Technical Sciences, 2020, 23(2), 157–174

UNIWERSYTET WARMIŃSKO-MAZURSKI W OLSZTYNIE

Quarterly peer-reviewed scientific journal
ISSN 1505-4675
e-ISSN 2083-4527
TECHNICAL SCIENCES
Homepage: www.uwm.edu.pl/techsci/

DOI: https://doi.org/10.31648/ts.5689

EFFECTS OF SONICATION AND FREEZING ON THE COLOR, MECHANICAL AND THERMOPHYSICAL PROPERTIES OF OSMO-MICROWAVE-VACUUM DRIED CRANBERRIES

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Received 16 July 2020, accepted 4 September 2020, available online 2 December 2020.

Keywords: cranberries, osmotic dehydration, ultrasound, freezing, microwave-vacuum drying.

Abstract

The aim of this study was to determine the effects of sonication (S), convective freezing (F), convective freezing preceded by sonication (SF) as well as cryogenic freezing (N) on the osmo-microwave-vacuum drying kinetics, energy usage and properties of dried cranberries such as moisture content, moisture diffusion, water activity, density, porosity, thermal conductivity, thermal diffusivity, volumetric heat capacity, lightness, redness, yellowness, total differences in color, saturation and hue, hardness, cohesiveness, springiness and chewiness. Osmo-microwave-vacuum drying of cranberries took from 13.5 to 16.0 min. All initial treatments increased the moisture diffusivity and thus reduced the drying time. The most energy effective method was osmo-microwave-vacuum drying preceded by sonication (S) of fruits. Osmo-microwave-drying of cranberries subjected to convective freezing preceded by sonication (SF) resulted in the highest lightness (32.5±0.5), redness (33.9±0.7) and yellowness (11.3±0.5) of fruits, as well as the lowest cohesion (the lowest resistant to stress associated with manufacturing, packaging, storage, and delivery). The lowest hardness, i.e. 12.3±0.4 N and the highest cohesiveness and springiness, i.e. 0.38±0.02 and 0.74±0.03 of dried fruits, were noted for berries subjected to initial cryogenic freezing (N). Cryogenic

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freezing (N) combined with osmo-microwave-vacuum drying resulted in the largest color changes of fruits and the highest thermal conductivity. Sonicated and convectively frozen (SF) fruits were characterized by the highest thermal diffusivity. Sonication (S), convective freezing (F) and their combination (SF) significantly reduced the volumetric heat capacity of cranberry fruits.

Introduction

Cranberry fruit is a rich source of bioactive compounds with antioxidant properties (ZIELINSKA et al. 2017). High moisture content, seasonality, production scale, as well as consumer preferences cause that they are often preserved by drying (ZIELINSKA, MARKOWSKI 2018). Recently, they have become of interest to the food producers as they may constitute valuable ingredients to cookies, cakes, cereals, sauces and salads due to the presence of anthocyanins and their antioxidant activity (BEAUDRY et al. 2003).

As the natural waxy layer on the surface of cranberry fruits acts as a barrier to heat and mass transfer, convective drying of cranberries is time-consuming and generates high demands for energy and operational costs. In addition, high temperature may decrease the content of thermolabile compounds and their antioxidant properties. Osmotic dehydration, which consists of immersion of fruits into a concentrated sugar solution, for example, may significantly slow down the rate of moisture removal during convective drying of cranberries (GRABOWSKI et al. 2002). Microwave-assisted drying of cranberries may provide an alternative to convective drying (WRAY, RAMASWAMY 2013, 2015, STANISZEWSKA et al. 2019, 2020, ZIELINSKA et al. 2018a, 2018b, 2019, ZIELINSKA, ZIELINSKA 2019). Microwave dielectric heating results from the ability of a given reagent to absorb the energy assigned to microwave radiation and its conversion into thermal energy. This heating, caused by the electrical component of electromagnetic radiation, occurs through the rotation of dipole molecules and ionic conductivity (NOWAK, KOWALSKA 2007). The vacuum lowers the boiling point of water. The temperature inside the dried particles is higher than that on the surface of the product. It may lead to an increase in the partial pressure that drives the evaporating water to the outer layer. The gradient between a vapor pressure in the center of the material and its surface results in high drying rates (ZHENG et al. 2003). The advantages of microwave-vacuum drying include short drying time, explosion puffing of fruits and vegetables and high quality of the final product (ZIELINSKA et al. 2019, ZIELINSKA, ZIELINSKA 2019).

Due to the natural waxy layer on the fruit surface, cranberries require special treatment to increase the permeability of the surface layer to heat and moisture transfer (NOWAK et al. 2019). Convective freezing of the material before drying may increase the efficiency of drying due to the reduction of skin thickness and then reduction of the mechanical resistance of the surface layer (ZIELINSKA et al. 2015). Since the amount of water that migrates from the cells to intercellular space is minimal, cryogenic freezing reduces damage to the tissue structure (ZIELINSKA et al. 2019). Sonication also performed at a frequency between 18 and 100 kHz and intensity higher than 1 W/cm^2 can be used to influence food products containing water by inducing microcavitation in their structure, which may result in the so-called sponge effect, i.e. the creation of microchannels that improve heat and mass transfer between the cells and their environment (STANISZEWSKA et al. 2019). Berries can also be subjected to osmotic dehydration before drying (SIUCINSKA et al. 2016a, 2016b). Osmotic dehydration allows for removing water from raw material. When properly conducted, i.e. with the use of an appropriate osmotic substance, immersion time, temperature and the ratio of the mass of the solution to the mass of the material, it also allows maintaining the nutritional and sensory values of the preserved food (CORREA et al. 2016, KOWALSKA et al. 2016, ZIELINSKA, MARKOWSKI 2018). Osmotic dehydration significantly affects the structure of the dehydrated product, because the dehydrated cells can shrink and may even be destroyed by treating them with osmotic solutions of high concentrations. The advantages of osmotic dehydration include a reduction of enzymatic browning, nonenzymatic browning, inhibition of polyphenol oxidase activity, retention of volatile components, reduction of the product's water activity (and thus inhibition of microbial growth), enrichment of the material with nutrients from the osmotic solution, extension of product shelf life, improvement of the quality food products such as organoleptic properties, etc. (CZAJKOWSKA et al. 2016). However, this process is time-consuming and dehydrated material still needs to finish drying.

