{dm}. The effect of variable temperature drying was noticeable. During continuous drying at 70 ^oC, the value of Me was the highest and gradually decreased with the number of drying stages. The samples with blanching pretreatment had the value of Me between 0.31 and 0.39 kg_w / kg_{dm}. The results indicated the blanching had a great influence on the final moisture content of beetroot slices. This pretreatment increases the Me value of the beetroot samples during drying process.

4.2. Drying time and specific energy consumption

Drying time strongly depended on the sample mass and drying regime. The shortest drying time was recorded for E1 (non-treated samples dried at constant 70^{o}C temperature), while the longest time was recorded for E6 (blanched samples three-stage drying), respectively 120 min and 250 min. Drying time was generally significantly longer for the experiments with greater sample mass. Average temperature during the experiments (shown in Table 3) was calculated by averaging the temperatures of each stage of drying, taking into account the duration of each stage. It can be seen that for both blanched and untreated samples, the drying time decreases with increase in average drying temperature. The specific energy consumption was directly dependent on drying time, but also on drying regime. The values of drying time and specific energy consumption for each experiment are given in Table 4.

Table 4. Drying time and specific energy consumption for beetroot chips drying

	Untreated samples			Blanched samples		
Drying regime (temperatures)	E1 (70)	E2 (80-55)	E3 (80-65-55)	E4 (B-70)	E5 (B-80-55)	E6 (B-80-65-55)
Drying time (min)	120	185	145	190	225	250
Specific energy consumption (MJ/kg)	161.9	128.8	145.1	124.6	102.9	125.3

As it could be seen from Table 4, the specific energy consumption was on average lower for blanched samples, which can be explained by the fact that treated samples had modified structure of the material, allowing for easier water removal. In addition, the two-stage drying regime with greatest temperature difference between stages proved to be the most efficient method of beetroot chips drying, as the specific energy consumption for this regime for both blanched and untreated samples was the lowest compared to one- and three-stage regimes. This means that abrupt change of the drying temperature causes internal stresses of the material, causing cell ruptures and increased transfer from intracellular to intercellular water, and hence easier water removal.

4.3. Drying kinetics

In Figure 2 all experimental MR – time curves (left) and all drying rate curves (right) with and without blanching pretreatment are presented. The experiments with untreated samples showed more response to the change of drying regimes. Namely, during two- and three-stage regimes, whenever there was a change of temperature there was also a noticeable difference in the slope of the drying curves. Maximum drying rate values were lower for blanched samples in comparison to untreated ones because of the initial mass of the samples, which was considerably greater for blanched samples.

However, the maximum drying rates and slope of the drying rate curves were almost identical for all blanched samples, regardless of the sample mass, indicating that blanching had strong influence on the character of the drying curves. Untreated samples had different maximum drying rates and character during drying.

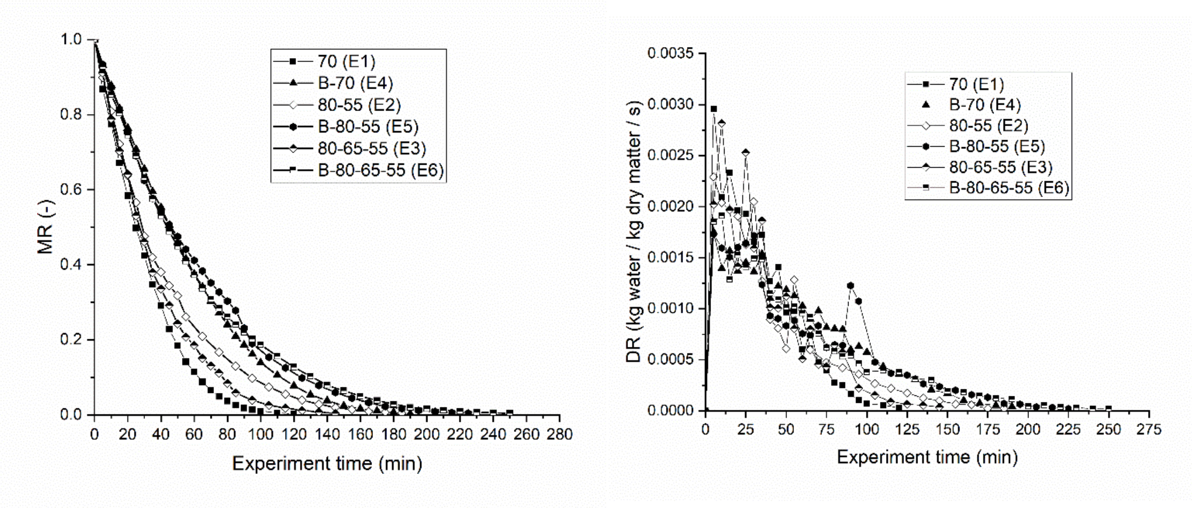

Figure 2. MR – time curves (left) and drying rate curves (right) for all experiments

