Microwave dehydration of potato slices and assessment of energy efficiency

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Abstract. The dehydration parameters (thickness, mass load, and power level) statistically significantly ($p<0.05$) affect the microwave dehydration of potato slices. Potato slices with thicknesses of 3, 6, and 9 mm were dehydrated as monolayers at different mass loads (1.00, 0.63, and 0.38 kg m^{-2}) and microwave power levels (80, 240 W). The optimal model of potato slices with a 3 mm thickness, 0.38 kg m^{-2} mass load, dehydrated on 240 W, had the shortest dehydration time (15 minutes), the most negligible energy consumption (0.064 kWh), and the most insignificant emission of carbon dioxide (0.063 kg). The model of potato slices of 9 mm slice thickness dehydrated on 240 W, with 0.38 kg m^{-2} mass load, showed the highest resistance to mass transfer (the maximum effective moisture diffusivity $1.1847 \times 10^{-7} \pm 2.6080 \times 10^{-9}$ m^2 s^{-1}). The average activation energy for all models was determined to be 11.635 W g^{-1}. The thinner potato slices showed better results in dehydration time and energy consumption and good moisture diffusivity.

1 Introduction

Potato is one of the most important vegetable crops in human nutrition because of its high carbohydrate intake. The dehydrated potato products have been widely used in a percentage of 12 % [1, 2].

The different dehydration methods of potato have significant effects on the potato quality, such as enzymatic and non-enzymatic coloring reactions, shrinkage, and various sensory properties [3, 4]. These methods are highly energy-consuming processes, with a long dehydration period, low energy efficiency, and high costs. Due to these difficulties, more rapid and low-energy efficiency dehydration methods are required. Dehydration involves mass and heat transfer mechanisms. In microwave dehydration methods (MW), the dehydration time is short due to quick energy absorption by water molecules, resulting

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in high dehydrating rates of the native food material [5, 6]. During MW dehydration, the dry material bulk is heated volumetrically, resulting in a uniform and fast dehydration [7].

The theoretical mathematical models could describe the moisture removal behavior of food and agricultural product [8]. These models show the accurate description of heat and mass transfer during the dehydration process, governing equations, and mathematics [8]. Among the different theoretical models developed for predicting heat and mass transfer parameters, the knowledge of effective moisture diffusivity is indispensable to understand the diffusion phenomena and the material shrinkage behavior [9, 10].

This study aimed to describe the behavior of different MW power on the dehydration process of other potato slices and its energy efficiency/consumption, and the effective moisture diffusivity and activation energy of the dehydration process.

2 Materials and Methods

2.1 Microwave dehydration of potato slices

The fresh white potatoes (*Kennebec* variety) were harvested from a Paraćin area (43°51'46.9"N 21°24'19.7"E, Serbia), and stored in a refrigerator at 4 °C. The fresh potatoes' initial dry matter content was 6.83 ± 0.37 kg water kg^{-1} dry basis [11]. The fresh potatoes were taken out of the refrigerator, washed with cold water, stabilized at the ambient temperature for a few hours, peeled, and cut to the desired thicknesses (3, 6, and 9 mm), with the different mass load (1.00, 0.63, and 0.38 kg m^{-2}). Microwave dehydrator (MW2390MB, rated microwave power 800 W) was used to dry the potato slices to the constant weight. The experimental MW dehydration was obtained on 80 W and 240 W. The stronger (higher) MW dehydration power was affected on extremely non-enzymatic browning reactions (reactions of caramelization and Maillards' ractions).

2.2 The microwave dehydration modeling

The moisture ratio (*MR*) is defined according to Eq. (1):

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

M_t, M_o, and M_e represent the moisture content achieved after convective drying time t, the initial moisture content, and the equilibrium moisture content, respectively. The value of equilibrium moisture content (M_e) is usually deficient and can be deleted from Eq. (1) without a significant change of *MR* [12].

