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Energy consumption and dehydration parameters of microwave drying of carrot

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ABSTRACT

The parameters of microwave dehydration (thickness, mass load, and microwave power level) of carrot slices had a statistically significant ($P < 0.05$) effect on the drying process. Carrot slices (thicknesses of 3, 6, and 9 mm) were dehydrated as monolayers at microwave power levels (80, 240 W) at different mass loads (1.00, 0.63, and 0.38 kg m^{-2}). The optimal microwave model for the carrot slice microwave dehydration was the model with the microwave power level of 240 W, mass load of 0.38 kg m^{-2}, and 3 mm thickness, with the shortest dehydration time (15 ± 1 minute) and the lowest energy consumption (0.099 ± 0.002 kWh). The minimum resistance to mass transfer (effective moisture diffusivity) was observed in the models with the thickness of 3 mm, a 1.00 kg m^{-2} mass load, dehydrated at 80 W ($8.2519 \times 10^{-8} \pm 8.8815 \times 10^{-10}$ m^2 s^{-1}). The average activation energy for the analyzed models was 8.972 ± 0.009 W g^{-1}. Therefore, the application of the microwave dehydration method can be considered a proper alternative for the dehydration of carrot slices.

Keywords: carrot, microwave drying, dehydration parameters, energy consumption.

ИЗВОД

Параметри микроталасног сушења (дебљина, маса која се суши и ниво микроталасне снаге) режњева шаргарепе утицали су статистички значајно ($P < 0.05$) на процес сушења. Режњеви шаргарепе (дебљине 3, 6 и 9 mm) сушени су у танком слоју као монослој на нивоима микроталасне снаге (80, 240 W) при различитој маси која се суши (1,00; 0,63 и 0,38 kg m^{-2}). Оптимални модел за микроталасно сушење режњева шаргарепе био је модел микроталасне снаге од 240 W, масе која се суши од 0,38 kg m^{-2} и дебљине 3 mm, са најкраћим временом дехидрације (15 ± 1 минут) и најнижом потрошњом енергије (0,099 ± 0,002 kWh). Минималну отпорност на пренос масе (коефицијент дифузије) имали су модели дебљине 3 mm, са сушеном масом од 1,00 kg m^{-2}, сушени на 80 W ($8.2519 \times 10^{-8} \pm 8.8815 \times 10^{-10}$ m^2 s^{-1}). Просечна енергија активације за анализиране моделе износила је 8,972 ± 0,009 W g^{-1}. Зато се примена методе микроталасног сушења може сматрати одговарајућом алтернативом за дехидрацију режњева шаргарепе.

Кључне речи: шаргарепа, микроталасно сушење, параметри сушења, потрошња енергије.

1. Introduction

Carrot (*Daucus carota* L.) is a popular root vegetable grown throughout the world. In Serbia, in 2020, carrots were planted on about 1,181.5 ha, while the cultivation area in the Pomoravlje (Morava River Valley) region was 61.4 ha (makroekonomija.org, 2022). Carrot is a source of water (86–89%), carbohydrates (mostly sugars, 6–10.9 %), minerals (Fe 0.4–2.2 mg 100 g^{-1}, P 25–53 mg 100 g^{-1}, Mg ~ 9 mg 100 g^{-1}, Ca 34–80 mg 100 g^{-1}, Na 40 mg 100 g^{-1}, K mg 100 g^{-1}, Cu 0.02 mg 100 g^{-1}, Zn 0.2 mg 100 g^{-1}), proteins (0.7–0.9 %), fats (0.2–0.5 %), crude fibers (1.2 %), ash (1.1 %), carotenes (5.33–39 mg 100 g^{-1}), vitamins (B1 ~ 0.04 mg 100 g^{-1}, B2 ~ 0.02 mg 100 g^{-1}, B3 ~ 0.2 mg 100 g^{-1}, vitamin C 4 mg 100 g^{-1}), with the energy value of 126 kJ 100g^{-1} (Sharma et al., 2011).