There is a scarce knowledge on the effect of sonication and freezing on the osmo-microwave-vacuum drying kinetics and quality of waxy fruits, particularly cranberries. Therefore, the objective of this study was to investigate the effects of sonication (S), convective freezing (F), convective freezing preceded by sonication (SF) and cryogenic freezing (N) on the osmo-microwave-vacuum (OM) drying kinetics, energy usage as well as color, mechanical and thermophysical properties of cranberries. To compare, raw fruits (R) without any treatment were also subjected to osmo-microwave-vacuum (OM) drying. Among the properties of dried cranberries, moisture content, moisture diffusion, water activity, density, porosity, thermal conductivity, thermal diffusivity, volumetric heat capacity, lightness, redness, yellowness, total differences in color, saturation and hue, hardness, cohesiveness, springiness and chewiness were analyzed. The results of this study can help producers and suppliers of dried berries as well as manufacturers of equipment used to process cranberry fruits.

Materials and methods

Material and initial treatments

Fresh cranberries (*Vaccinium macrocarpon* L.) were obtained from a local farm (Lublin region, Poland). Fresh fruits were free from any diseases and discoloration. They were similar in freshness and size. Raw cranberries were packed in plastic containers and stored in a refrigerator (2±2°C) for up to two weeks. The initial moisture content of fresh fruits was about 7.49±0.02 kg H_2O/kg DM. Whole cranberries of a mass of 0.250±0.003 kg were subjected to different initial treatments: sonication (S), convective freezing (F), convective freezing preceded by sonication (SF) as well as cryogenic freezing (N). Pre-treated fruits were subjected to osmo-microwave-vacuum drying (OM). The control sample was composed of non-treated, raw (R) cranberries.

Sonication (S) at a frequency of 25±5 kHz and ultrasound power of 600 W was conducted for 10 minutes in a water bath filled with 1 dm^3 of distilled water using an ultrasonic disruptor Scientz-650E (Ningbo Scientz Biotechnology Co. Ltd., Zhejiang, China).

Convective freezing (F) was conducted in Liebherr GR 4932 freezer (Liebherr-Hausgeräte GmbH, Ochsenhausen, Germany) for 24 h at a temperature of −18°C. Approximately 3 h before dehydration, frozen cranberries were thawed on a tray at room temperature to reach equilibrium temperature (21±1°C).

Cryogenic freezing (N) was conducted in a styrofoam container filled with liquid nitrogen for 1 min. The boiling point of liquid used for the freezing experiment was −196°C. Cryogenic freezing was considered to be completed when the evaporation of liquid nitrogen was no longer observed. After cryogenic freezing (N), cranberries were removed from the container and left for 3 h to reach ambient temperature.

All of the initial treatments were conducted in triplicate.

Dehydration process

Pre-treated whole cranberries were subjected to osmo-microwave-vacuum drying (OM). Osmotic dehydration of whole cranberries was conducted in a bath (EMAG Emmi 20 HC, EMAG AG, Moerfelden-Walldorf, Germany) filled with a sucrose solution. The concentration of sucrose solution was 65°Brx. Raw (non-treated) and pre-treated cranberries were dehydrated at room temperature (20°C) and atmospheric pressure for 6 h. The sample to solution ratio was 1:4. After completion of the osmotic dehydration, samples were rinsed and blotted with tissue paper. Osmotic dehydration experiments were conducted in triplicate.

After osmotic dehydration, the fruits were dried in a microwave-vacuum dryer (PROMIS TECH, Wroclaw, Poland) at a microwave power of 300 W and absolute pressure of 5±1 kPa. The mass of the sample used in each drying experiment was 0.200±0.003 kg. Microwave-vacuum drying was stopped when the surface temperature of fruits increased to 80°C. The microwave-vacuum dryer (Promis Tech, Wroclaw, Poland) was equipped with a pyrometer to measure the surface temperature of cranberries. The drying experiments were conducted in duplicate.

The moisture content (MC) of cranberries was measured by a DZ ZBC II vacuum drying oven (Chemland, Stargard Szczeciński, Poland) according to the standard (AOAC, 2002). The oven temperature was set at 70°C (13.3 kPa) and the heating time was 24 h. The result was the mean of two replications. Water activity (a_w) was measured using the Aquaspector AQS-31-TC (NAGY, Gaufelden, Germany). The result was the mean of two replications.

The coefficient of moisture diffusion was determined from the equation (1) assuming constant values of the effective moisture diffusion coefficient and fruit shape as well as considering initial (2) and boundary conditions (3) (ZIELINSKA, MARKOWSKI 2018):

$$\frac{u(\tau) - u_r}{u_0 - u_r} = \frac{6}{\pi^2} \cdot \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n^2 \cdot n^2 \cdot \frac{D_{eff} \cdot \tau}{R^2}\right) \tag{1}$$

$$u(t = 0, x, y, z) = u_0 \tag{2}$$

$$t > 0 \to u(t, x, y, z) = u_r \tag{3}$$

where:

$u(\tau)$ – indicates the moisture content at a particular drying time τ [kg H_2O/kg DM],
u_r – indicates the equilibrium moisture content [kg H_2O/kg DM],
u_0 – indicates the initial moisture content [kg H_2O/kg DM],
n – indicates the number of measurements [–],
D_{eff} – indicates the effective moisture diffusivity [m^2/s],
τ – indicates drying time [s],
R – indicates the radius of a sphere [m].