From Fig. 2 (right) it can be clearly seen that drying takes place in a falling rate period. Single-stage drying of untreated samples showed faster moisture removal, and thus consequently higher maximal drying rate values in comparison to the blanched ones, as shown in Fig. 3. This is due to the mass of the samples, which was considerably higher for blanched samples.

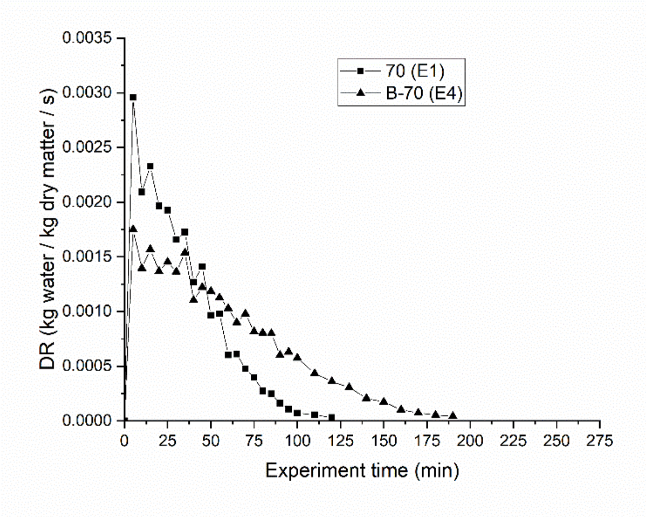

Figure 3. Drying rate of one-stage drying of blanched (70B) and untreated sample (70)

For two-stage regimes (80-55) the temperature difference between the first and second stage was significant. Consequently, we can identify three distinguishable drying periods, both with samples with pretreatment and without. First stage with temperature set to 80°C starts at the beginning of drying process and lasts 30 min, when the temperature is changed to 55 °C. The second stage starts immediately after the first stage, i.e. the change of the temperature. During the second drying stage, after 60 min and 90 min from the beginning of the drying for untreated and blanched samples, respectively, a change in the slope of the curves occurs (Fig. 4 left), which marks the beginning of the third phase which lasts until the end of the experiment. This change of slope of drying curves is a consequence of sudden significant decrease of drying temperature of 25°C (from 80°C to 55°C). This phenomenon could be explained by the buildup of the internal stresses within the samples. The change in drying temperature causes internal stresses in the beetroot chips samples, which consequently causes shrinkage of the samples. Shrinkage causes rupture of the tissue, allowing for more bound moisture to be exposed to the hot air. Complementary, the change in the slope of the MR-time curve reflects in abrupt increase of drying rate, as we can see in Figure 4 (right). There is a "spike" in DR-time curve at that moment of slope change for both blanched and not blanched samples.