Dehydration is a single operation process used to prolong the shelf life of many vegetables, fruits, and herbs. Microwave dehydration (*MWD, MD*) is an alternative drying method to hot air conventional drying because of the uniform heating of the dehydration material, the efficiency of energy conversion, and the improved quality of the final product (Béttega et al., 2014). Microwave heating occurs mainly in the entire volume of the material through the interaction between electromagnetic fields and water molecules. The electromagnetic waves in *MD* are in the 300–3000 MHz range. The rapid heating of the water in the material to the point of evaporation during *MD* creates a pressure difference that "pulls out" the water in the form of steam to the surface. Its time efficiency, low energy consumption, and high product quality are the main factors that the dehydration industry can take advantage of [Pu et al., 2016; Gitanjali et al., 2021). In the *MD* process, convective air carries volatile compounds continuously released from the dry material (Pu et al., 2016). Therefore, because of its high dehydration efficiency, *MD* could be used as a new (fourth-generation) drying technology to dehydrate heat-sensitive materials (Vadivambal and Jayas, 2007; Yan et al., 2010).

The objective of this study was to investigate the behavior of different microwave power ranges and their energy efficiency in the dehydration of carrot slices.

2. Materials and methods

2.1. Materials

Fresh carrots (*Daucus carota* subsp. *sativus*) were harvested from the Paraćin area (the village of Striža, 43°49'57.7"N 21°23'20.3"E), sorted, washed with cold water, and stored in a refrigerator at 4°C. They were taken out of the fridge for an hour before the experiment to reach ambient temperature, and then they were cut to the desired thicknesses *d* (3, 6, and 9 mm), with different mass loads *m* (1.00, 0.63, and 0.38 kg m^{-2}). The initial dry matter content of the fresh carrots was 5.03 ± 0.14 kg water kg^{-1} dry basis (84.57 ± 0.94 % on a wet basis (w.b.)) (Wang et al., 2018).

2.2. Methods

2.2.1. Microwave dehydration and its modeling of carrot slices

The microwave dehydrator (MW2390MB, rated microwave power 800 W) was used to dry the carrot slices to constant weight. The experimental *MD* was obtained at the *MW* power (*P*) 80 W and 240 W. Rapid mass transport by *MD* power may cause tissue damage or undesirable changes in the texture (Nijhuis et al., 1998). Stronger (higher) *MD* power induces non-enzymatic browning reactions (caramelization and the Maillard reaction), as in previous research by Onwude et al. (2016), and Petković et al. (2021a,b,c). The weight of the carrot trays was measured at intervals of 1 min (in triplicate for each power).

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

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

M_t, M_0, and M_e are the moisture content achieved after convective drying time *t,* the initial moisture content, and the equilibrium moisture content, respectively. The value of M_e was usually deficient ($M_e \approx 0$) (Petković et al., 2020).

The drying ratio (*DR*) is a change in the total mass loss of dehydrated materials ($M_{i-1} - M_i$) in the interval of time between measurements ($t_{i-1} - t_i$) on a particular tray during the drying process (Eq. (2)) (Petković et al., 2019; Petković et al., 2021a; Filipović et al. 2021]:

$$DR = \frac{M_{i-1} - M_i}{t_{i-1} - t_i} \quad (2)$$

2.2.2. Determination of effective moisture diffusivity (D_{eff})

Fick's second law of diffusion was appropriate for describing the internal diffusion phenomenon in the dehydration of carrots. The theoretical models were defined according to the product geometry (slices, Eq. (3) and (4)) (Doymaz, 2016; Filipović et al., 2020; Petković et al., 2021b).