The energy consumption during drying was measured using the energy meter (MPR-53/EPM-07, model MPR-53S, ENTES Elektronik Cihazlar Imalatve Ticaret A.S., Istanbul, Turkey). The specific moisture extraction rate (SMER) was expressed as follows (SCHMIDT et al. 1998):

$$\text{SMER} = \frac{M_{mr}}{E_{\text{input}}} \tag{4}$$

where:

M_{mr} – indicates the mass of moisture removed from the dried material [kg H_2O],

E_{input} – indicates the energy input [kWh].

Quality assessment

Color was measured with a spectrophotometer (Hunterlab MiniScan XE Plus, Reston, VA, USA) under standard illuminant D65, 10° observer and 8° diaphragm. The spectrophotometer cooperated with the MultiScan v.11.06 software. The color of fruits was expressed in CIE $L^*a^*b^*$ space, where the achromatic component L^*, as well as two chromatic components a^*, and b^* denoted lightness, redness and yellowness, respectively. The color of cranberries was measured directly on the fruit surface. The total changes in color (ΔE^*), saturation (ΔC^*) and hue (ΔH^*) during processing were calculated according to the formulas presented in the literature (ZIELINSKA, MARKOWSKI 2012). The results were averaged over 32 measurements.

The overall appearance was evaluated based on the macrographs of the fruit surface. The macrographs were obtained using a digital camera (Sony DSC-HX50, Sony Corporation, Tokyo, Japan).

Texture profile analysis was performed using a TA-HD plus texture analyzer (Stable Micro Systems, Godalming, UK). Mechanical properties of fruits were automatically computed using Texture Exponent Stable Micro Systems v.6.1.11 texture-analyzing software. Hardness was defined as the maximum force measured during the first compression. Cohesiveness was defined as the ratio of the area during the second compression of the sample to the area of the first sample compression. Springiness was defined as the ratio of time from the start of the second area up to the second probe reversal over time between the start of the first area and the first probe reversal. Chewiness was defined as the product of hardness, cohesiveness and springiness (CHONG et al. 2014). The results were averaged over 15 measurements.

Particle density (ρ_p) was measured using the hydrostatic method and calculated using the following formula (RAHMAN 1995):

$$\rho_p = \frac{m_p}{m_p - m_w} \cdot \rho_w \tag{5}$$

where:

ρ_p – indicates particle density [kg/m^3],

ρ_w – indicates water density [kg/m^3],

m_w – indicates the mass of sample immersed in water [kg],

m_p – indicates the mass of sample in the air [kg].

The true density of cranberries was measured with a pycnometer. Cranberries were dried at 70°C (13.3 kPa) for 24 h in the vacuum drying oven DZ ZBC II (Chemland, Stargard Szczeciński, Poland) according to the standard (AOAC, 2002) and ground in a laboratory mill. A sample mass of approximately 0.002 kg was used in each experiment. The mass of the sample was measured using an electronic balance (RADWAG, WPS 4000/C/2, Radom, Poland). Non-water miscible liquid (xylene) and a calibrated glass pycnometer with an estimated volume of 50 ml (LG-3838-3658, Chemland Ltd., Poland) were used. The density of xylene was determined at 864±1 kg/m^3. The true density of fruits (6) and volumetric shrinkage (7) were calculated according to the formulas presented in the literature (ZIELINSKA et al., 2015):

$$\rho_T = \frac{864 \cdot (W_3 - W_1)}{W_2 + (W_3 - W_1) - W_4} \tag{6}$$

where:

ρ_T – indicates true density [kg/m^3],
W_1 – indicates the mass of an empty pycnometer [kg],
W_2 – indicates the mass of the pycnometer filled with the non-solvent [kg],
W_3 – indicates the total mass of the pycnometer and the sample [kg],
W_4 – indicates the total mass of the pycnometer, the non-solvent and the sample [kg].

The volumetric shrinkage (S_V) was calculated according to the following formula (ZIELINSKA et al. 2015):

$$S_V = \left(1 - \frac{V_{(\tau)}}{V_0}\right) \cdot 100\% \tag{7}$$

where:

S_V – indicates volumetric shrinkage [%],
V_0 – indicates the initial volume of the sample [m^3],
$V_{(\tau)}$ – indicates the volume of the sample at a particular drying time τ [m^3].

Apparent porosity (ε_{ap}) was calculated from the following formula (NOWAK et al. 2019):

$$\varepsilon_{ap} = \left(1 - \frac{\rho_p}{\rho_T}\right) \cdot 100\% \tag{8}$$

where:

ε_{ap} – indicates apparent porosity [%],
ρ_p – indicates particle density [kg/m^3],
ρ_T – indicates true density [kg/m^3].

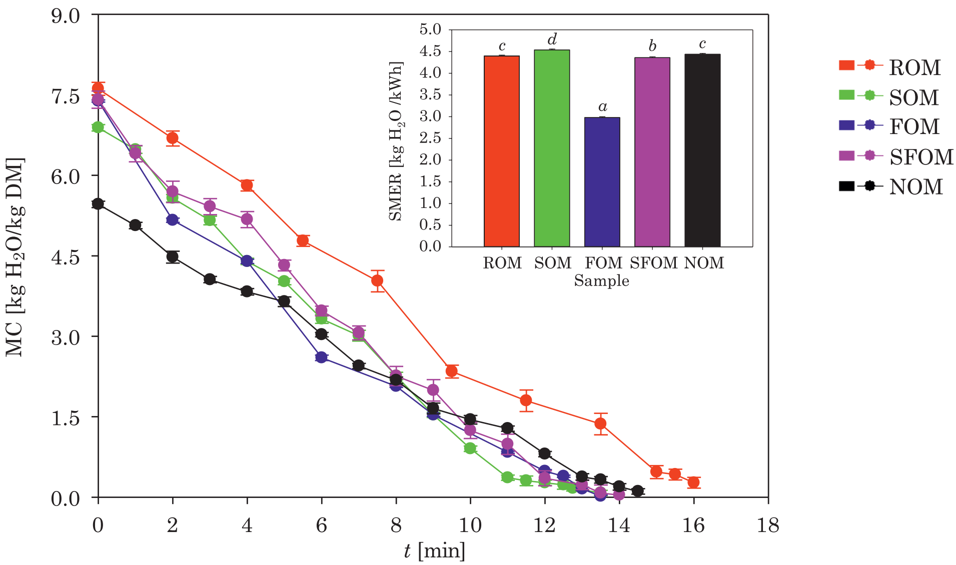
Thermal conductivity (λ), thermal diffusivity (a) and volumetric heat capacity (C_V) of cranberries were determined using a thermal analyzer (KD2 Pro meter, Decagon Devices, Pullman, USA) with a dual-needle SH-1 sensor. The dual-needle sensor was inserted into the fruits (ZIELINSKA et al. 2018a). The measurements were performed in five replicates.