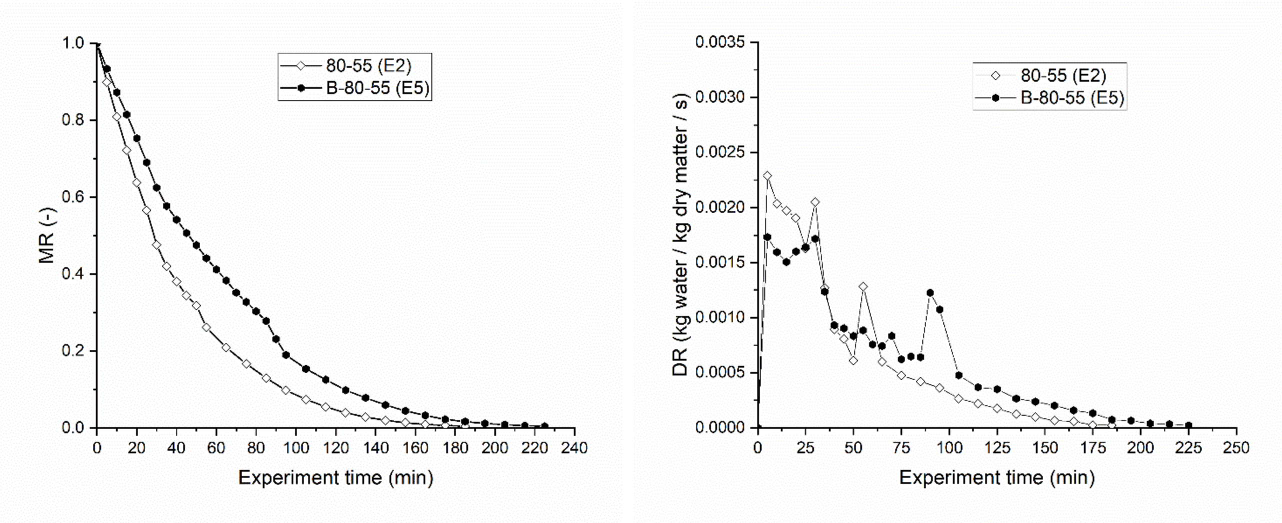

Figure 4. Two-stages drying MR-time curve (left) and Drying rate curve (right) for blanched and untreated samples

On the other hand, three-stage drying produced much "smoother" curves, especially if the samples were treated by blanching pretreatment (Fig. 5). The differences in temperatures between drying stages are smaller: 15°C between first and second stage (from 80 to 65 °C) and 10°C between second and third stage (from 65 to 55 °C), and consequently, the slope of the MR-time curves does not change severely and "spikes" at drying rate curves are much smaller.

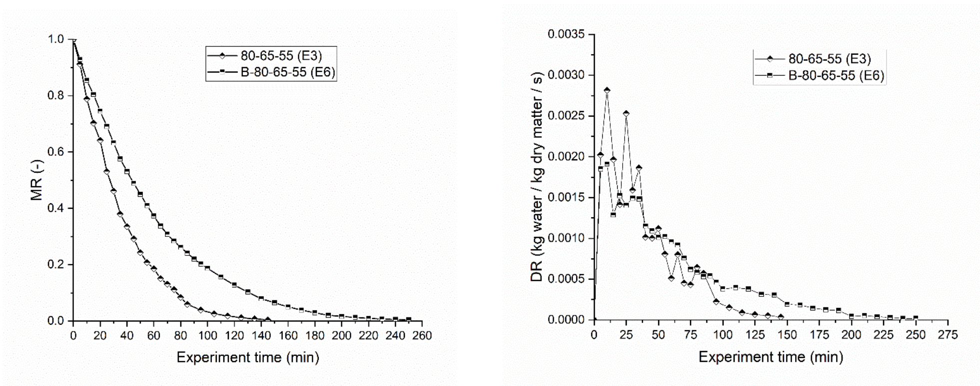

Figure 5. Three-stage drying (with and without blanching) MR-time curve (left) and DR curve (right)

4.4. Fitting the experimental curves with drying models

In order to find the best semi-empirical model to describe the process of drying beetroot chips, experimental results were fitted with a few mathematical drying models. The results are shown in Table 5.

Table 5. Fit of experimental results against few semi-theoretical models

Models		Non-treated samples			Blanched samples		
		E1	E2	E3	E4	E5	E6
Page	R^2	0,99846	0.99846	0.99922	0.99866	0.99689	0.99962
	Chi-Square	1.44E-04	1.48E-04	7.47E-05	1.37E-04	3.02E-04	3.48E-05
Wang and Singh	R^2	0.40817	0.50434	0.45185	0.56651	0.55818	0.49647
	Chi-Square	0.05536	0.04748	0.05229	0.04449	0.04291	0.04585
Modified Page Equation	R^2	0.99846	0.99846	0.99306	0.96677	0.98203	0.99704
	Chi-Square	1.50E-01	1.53E-04	6.62E-04	3.41E-03	1.75E-03	2.69E-04
Logarith mic	R^2	0.99432	0.99881	0.99721	0.99549	0.99704	0.99925
	Chi-Square	5.52E-04	1.19E-04	2.77E-04	4.78E-04	2.96E-04	7.05E-05
Henderso n and Pabis	R^2	0.99086	0.99832	0.9956	0.98936	0.99383	0.99828
	Chi-Square	8.55E-02	1.61E-04	4.19E-04	1.06E-03	5.99E-04	1.56E-04

The goodness of the fit was evaluated with R^2 and Chi-Square correlation parameters. The highest average value of R^2 was obtained for Page model and it was 0.99855 which indicates that this model best describes the drying of red beetroot chips.