D_{eff} is effective moisture diffusivity ($m^2\ s^{-1}$), *t* is dehydration time (s), *MR* is moisture ratio, and J_0 is the roots of the Bessel function. A_1 and A_2 are geometric constants, and *L* is carrot thickness. *MD* occurred through only one side of the carrot area (Eq. 4). Eq. 3 was derived for the constant values of D_{eff} and for sufficiently long drying time. The drying constant (*k*) was equal to the slope of the linear dependence of *ln*(*MR*) versus *t* (Eq. (5)). Finally, D_{eff} was calculated (Eq. (6)) (Petković et al., 2021a).

$$MR = A_1 \cdot \sum_{i=1}^{\infty} \frac{1}{J_0^2} \cdot e^{-\frac{J_0^2 \cdot D_{eff}}{A_2}} \quad (3)$$

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

$$ln(MR) = ln(a) - k \cdot t \quad (5)$$

$$k = -\frac{\pi^2 \cdot D_{eff}}{A_2} \quad (6)$$

2.2.3. Determination of activation energy (E_a)

The activation energy of *MD* was calculated by plotting the natural logarithm of D_{eff} versus mass load/power instead of air temperature (*m/P*). The plot is a straight line in the range of *MW* power studied, indicating the Arrhenius dependence (Eq. (7)) (Dadali et al., 2007):

$$D_{eff} = D_0 \times e^{-E_a \times \frac{m}{P}} \quad (7)$$

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

2.2.4. Estimation of energy consumption (E)

Energy consumption for the *MD* of carrot slices 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). The energy consumption was mathematically correlated with the carbon dioxide emission (1 kWh releases 0.998 kg CO_2). The two-tariff electricity consumption meter could calculate the energy consumption price, in accordance with the electricity saving measures (Petković et al. 2021b).

2.2.5. Statistical analysis of MD models

Analysis of variance (ANOVA) was selected to assess the dehydration variables of the *MD* of carrot slices (thickness, mass load, and *MW* power). StatSoft Statistica ver.12.0 was used (the post-hoc Tukey HSD test and the second-order polynomial models Microsoft Excel ver. 2016) (Petković et al. 2021b).

3. Results and discussions

The *MD* parameters of carrot slices (drying ratio *DR*, the moment of the maximum *DR* t_{DR}, effective moisture diffusivity D_{eff}, dehydration time *t*, energy consumption *E*, and the emission of carbon dioxide CO_2) for the mass load (1.00, 0.63, and 0.38 kg m^{-2}), carrot slice thickness (3, 6, 9 mm) and *MW* power levels (80 and 240 W) are presented in Table 1. The *MD* parameters statistically significantly ($P < 0.05$) depended on the *MD* parameters *P*, *d*, and *m*.

Table 1.
Average values and standard deviations of *DR*, t_{DR}, D_{eff}, *t*, and *E* for the *MW* dehydration of carrot slices