The calculations were done using STATISTICA 12.0 software (StatSoft Inc., Tulsa, OK, USA). One-way ANOVA analysis (Duncan's test) was performed for samples with a normal distribution ($p \leq 0.05$). The analysis of variance for independent samples (Kruskal-Wallis's test) was carried out for samples without a normal distribution ($p \leq 0.05$).

Results and discussion

Osmo-microwave-vacuum drying of cranberries took from 13.5 to 16.0 min (Fig. 1). The longest drying time was recorded for non-treated samples (R). Osmo-microwave-vacuum drying of raw (non-treated) cranberries was longer by 33% than microwave-vacuum drying of whole fruits, while osmo-microwave-vacuum drying of fruits subjected to S, F and SF treatment was shorter by 7%, 4% and 3% than microwave-vacuum drying of whole fruits (STANISZEWSKA et al. 2019). There were no significant differences between the drying times of microwave-vacuum and osmo-microwave-vacuum cryogenically frozen fruits (STANISZEWSKA et al. 2019). The initial moisture content (MC_I) of osmotically dehydrated fruits that were not subjected to any additional treatment was 7.61±0.02 kg H_2O/kg DM. The use of N, S, F and SF treatments reduced MC_I of fruits by 28%, 9%, 3% and 3%, respectively (Fig. 1). The highest moisture losses were observed during osmotic dehydration of cryogenically frozen berries. They could be attributed to the considerable skin ruptures. However, initial cryogenic freezing (N) reduced osmo-microwave-vacuum drying time only by 9%. Sonication (S) and convective freezing (F) intensified the moisture removal during drying and resulted in the shortest osmo-microwave-vacuum drying time, i.e. 13.5 min. The reason could be severe damage to the cranberry's microstructure during convective freezing (F) and rupture of the berry fruit surface due to high-frequency ultrasound (S) treatment (STOJANOVIC, SILVA 2007, ZIELINSKA et al. 2018a).

In the present study, the specific moisture evaporation rate of drying (SMER) ranged from 2.98±0.02 to 4.54±0.02 kg H_2O/kWh (Fig. 1). SMER of osmo-microwave-vacuum drying of non-treated fruits (R) was 4.40±0.02 kg H_2O/kWh. SMER of osmo-microwave-vacuum drying of initially sonicated (S) fruits was significantly higher than that of osmo-microwave-vacuum drying of raw (R) fruits dried without any initial treatment. It indicates that for the same energy input sonication allowed to evaporate a greater amount of moisture than from non-treated berries. The changes in SMER values are related to the changes in the local temperature of the whole cranberries during microwave-vacuum drying (STANISZEWSKA et al. 2019). The results indicated the lowest changes in the local temperature of the material during osmo-microwave-vacuum



abcd – the same letters in columns mean no statistical differences between samples ($p \leq 0.05$); Symbols: MC – moisture content [kg H_2O/kg DM], t – time [min], SMER – specific moisture evaporation rate during microwave-vacuum drying at a microwave power of 300 W [kg H_2O/kWh], R – raw (non-treated), S – sonication, F – convective freezing, SF – sonication combined with convective freezing, N – cryogenic freezing, OM – osmo-microwave-vacuum drying

Fig. 1. Changes in moisture contents vs. drying times and specific moisture evaporation rates during osmo-microwave-vacuum drying of non-treated and pre-treated cranberries

drying of sonicated (S) fruits. On the other hand, osmo-microwave-vacuum drying of convectively frozen (F) berries was characterized by the highest energy consumption used for moisture evaporation. SMER of osmo-microwave-vacuum drying of berries subjected to initial freezing (F) was significantly lower (by 32%) than SMER of osmo-microwave-vacuum drying of fruits without any initial treatment (R). The study on the effectiveness of initial treatments on the improvement of SMER of osmo-microwave-vacuum drying showed the best results for sonication (S). There were no significant differences between SMER of osmo-microwave-vacuum drying of cryogenically frozen (N) and non-treated (R) fruits. Convective freezing preceded by sonication (SF) and convective freezing alone (F) decreased SMER of osmo-microwave-vacuum drying and thus reduced the energy efficiency of drying compared to osmo-microwave-vacuum drying of fruits without any initial treatment (Fig. 1). However, SMER of microwave-vacuum drying of convectively frozen (F) cranberries was 54% higher than SMER of osmo-microwave-vacuum drying of cranberry fruits (STANISZEWSKA et al. 2019). This indicated that microwave-vacuum drying of convectively frozen (F) fruits was much more energy-efficient than osmo-microwave-vacuum drying. Osmo-microwave-vacuum drying of raw (R), sonicated (S), sonicated and convectively frozen (SF) as well as cryogenically frozen (N) cranberries was more effective than microwave-vacuum drying of fruits (STANISZEWSKA et al. 2019).

The effective moisture diffusivity (D_{eff}) of whole cranberries was significantly influenced by the pre-treatments (Tab. 1). The values of D_{eff} of osmo-microwave-vacuum dried cranberries ranged from 2.83±0.02 to 5.09±0.02 × 10^{-9} m^2/s. Convective freezing (F), sonication (S), their combination (SF) as well as cryogenic freezing (N) increased the moisture diffusivity of fruits and shortened the drying time. The highest D_{eff} value was noted for samples subjected to convective freezing (F) (Tab. 1). Among different pre-treatments, cryogenic freezing (N) resulted in the lowest increase in D_{eff} values of dried fruits. The reason can be the freeze-cracking of cranberry fruits when subjected to a very high freezing rate and/or a very low freezing temperature (ZIELINSKA et al. 2019).