2.3 Determination of effective moisture diffusivity (D_{eff})

The internal diffusion phenomenon on dehydration of vegetables and fruits were derived from Fick's second law of diffusion. The theoretical models were desribed according to the product geometry (slices, Eq. (1) and (2)) were given below [11, 13]:

$$MR = A_1 \cdot \sum_{i=1}^{\infty} \frac{1}{J_o^2} \cdot e^{-\frac{J_0^2 \cdot D_{eff}}{A_2}} \quad (2)$$

$$A_1 = \frac{8}{\pi^2}; \quad A_2 = 4 \cdot L^2 \quad (3)$$

where D_{eff} is the effective moisture diffusivity (m^2 s^{-1}), t is time (s), MR is the moisture ratio, J_0 is the roots of the Bessel function, A_1, A_2 are geometric constants, and L is the thickness (MW dehydration has occurred through only one side. Eq. 1 is derived for the constant values of D_{eff} and for sufficiently long drying time:

$$ln(MR) = ln(a) - k \cdot t \tag{4}$$

$$k = -\frac{\pi^2 \cdot D_{eff}}{A_2} \tag{5}$$

The variation of $ln(MR)$ versus t is linear (Eq. (4)). The slope is equal to the drying constant (k), and the D_{eff} was calculated (Eq. (5) [14].

2.4 Determination of activation energy (E_a)

This method is assumed as related to D_{eff} and the ratio of MW output power to sample weight (m/P) instead of air temperature. The activation energy was calculated by plotting the natural logarithm of D_{eff} versus mass load/power (m/P). The plot was found to be a straight line in the range of MW power studied, indicating Arrhenius dependence. The following equation can represent the effective diffusivity of potato samples on the MW power could be presented by the equation:

$$D_{eff} = D_0 \times e^{-E_a \times \frac{m}{P}} \tag{6}$$

where E_a is the activation energy (W g^{-1}), m is the mass of the mass load (g), D_0 is the pre-exponential factor (m^2 s^{-1}), and P is the microwave power (W).

2.5 The assessment of energy efficiency

Energy consumption (E) for the MW potato slices dehydration was measured by Prosto PM 001 (230 V, 50 Hz, 0 – 16 A, 2 – 3680 W, 0 – 9999 kWh, –10 °C to +40 °C, ≤ 85% of relative humidity, the altitude of use max 2000 m). This two-tariff electricity consumption meter also can calculate the price of consumed energy, so it is instrumental in planning the implementation of electricity-saving measures. The amount of consumed energy is mathematically correlated with the emitted carbon dioxide (1 kWh releases 0.998 kg CO_2) [11, 15].

2.6 Statistical analysis of microwave dehydration models

Analysis of variance (ANOVA) was selected to estimate the dehydration variables of potato slices (MW power range, thickness, and mass load) and application of post-hoc Tukey HSD test. StatSoft Statistica ver.12.0 was used, and for Anova calculation, the second-order polynomial models' Microsoft Excel ver. 2016 was used as well [13].

3 Results and Discussion

The average dehydration time (t), the effective moisture diffusivity (D_{eff}), the energy consumption (E), and the emission of carbon dioxide (CO_2) of MW dehydration of potato slices, based on the different mass load (1.00, 0.63, and 0.38 kg m^{-2}), different potato slice thickness (3, 6, 9 mm) and MW power levels (80 and 240 W) are presented in Tables 1. All experimental results were analyzed in triplicates.

The initial and final moisture contents of the dehydrated native material, as well as the experimental parameters, such as the dehydration method and the dehydrated material properties (tissue structure, the material form such as a cube or slab or sphere, infinite slab, MW power levels, etc.), are the main factor controlling the dehydration process.

The dehydration time (t) statistically significantly (p<0.05) depends on MW dehydration parameters: MW power levels (P), the potato slice thickness (d), and mass load (m). Increasing m and d and decreasing the P (while the other dehydration parameters were constant), the t was increased. The drying rate reduction (the wider distance the moisture travels in dehydrated material with large thickness) was slower, and the average kinetic energy of the moisture was decreased, and the diffusion process of moisture was harder [11, 16]. The minimum dehydration time (15 ± 1 min) had the MW model of 3 mm of potato slice thickness, with the mass load of 0.38 kg m^2, and the MW power levels 240 W. At the same time, the maximum value belonged to the potato slicess with the thickness of 9 mm, mass load 1.00 kg m^2, and MW power levels of 80 W (685 ± 19 min). The mass transfer within the potato slices was more rapidly with the increasing MW levels because more heat was generated, creating a large vapor pressure difference between the center and the surface of the product due to characteristic MW heating [5–7]. The experimental results of dehydration time are in a correlation with the results by Darvishi et all. (2013) and Azimi-Nejadian & Hoseini (2019).