P (W)	*d* (mm)	*m* (kg m^{-2})	*DR* ($g\ h^{-1}$)	t_{DR} (min)	D_{eff} ($m^2\ s^{-1}$)	*t* (min)	*E* (kWh)	CO_2 (kg)
80	3	0.38	45 ± 3 a, b	18 ± 1 d	$2.0739 \times 10^{-7} \pm 2.3214 \times 10^{-9}$ c	73 ± 3 d	0.177 ± 0.006 b, c	0.176 ± 0.006 b, c
	6		37 ± 3 b	13.5 ± 1 c, d	$4.5422 \times 10^{-7} \pm 5.7357 \times 10^{-9}$ f	84 ± 3 e	0.201 ± 0.009 b, c, d	0.200± 0.009 b, c, d
	9		36.5 ± 2.5 a	13 ± 1 c, d	$9.4641 \times 10^{-7} \pm 6.6357 \times 10^{-9}$ j	93 ± 3 f	0.205± 0.010 c, d	0.204± 0.010 c, d
240	3	0.38	177 ± 5 d, e	5 ± 0.5 a	$8.3139 \times 10^{-7} \pm 1.7621 \times 10^{-9}$ i	15 ± 1 a	0.099 ± 0.002 a	0.098± 0.002 a
	6		167 ± 5 c, d	4.5 ± 0.4 a	$1.8373 \times 10^{-6} \pm 2.4598 \times 10^{-8}$ m	21 ± 1 a, b	0.129 ± 0.003 a, b	0.128± 0.003 a, b
	9		154 ± 4 c	4 ± 0.4 a	$5.4747 \times 10^{-6} \pm 2.5461 \times 10^{-8}$ p	25 ± 1 b	0.132 ± 0.004 a, b	0.131 ± 0.004 a, b
80	3	0.63	51 ± 3 a, b	27.5 ± 2.5 e	$1.3948 \times 10^{-7} \pm 6.1114 \times 10^{-9}$ b	94 ± 3 f	0.217 ± 0.011 c, d	0.216 ± 0.01 c, d
	6		49 ± 3 a, b	25 ± 2 e	$3.4468 \times 10^{-7} \pm 8.4521 \times 10^{-9}$ e	123 ± 4 g	0.294 ± 0.023 e	0.293 ± 0.023 e
	9		47 ± 3 a, b	24 ± 2 e	$7.4595 \times 10^{-7} \pm 8.6524 \times 10^{-9}$ h	136 ± 4 h	0.300 ± 0.031 e	0.299 ± 0.031 e
240	3	0.63	202 ± 7 f, e	8 ± 0.8 a, b, c	$4.6700 \times 10^{-7} \pm 2.4223 \times 10^{-9}$ f	26 ± 1 b	0.150 ± 0.005 a, b, c	0.149 ± 0.005 a, b, c
	6		184 ± 6 e, f	7.5 ± 0.8 a, b	$1.4824 \times 10^{-6} \pm 2.7752 \times 10^{-8}$ l	28 ± 1 b	0.171 ± 0.006 a, b, c	0.170 ± 0.006 a, b, c
	9		183 ± 6 e, f	7 ± 0.7 a, b	$3.3354 \times 10^{-6} \pm 2.8887 \times 10^{-8}$ o	29 ± 1 b	0.183 ± 0.008 b, c	0.182 ± 0.008 b, c
80	3	1.00	55 ± 3 b	43 ± 3 f	$8.2519 \times 10^{-8} \pm 8.8815 \times 10^{-10}$ a	153 ± 4 i	0.335 ± 0.036 e	0.334 ± 0.036 e
	6		54 ± 3 a, b	42 ± 3 g	$3.0232 \times 10^{-7} \pm 9.3172 \times 10^{-9}$ d,e	178 ± 5 j	0.426 ± 0.047 f	0.425 ± 0.047 f
	9		52 ± 3 a, b	36 ± 3 g	$5.9479 \times 10^{-7} \pm 9.6733 \times 10^{-9}$ g	188 ± 5 k	0.472 ± 0.051 f	0.471 ± 0.051 f
240	3	1.00	215 ± 8 e	14 ± 1 c, d	$2.7786 \times 10^{-7} \pm 1.8872 \times 10^{-9}$ d	46 ± 2 c	0.270 ± 0.026 d, e	0.269 ± 0.026 d, e
	6		189 ± 7 e,f	13.5 ± 1 c, d	$1.0632 \times 10^{-6} \pm 2.1442 \times 10^{-8}$ k	47 ± 2 c	0.296 ± 0.028 e	0.295 ± 0.028 e
	9		188 ± 6 e, f	13 ± 1 b, c	$2.5073 \times 10^{-6} \pm 2.3823 \times 10^{-8}$ n	48 ± 2 c	0.301 ± 0.032 e	0.300 ± 0.032 e

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

The experimental results showed that by increasing *d* (*P, m* were constant values), D_{eff}, *t, E,* and CO_2 increased, and *DR* and t_{DR} decreased. The same results were obtained under experimental conditions. *P* and *d* were constant values, and *m* increased; only the D_{eff} parameter was reduced with an increase in *m*. When *d* and *m* values were constant, with increasing *P*, the parameters *DR*, D_{eff} increased, and t_{DR}, t, E, CO_2 decreased.