Osmo-microwave-vacuum drying produced berries of water activity (a_w) lower than the critical value ($a_w \leq 0.6$), which limit the growth of microorganisms (YOGENDRARAJAH et al. 2015) (Tab. 1).

Particle density (ρ_p) of berry fruits decreased significantly during osmo-microwave-vacuum drying, while their particle porosity (ε_{ap}) increased (Tab. 1). The reason for this can be a "puffing effect", which resulted in the concentration of dry matter components and an increase in the number of pores (FIGIEL 2009). Osmo-microwave-vacuum dried samples subjected to convective freezing (F) and sonication combined with convective freezing (SF) were characterized by the highest porosity, i.e. 89%±1%. Osmo-microwave-vacuum dried samples subjected to initial cryogenic freezing (N) were characterized by the lowest porosity, i.e. 81%±5%, and the highest density, i.e. 263%±68 kg/m^3. However, convective freezing (F) and convective freezing combined with sonication (SF) resulted in significantly lower (19% and 21%, respectively) density of osmo-microwave-vacuum dried cranberries than that dried without any initial treatment (R). The results are consistent with published data (NOWAK et al. 2019). Most probably, the formation of ice crystals during slow mechanical freezing and further thawing of fruits resulted in a significant change in the fruit structure, with severe cell damage, water loss, density decrease and porosity increase (NOWAK et al. 2019). There was no significant effect of the pre-treatments on the volumetric shrinkage of osmo-microwave-vacuum dried cranberries (Tab. 1).

Osmo-microwave-vacuum drying significantly decreased thermal conductivity (λ) and volumetric heat capacity (C_V), as well as significantly increased thermal diffusivity (a) of cranberry fruits (Tab. 1). Lower values of thermal conductivity (λ) of dried cranberries resulted from a significant decrease in moisture content and a significant increase in porosity of fruits (thermal conductivity and volumetric heat capacity of water are much higher than other food constituents, such as proteins, fat, carbohydrates) (ZIELINSKA et al. 2018a). The values of λ, α and C_V of osmo-microwave-vacuum dried cranberries subjected to initial treatments ranged from 0.061±0.006 to 0.083±0.002 W/mK, from 1.23±0.04 to 1.60±0.08 × 10^{-7} m^2/s

Table 1

Thermophysical properties of raw (non-treated) and pre-treated cranberries subjected to osmo-microwave-vacuum drying

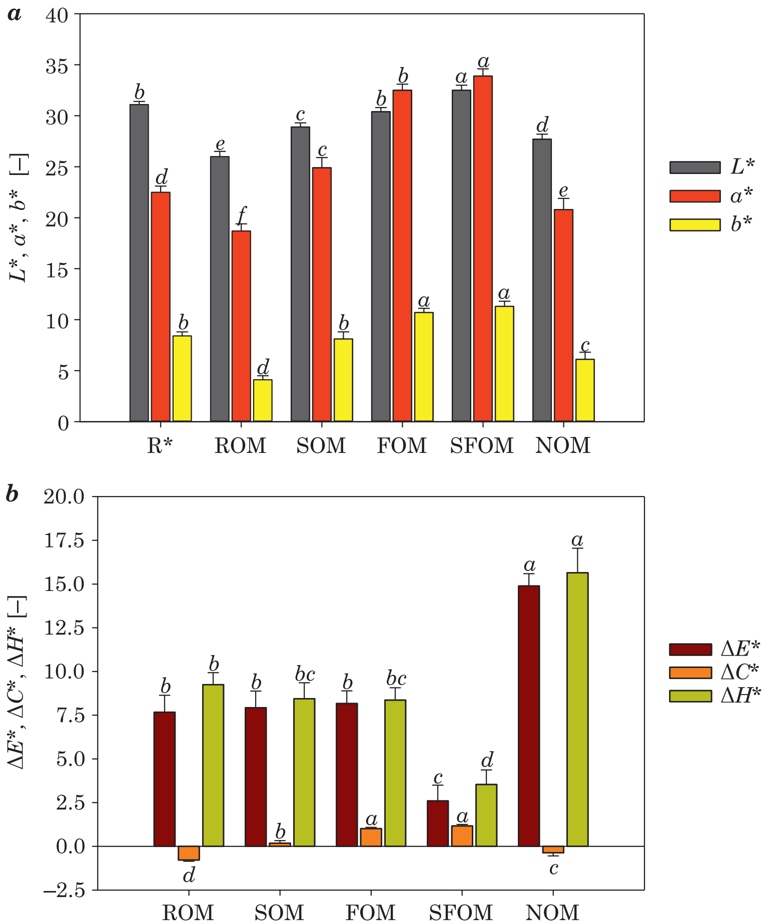
Sample	MC [kg H_2O/kg DM]	$D_{eff} \times 10^9$ [m^2/s]	a_w [-]	ρ_p [kg/m^3]	ε_{ap} [%]	S_v [%]	λ [W/mK]	$\alpha \times 10^7$ [m^2/s]	C_V [MJ/m^3K]
R*	7.49 ± 0.02^a	-	0.965 ± 0.002^d	672 ± 7^d	52 ± 1^a	-	0.248 ± 0.003^d	1.06 ± 0.01^d	2.351 ± 0.040^c
ROM	7.61 ± 0.12^a	2.83 ± 0.02^a	0.277 ± 0.004^b	188 ± 17^b	87 ± 1^{bc}	45 ± 4^a	0.071 ± 0.003^{ab}	1.21 ± 0.03^c	0.589 ± 0.018^b
SOM	6.89 ± 0.06^c	4.10 ± 0.02^d	0.282 ± 0.001^b	190 ± 1^b	86 ± 2^{bc}	51 ± 7^a	0.061 ± 0.006^a	1.23 ± 0.04^c	0.495 ± 0.039^a
FOM	7.39 ± 0.02^b	5.09 ± 0.02^e	0.280 ± 0.006^b	149 ± 18^a	89 ± 1^c	47 ± 4^a	0.069 ± 0.006^{ab}	1.42 ± 0.04^b	0.482 ± 0.034^a
SFOM	7.41 ± 0.16^a	3.68 ± 0.02^c	0.264 ± 0.004^a	152 ± 10^a	89 ± 1^c	51 ± 4^a	0.078 ± 0.002^c	1.60 ± 0.08^a	0.492 ± 0.022^a
NOM	5.46 ± 0.06^d	3.06 ± 0.01^b	0.312 ± 0.001^c	263 ± 68^c	81 ± 5^b	56 ± 4^a	0.083 ± 0.002^c	1.39 ± 0.03^b	0.602 ± 0.017^b