The calculated average values for the effective moisture diffusivity of the potato slices at various MW parameters drying are presented in Table 1. Increasing d and P, as well as decreasing the m (while the other dehydration parameters were constant), the D_{eff} was statistically significantly (p<0.05) increased. Accordingly, the minimum D_{eff} (the minor resistance to mass transfer) belonged to the potato slices with the thickness of 3 mm, the mass load of 1.00 kg m^2, and MW power of 80 W ($2.9210 \times 10^{-10} \pm 2.1826 \times 10^{-11}$ m^2 s^{-1}), while the maximum D_{eff} was obtained for the thickness of 9 mm, the mass load of 0.38 kg m^2, and MW power of 240 W ($1.1847 \times 10^{-7} \pm 2.6080 \times 10^{-9}$ m^2 s^{-1}). The experimental results of D_{eff} are in correlation with the results by Darvishi et al. (2013) and Azimi-Nejadian & Hoseini (2019). The quick surface hardening of the dehydrated material has been found as the main reason for these results; Nguyen and Price (2007), as well as Hafezi et al. (2015) and Onwude et al. (2018), reported that quick surface hardening of thin slabs occurred rapidly because the moisture evaporation of thin slabs was restrained. The effective moisture diffusivity was lower [16–18].

The activation energy (E_a) is the energy required to start the water diffusion from the internal areas to the surface of the dehydrated material. Generally, high E_a was related to strongly bounded water in materials structure. The water evaporation (removal) was carried out by material structure. In the present work, E_a was statistically significantly (p<0.05) decreased with the increasing potato slice thickness, the MW power, and the decreasing mass load. The average E_a of all MW models was found to be 11.635 W g^{-1}. The obtained results are comparable with the values for MW dehydration (14.945 W g^{-1}) presented in Darvishi et al. work (2013). These results are higher because the MW dehydration was observed for the MW power levels range up to 500 W.

Table 1. Average values and standard deviations of D_{eff}, t, E, and emission of CO_2 for the MW dehydration of potato slices

P (W)	d (mm)	m (kg m^2)	D_{eff} (m^2 s^{-1})	t (min)	E (kWh)	CO_2 (kg)
80	3	0.38	$1.0954 \times 10^{-9} \pm 2.3510 \times 10^{-11,\ a}$	173 ± 4^{d}	0.230 ± 0.007^{b}	0.228 ± 0.006^{b}
	6		$2.9210 \times 10^{-9} \pm 6.2694 \times 10^{-11,\ a}$	235 ± 5^{e}	0.306 ± 0.009^{b}	0.302 ± 0.009^{b}
	9		$4.4363 \times 10^{-9} \pm 9.5217 \times 10^{-11,\ a}$	305 ± 7^{f}	0.398 ± 0.011^{c}	0.390 ± 0.011^{c}
240	3	0.38	$1.3923 \times 10^{-8} \pm 3.0653 \times 10^{-10,\ b}$	15 ± 1^{a}	0.064 ± 0.007^{a}	0.063 ± 0.007^{a}
	6		$5.9662 \times 10^{-8} \pm 1.3135 \times 10^{-9,\ f}$	$16 \pm 1^{a,\ b}$	0.071 ± 0.008^{a}	0.075 ± 0.008^{a}
	9		$1.1847 \times 10^{-7} \pm 2.6080 \times 10^{-9,\ g}$	$17 \pm 1^{a,b}$	0.090 ± 0.010^{a}	0.089 ± 0.010^{a}
80	3	0.63	$2.7993 \times 10^{-10} \pm 2.2231 \times 10^{-10,\ a}$	382 ± 12^{g}	$0.468 \pm 0.029^{c,\ d}$	$0.463 \pm 0.036^{c,\ d}$
	6		$1.5092 \times 10^{-9} \pm 1.1986 \times 10^{-9,\ a}$	465 ± 16^{i}	0.583 ± 0.036^{e}	0.576 ± 0.045^{e}
	9		$3.8614 \times 10^{-9} \pm 3.0666 \times 10^{-9,\ a}$	563 ± 16^{j}	0.676 ± 0.041^{f}	0.668 ± 0.053^{f}
240	3	0.63	$5.6960 \times 10^{-9} \pm 3.9760 \times 10^{-10,\ a}$	$40 \pm 3^{a,\ b,\ c}$	0.223 ± 0.015^{b}	0.220 ± 0.015^{b}
	6		$2.2346 \times 10^{-8} \pm 1.5598 \times 10^{-9,\ c}$	$43 \pm 3^{a,\ b,\ c}$	0.241 ± 0.016^{b}	0.240 ± 0.016^{b}
	9		$4.9183 \times 10^{-8} \pm 3.4332 \times 10^{-9,\ e}$	$46 \pm 3^{a,\ b,\ c}$	0.257 ± 0.017^{b}	0.250 ± 0.017^{b}
80	3	1.00	$2.9210 \times 10^{-10} \pm 2.1826 \times 10^{-11,\ a}$	419 ± 12^{h}	$0.504 \pm 0.028^{d,\ e}$	$0.498 \pm 0.028^{d,\ e}$
	6		$9.9801 \times 10^{-9} \pm 7.4572 \times 10^{-10,\ a}$	563 ± 16^{j}	0.732 ± 0.041^{f}	0.723 ± 0.041^{f}
	9		$3.5052 \times 10^{-9} \pm 2.6191 \times 10^{-10,\ a}$	685 ± 19^{k}	0.894 ± 0.050^{g}	0.884 ± 0.050^{g}
240	3	1.00	$6.5032 \times 10^{-9} \pm 2.9024 \times 10^{-10,\ a}$	$52 \pm 4^{b,\ c}$	0.248 ± 0.028^{b}	0.245 ± 0.009^{b}
	6		$1.4070 \times 10^{-9} \pm 9.0680 \times 10^{-9,\ b}$	57 ± 4^{c}	0.282 ± 0.041^{b}	0.279 ± 0.011^{b}
	9		$4.0200 \times 10^{-8} \pm 2.5910 \times 10^{-9,\ d}$	59 ± 4^{c}	0.297 ± 0.050^{b}	0.290 ± 0.011^{b}