MD has a higher dehydration rate than most conventional drying methods (Cui et al., 2004). In the initial stage of *MD*, the fastest water removal was noticed. The moment of the maximum drying ratio (a peak at which the evaporation rate was maximal) strongly depended on *P*, *d*, and *m*; t_{DR} occurred in the first 5–15 minutes of *MD* at 240 W, unlike the 13–43 minutes of *MD* at 80 W. The maximum *DR* (215 ± 8 g h-1) was obtained for the model dehydrated at 240 W, with a mass load of 1.00 kg m^{-2} and carrot slice thickness of 9 mm, which occurred after the 14 ± 1 minute of *MD*. The experimental results are consistent with the results obtained by Petković et al. (2021a), and Abbaspour-Gilandeh et al. (2020). The strong dependence of *DR* on *P* was found in the research of Bettega et al. (2014) as well.

The drying rate reduction (the greater distance that moisture travels in a dehydrated material of a significant thickness) was slower, the moisture's average kinetic energy was lower, and the moisture diffusion process was more difficult (Petković et al., 2021b). The minimum t (15 ± 1 min) was required for the *MD* model of 3 mm carrot slice thickness, with a mass load of 0.38 kg m^{-2}, and a power level of 240 W. The minimum E consumption (0.099 ± 0.002 kWh) and CO_2 emission were associated with the same *MD* model, while the maximum E (0.472 ± 0.051 kWh) and CO_2 emission were obtained for the carrot thickness of 9 mm, mass load of 1.00 kg m^{-2}, and *MW* power of 80 W. The results correlate with the findings presented in Akal and Kahveci (2016). The cube shape of carrot slices prolonged the t of thin-layer *MD* because a smaller carrot area was exposed (Bettega et al., 2014).

The maximum resistance to mass transfer (D_{eff} min) was observed for the *MD* models with the d of 3 mm, m of 1.00 kg m^{-2}, and P of 80 W (8.2519 × 10-8 ± 8.8815 × 10^{-10} m^2 s^{-1}), and the D_{eff} max for the *MD* models with d of 9 mm, m of 0.38 kg m^{-2}, and P of 240 W (5.4747 × 10^{-6} ± 2.5461 × 10^{-8} m^2 s^{-1}). Petković et al. (2021c) showed the experimental results that were correlated. As the *MD* level was increased and more heat was generated, the (water) mass transfer rate in the carrot slices was faster. Due to the characteristic heating of the *MD*, a significant vapor pressure difference was developed between the center and the surface of the carrot slice. The rapid surface hardening of the thin plate occurred very quickly because the water evaporation from the thin plate was limited. As a result, the effective moisture diffusion rate was low (Pu et al., 2016). Gilandeh et al. found the D_{eff} values 7.12 × 10^{-9} to 2.78 × 10^{-8} m^2 s^{-1} for the MD carrot slices of 4 mm thickness, 90 g per tray (approx 1.125 kg m^{-2}), and *MW* power of 90 W (Abbaspour-Gilandeh et al., 2020).

The E_a is the energy necessary to initiate water diffusion from the dehydrated material's interior regions to the surface. If water was more strongly bound in the material's structure, higher E_a was necessary to evaporate and strongly depended on the dehydrated material structure. The variation in E_a was observed within the m parameter (Fig. 1); a more significant amount of dehydrated carrot slices will require higher E_a. The average E_a of the experimental *MD* model was found to be 8.972 W g^{-1}. The experimental results are comparable with the E_a values in the research of Abano et al. (15.079 Wg^{-1} for 5 mm, 7.599 W g^{-1} for 10 mm, and 9.542 W g^{-1} for 15 mm dried carrot slices (Abano et al., 2019).