Table contains mean values ± standard errors;
^{abcd} – the same letters in columns indicate no statistical differences between samples ($p \leq 0.05$);
* – data obtained from the outside source (ZIELINSKA et al. 2018a);
symbols: MC – moisture content [kg H_2O/kg DM], D_{eff} – coefficient of effective moisture diffusivity [m^2/s], a_w – water activity [-], ρ_p – particle density [kg/m^3], ε_{ap} – particle porosity [%], S_v – volumetric shrinkage [%], λ – thermal conductivity [W/mK], α – thermal diffusivity [m^2/s], C_V – volumetric heat capacity [MJ/m^3K], R – raw (non-treated), S – sonication, F – convective freezing, SF – sonication combined with convective freezing, N – cryogenic freezing, OM – osmo-microwave-vacuum drying

and from 0.482±0.034 to 0.602±0.017 MJ/m^3K, respectively. Osmo-microwave--vacuum drying of fruits combined with cryogenic freezing (N) resulted in 20% higher values of thermal conductivity than osmo-microwave-vacuum drying of berries without any initial treatment (Tab. 1). Osmo-microwave-vacuum drying combined with sonication and convective freezing (SF) produced berries of the highest thermal diffusivity i.e. 1.60±0.08 × 10^{-7} m^2/s. Osmo-microwave--vacuum drying preceded by S, F or SF treatments resulted in significantly lower (up to 18%) values of volumetric heat capacity of fruits than osmo-microwave--vacuum drying of berries without any initial treatment (Tab. 1).

The color of dried cranberries was significantly affected by drying and pretreatment methods (Figs. 2*a* and 2*b*). Osmo-microwave-vacuum drying of non--treated berries caused a decrease in lightness (L^*), redness (a^*) and yellowness (b^*) of fruits by 16%, 17% and 51%, respectively (Fig. 2*a*). Osmo-microwave-vacuum drying preceded by any initial treatment used in this study resulted in lighter, more red and more yellow fruits than osmo-microwave-vacuum drying without any initial treatment. Convective freezing, both alone (F) and in combination with sonication (SF), significantly increased a^* and b^* of osmo-microwave-vacuum dried fruits (Figs. 3*a*, 3*d* and 3*e*). As the color of cranberries is determined mostly by the content of monomeric anthocyanins (mainly peonidin-3-O-galactoside and cyanidin-3-O galactoside) and yellow flavonoids, it is expected that osmo--microwave-vacuum drying of convectively frozen fruits, both alone (F) and in combination with sonication (SF), will result in a high antioxidant activity of fruits (ZIELINSKA et al. 2018b). The lowest total changes in color (ΔE^*) and hue (ΔH^*) were observed during osmo-microwave-vacuum drying of fruits subjected to convective freezing preceded by sonication (SF) and they were 2.6±0.9 and 3.5±0.8, respectively (Fig. 2*b*). Osmo-microwave-vacuum drying of fruits subjected to convective freezing preceded by sonication (SF) produced berries of the highest L^* (32.5±0.5), a^* (33.9±0.7), and b^* (11.3±0.5) values. The values of L^*, a^*, and b^* of fruits subjected to convective freezing preceded by sonication (SF) were even higher than that achieved by raw (non-treated) berries (31.1± 0.3, 22.5±0.6 and 8.4±0.4) (Fig. 2*a*). The reason for this may be that ice crystals formed during convective freezing (F) destroyed the structure of the fruits and resulted in a greater release of berry juice, which could have influenced color intensification (ZIELINSKA, ZIELINSKA 2019).

However, the lowest total color change (ΔE^*) indicated that osmo-microwave--vacuum drying of cranberries subjected to initial SF treatment produced berries of the most similar color to the raw (R) fruits (Figs. 3*a* and 3*e*). The lowest L^*, a^*, and b^* parameters were achieved by non-treated cranberries subjected to osmo-microwave-vacuum drying (ROM) (Fig. 2*a*). Samples subjected to cryogenic freezing (N) were characterized by the highest values of ΔE^* and ΔH^*, i.e. 14.9±0.7 and 15.6±1.4, respectively (Fig. 2*b*). The results indicate that cryogenic freezing (N) combined with osmo-microwave-vacuum drying resulted in the greatest changes in sample color (Fig. 3*a* and 3*f*).