$^{a\text{-}k}$ Different letters in superscript in Table 1 indicate the statistically significant difference between values, at a significance level of $p<0.05$

The experimental results showed that the energy consumption (*E*) statistically significantly ($p<0.05$) depends on MW dehydration parameters of potato slices. Increasing *d* and *m* and decreasing the *P* (while the other dehydration parameters were constant), the MW models needed more energy supply (higher energy consumption *E*) to dehydrate the potato slices dehydration time will be prolonged. The results correlate with the results presented in Petković et al. (2021) and Azimi-Nejadian & Hoseini (2019). The minimum *E* belonged to the potato slices with the thickness of 3 mm, the mass load of 0.38 kg m^2, and MW power of 240 W (0.064 ± 0.007 kWh), while the maximum *E* was obtained for the thickness of 9 mm, the mass load of 1.00 kg m^2, and MW power of 80 W (0.894 ± 0.050 kWh). The emission of CO_2 monitors the energy consumption by the mathematical correlation, which was already mentioned before.

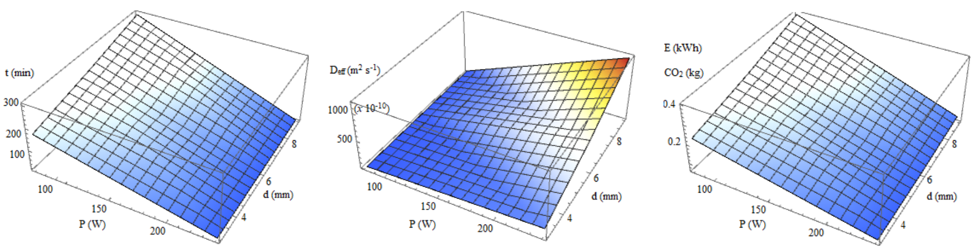

Fig. 1. 3D presentation of MW dehydration models of potato slices

Trends of the effects of all independent variables (t, D_{eff}. E, and CO_2) on dehydration parameters can be visualized on graphical presentations of developed mathematical models presented in Figure 1. It could be concluded that thinner potato slices showed better results in terms of dehydration time and energy consumption and good moisture diffusivity.

Comparing the results from this research with the previous one, which refers to the convective dehydration of potato slices published by Petković et all. (2021), the correlation between the analyzed parameters was found. The advantage of MW dehydration was the shorter dehydration time, less energy consumption, the CO_2 emission, and much lower activation energy.

4 Conclusion

The effective moisture diffusivity, dehydration time, energy consumption, and carbon dioxide emission, as well as the average activation energy of microwave dehydration of potato slice statistically significantly ($p<0.05$), depending on dehydration parameters (potato slice thickness, mass load, and the microwave power levels). The optimum microwave model for the potato slice thickness was the model with MW power level 240 W, 0.38 kg m^2 mass load, and the 3 mm thickness of potato slices. This model has the shortest dehydration time (15 ± 1 min) and the lowest energy consumption (0.064 ± 0.007 kWh). The values of the effective moisture diffusivity ranged from 2.9210 × 10^{-10} m^2 s^{-1} to 1.1847 × 10^{-7} m^2 s^{-1}), while the average activation energy was found to be 11.635 W g^{-1}.

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