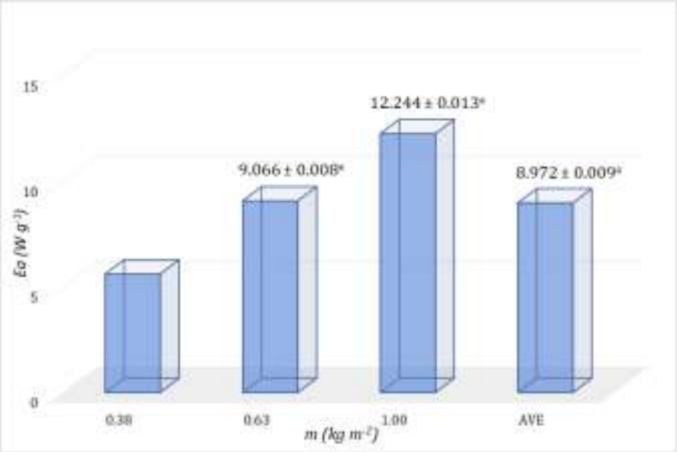

Figure 1. The average activation energy (E_a) of microwave dehydration of carrot slices

Trends of the effects of the *MD* of carrot slices on the experimental dehydration parameters could be visualized in the graphical representation of the developed mathematical models presented in Fig. 2. Lower values of P cause lower resistance to mass transfer ($D_{eff\ min}$). In comparison, higher P values shorten the t of the *MD* process, and lead to less E, and lower CO_2 emissions.

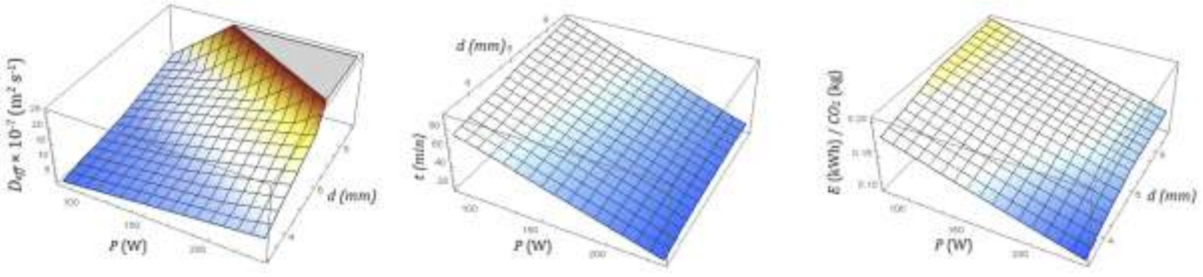

Figure 2. *3D* presentation of the *MW* dehydration models of carrot slices

Therefore, a thin-layer *MD* model may be recommended for the drying of carrot slices with better energy efficiencies than the thin-layer convective method, as confirmed by Behera et al. (2021). And, a new *MD* system with humidity control (complementary water) should be experimentally analyzed in the future (Pu et al., 2016).

4. Conclusions

The processing of carrots into products like slices is one way to make this important vegetable available throughout the year. The use of the microwave dehydration method for the drying of carrot slices can be considered a proper alternative to the thin-layer convective dehydration model. The drying rate increased significantly as the microwave power level increased. The effect of carrot thickness, microwave power level, and mass load on the drying ratio was significant; lower values of the microwave power level caused lower resistance to mass transfer, prolonged the dehydration time, and increased consumption energy and CO_2 emissions.

The optimal microwave model for carrot slice microwave dehydration was characterized by the microwave power level of 240 W, mass load of 0.38 kg m^{-2}, and 3 mm thickness, with the shortest dehydration time (15 ± 1 minute), the lowest energy consumption (0.099 ± 0.002 kWh) and the lowest emission of CO_2. The average activation energy for the analyzed models was 8.972 ± 0.009 W g^{-1}. Therefore, microwave dehydration may be recommended for the drying of carrot slices with better energy consumption.

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Declaration of competing interest

The authors deny any personal and/or financial relationships with other people or organizations that could inappropriately influence (bias, non-compliance with the academic code) their work.

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