*abc***d** – the same letters in columns mean no statistical differences between samples ($p \leq 0.05$);
* – data obtained from the outside source (ZIELINSKA, ZIELINSKA 2019);
Symbols: L^* – lightness [-], a^* – redness [-], b^* – yellowness [-], ΔE^* – total color difference [-], ΔC^* – total saturation difference [-], ΔH^* – total hue difference [-], R – raw (non-treated), S – sonication, F – convective freezing, SF – sonication combined with convective freezing, N – cryogenic freezing, OM – osmo-microwave-vacuum drying

Fig. 2. Color parameters and total differences in color, saturation and hue between raw (non-treated) and pre-treated cranberries subjected to osmo-microwave-vacuum drying: *a* – lightness, redness and yellowness, *b* – total color difference, total saturation difference and total hue difference

The values of hardness (H), chewiness (Ch), cohesiveness (C) and springiness (Sp) of cranberries subjected to different pre-treatments and osmo-microwave-vacuum drying are shown in Figures 4*a* and 4*b*. Hardness (H), chewiness (Ch), cohesiveness (C) and springiness (Sp) of raw (R) non-dried fruits were 63.7±2.5 N, 10.2±0.8 N, 0.23±0.01 and 0.71±0.01, respectively (ZIELINSKA et al. 2019).

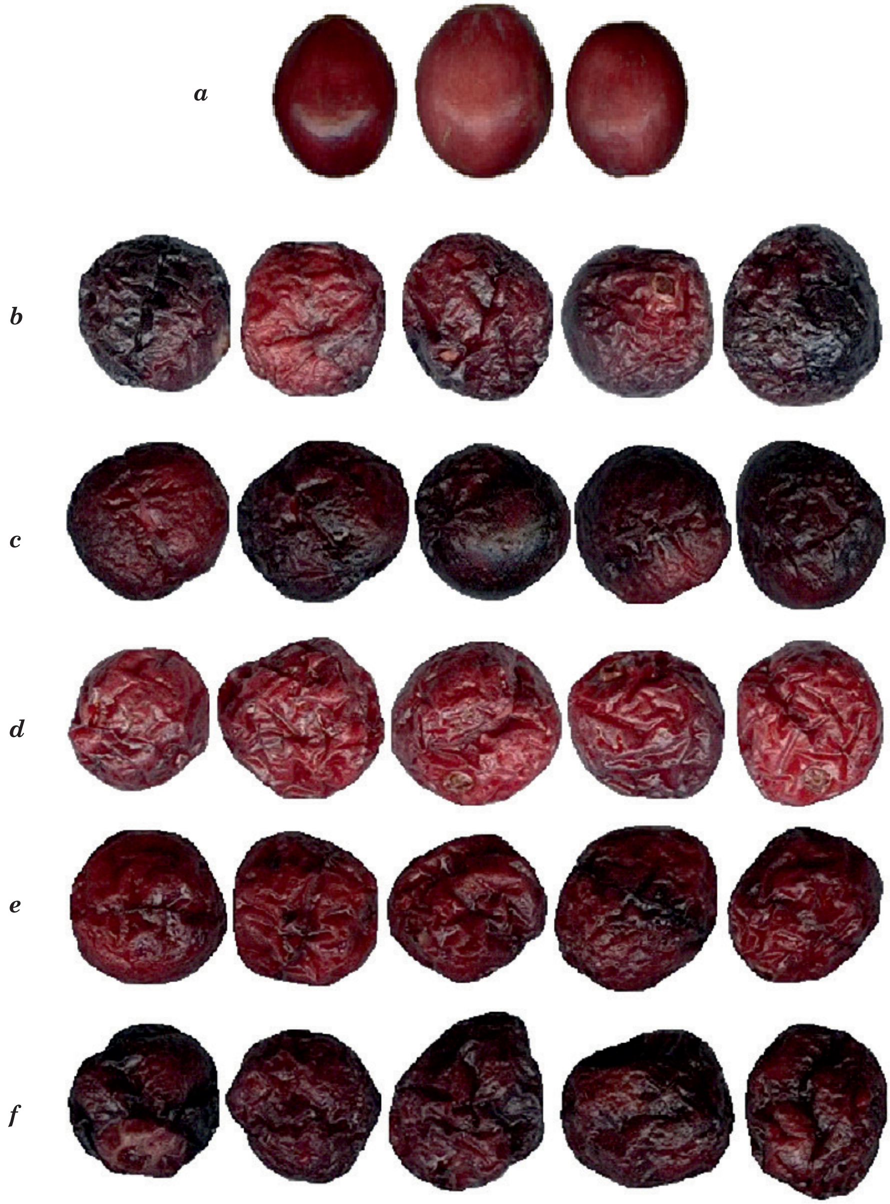
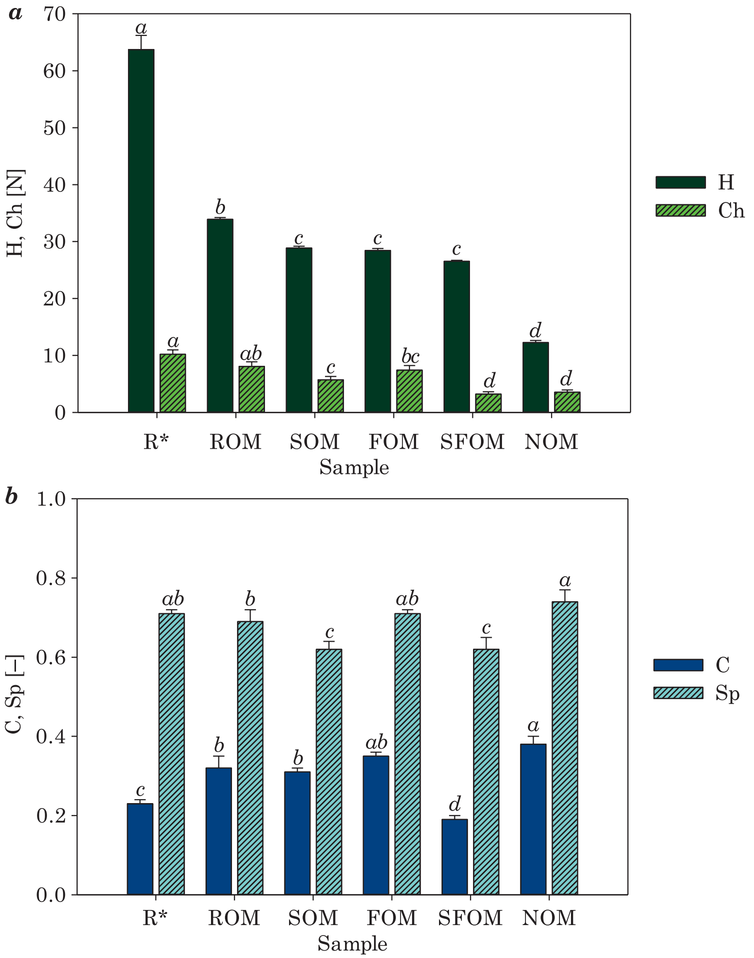