4.5. Moisture diffusion coefficients

The values of the effective diffusion coefficients (D_{eff}) calculated with Eq. 6 are shown in Fig. 6 and Table 6. Additionally, the D_{eff} was calculated for each stage of the drying process.

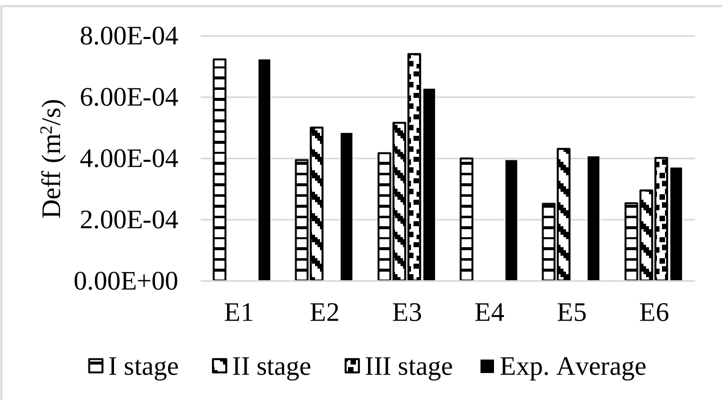

Figure 6. Values of D_{eff}

Table 6. Effective diffusion coefficients for all experiments D_{eff} * 10^{-9} (m^2/s)

	Average experiment temperature [°C]	I stage	II stage	III stage	Experiment average
E1	**70**	7.21	-	-	7.21
E2	**59**	3.94	4.99	-	4.82
E3	**62.2**	4.16	5.15	7.40	6.26
E4	**70**	3.99	-	-	3.93
E5	**58.3**	2.51	4.29	-	4.05
E6	**59.2**	2.53	2.94	4.00	3.70

For the samples that have not been subjected to the pretreatment (E1, E2 and E3), a correlation between average drying temperature and effective diffusion coefficient could be established. As we can see from the Table 6 and Fig.6, for these experiments, D_{eff} increases with the increase of average drying temperature. Experiments with blanching pretreatment (E4, E5 and E6), on the other hand, showed no significant influence of the average drying temperature on the D_{eff} value. The highest values of average D_{eff} were calculated for drying regime E1 and the lowest for E6. Also, it can be observed on Fig. 6. and Table 6., that in experiments with two- and three-stages (E2, E3, E5 and E6) the values of the D_{eff} increase as the drying progresses, i.e. the values of D_{eff} are lowest for the first stages, and higher for second and third stages, respectively, assuming no change in sample thickness.

5. Conclusions

In this work, the influence of changeable drying temperature and hot water blanching pretreatment on red beetroot chips drying kinetics was investigated. Moreover, the impact of the mass of the samples was also analyzed. It was concluded that the blanching treatment had significant influence on the equilibrium moisture content, which was significantly higher for blanched samples in comparison to the untreated ones. The strongest influence on drying time was the mass of the samples. However, it was concluded that two-stage regime had the smallest specific energy consumption for both non-treated and blanched samples, 128.8 MJ/kg and 102.9 MJ/kg, respectively. The influence of two and three-stage regimes was investigated, and it was concluded that variable temperature drying strongly influences the drying kinetics of the beetroot chips. A sudden decrease in the drying temperature causes shrinkage of the material and instant increase in drying rate. A drying model which had the best fitting parameters was found to be the Page model. Coefficient of diffusion depended on the average drying temperature, with the values between $2{,}53 \cdot 10^{-9}$ and $7{,}21 \cdot 10^{-9}$ m^2/s and was lower for blanched samples in comparison to untreated ones.

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Nomenclature

MR - Dimensionless moisture ratio, [-]

D_{eff} - Effective moisture diffusivity, $[m^2s^{-1}]$

DR - Drying rate, $[kg_w kg_{dm}^{-1}s^{-1}]$

Subscripts

w - water

wb - wet basis

dm - dry matter

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