Fig. 3. The overall appearance of: *a* – raw cranberries (R), *b* – raw (non-treated) fruits subjected to osmo-microwave-vacuum drying (ROM), *c* – fruits subjected to sonication and osmo-microwave-vacuum drying (SOM), *d* – fruits subjected to convective freezing and osmo-microwave-vacuum drying (FOM), *e* – fruits subjected to sonication combined with convective freezing and osmo-microwave-vacuum drying (SFOM), *f* – fruits subjected to cryogenic freezing and osmo-microwave-vacuum drying (NOM)

Osmo-microwave-vacuum drying of non-treated fruits significantly decreased their hardness and increased their cohesiveness by 47% and 39%, respectively. Osmo-microwave-vacuum drying did not affect the chewiness or springiness of fruits.

Hardness, chewiness, cohesiveness and springiness of dried cranberries ranged from 12.3±0.4 to 33.9±0.3 N, from 3.2±0.4 to 8.1±0.8 N, from 0.19±0.01 to 0.38±0.02 and from 0.62±0.02 to 0.74±0.03, respectively (Fig. 4).



abcd – the same letters in columns indicate no statistical differences between samples ($p \leq 0.05$);
* – data obtained from the outside source (ZIELINSKA et al. 2019);
Symbols: H – hardness [N], Ch – chewiness [N], C – cohesiveness [-], Sp – springiness [-], R – raw (non-treated), S – sonication, F – convective freezing, SF – sonication combined with convective freezing, N – cryogenic freezing, OM – osmo-microwave-vacuum drying

Fig. 4. The values of: *a* – hardness and chewiness, *b* – cohesiveness and springiness of raw (non-treated) and pre-treated cranberries subjected to osmo-microwave-vacuum drying

All of the initial treatments significantly reduced the hardness and chewiness of osmo-microwave-vacuum dried cranberries. Cryogenic freezing (N) combined with osmo-microwave-vacuum drying of whole cranberries produced dried fruits with the highest springiness (Sp) and the lowest chewiness (Ch). This can be applied to produce soft dried fruits eaten together with cereals. Sonication combined with convective freezing (SF) and osmo-microwave-vacuum drying produced cranberries of the lowest chewiness (Ch), cohesiveness (C) and springiness (Sp). This proves that SF treatment, combined with osmo-microwave-vacuum drying can be applied to produce dried healthy crispy snacks. On the other hand, sonication combined with convective freezing (SF) resulted in a significantly lower (0.19±0.01) cohesiveness (C) of dried fruits than convective freezing (F) alone (0.35±0.01) (Fig. 4*b*). The results show that products of high cohesiveness are more attractive and they have more desired sensory properties than fruits of low cohesiveness. Convective freezing (F) combined with osmo-microwave-vacuum drying can thus be recommended for the production of berries with high resistance to stress associated with manufacturing, packaging, storage and delivery.

Summary

All of the initial treatments used in the present study significantly affected the drying curves, times and energy usage as well as the color, mechanical and thermophysical properties of osmo-microwave-vacuum dried cranberries. Osmo-microwave-vacuum drying of cranberries took from 13.5 to 16.0 min. All pre-treatments increased the moisture diffusivity of fruits and thus reduced the drying time. Convective freezing (F) and sonication (S) resulted in the greatest increase in the moisture diffusivity of dried fruits and, thus, the shortest drying time, i.e. 13.5 min. Pre-treatments significantly influenced energy consumption during osmo-microwave-vacuum drying. Sonication (S) resulted in the lowest energy input required for moisture evaporation during osmo-microwave-vacuum drying of berries. Despite the same drying time, osmo-microwave-vacuum drying of cranberries subjected to sonication (S) was much more energy-efficient than that subjected to convective freezing (F). Nevertheless, convective freezing (F) and convective freezing combined with sonication (SF) gave good results in terms of the color of dried fruits. Convective freezing in combination with sonication (SF) significantly reduced total color changes (ΔE^*) during drying. It then improved the color of dried cranberries and produced berries with the highest lightness, redness and yellowness. Their color was most similar to the color of fresh fruits. Sonication combined with convective freezing (SF) and osmo--microwave-vacuum drying also allowed to produce cranberries with the lowest chewiness, cohesiveness and springiness and, thus, can be recommended for the production of dried crispy snacks. However, SF berries will be less resistant to stress associated with manufacturing, packaging, storage and delivery than non-treated (R), sonicated (S), convective frozen (F) and cryogenic frozen (N) fruits with higher cohesion values. Cranberries subjected to sonication (S), convective freezing (F) and convective freezing combined with sonication (SF) were characterized by lower volumetric heat capacity than berries dried without any initial treatment. In addition, sonication combined with convective freezing (SF) and osmo-microwave-vacuum drying produced berries with the highest thermal diffusivity. Among different initial treatments, cryogenic freezing (N) combined with osmo-microwave-vacuum drying allowed producing dried fruits with the highest values of density and thermal conductivity. It also produced berries of good quality in terms of mechanical properties, i.e. high springiness and low chewiness. However, it resulted in the biggest changes in the color of dried fruits.

Acknowledgements

This study was supported by the Polish National Science Center (grant No. 2015/17/B/NZ9/03601, title: *The effect of unconventional pretreatment methods on the kinetics of hybrid dehydration and physical and chemical properties of cranberries Vaccinum macrocarpon)* and the University of Warmia and Mazury in Olsztyn (grant No. 16.610.001-300).

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