Technical Sciences, 2019, 22(2), 151–167

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

APPLICATION OF SONICATION AND FREEZING AS INITIAL TREATMENTS BEFORE MICROWAVE-VACUUM DRYING OF CRANBERRIES

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Received 13 February 2019, accepted 27 February 2019,available online 7 March 2019

Keywords: Cranberry, vacuum drying, microwave drying, drying pretreatment, texture, density, color.

Abstract

The aim of study was to determine the influence of sonication and freezing on the kinetic of the microwave-vacuum drying, energy consumption and physical properties of whole cranberries as well as evaluate the applicability of sonication instead of freezing in order to change their physical properties and the drying kinetic of whole cranberries. Microwave-vacuum drying of whole cranberries with/without initial treatments took from 12±1 to 14.5±0.5 minutes. All of treatments did not significantly shorten the drying time of cranberries. However, they increased SMER values even by 31%. Despite of cryogenic freezing, all of treatments significantly increased the values of D_{ew}. Sonication combined with drying allowed to obtain dried berries characterized by the lowest cohesiveness (0.19±0.02), springiness (0.62±0.02) and chewiness (3.4±0.8 N), while cryogenic freezing combined with drying allowed to obtain dried fruits characterized by highest springiness (0.75±0.03) and low chewiness (3.3±0.5 N). The highest lightness (32.2±0.7), redness (32.6±0.8), and yellowness (11.1±0.7) were found for fruits subjected to initial convective freezing before drying. The efficiency of sonication in color change was comparable to cryogenic freezing and much lower than convective freezing. All of initial treatments increased such thermal properties of dried cranberries as thermal conductivity and thermal diffusivity.

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Introduction

Cranberries (*Vaccinium macrocarpon* L.) contain high amount of biologically active substances, including phenolic acids (benzoic, hydroxycinnamic and ellagic acids) and flavonoids (anthocyanins, flavonols and flavan-3-ols) (McKay, Blumberg 2007). They provide minerals, organic acids, pectins, vitamins such as A, B_1, B_2 and C to the body. Raw and dried cranberry fruits can be used as ingredients of breakfast cereals, salads and other dishes (Skrovankova et al. 2015). Cranberries consist mainly of water, which constitutes about 86% of the composition of fresh fruits. Due to their high moisture content, cranberries are usually processed in order to reduce microbial activity, minimize product deterioration and extend their shelf-life (Zielinska et al. 2018a). Dried fruits with sufficiently low A_W may ensure the both low enzymatic activity and microbial spoilage.

Hot air drying makes cranberries available to consumers throughout the whole year. Removal of moisture from the whole cranberries is difficult due to its waxy skin, which inhibits the moisture movement. For example, hot air drying takes from 310 to 11,700 minutes (Zielinska, Zielinska 2019). The exposure of berry fruits to high air temperature and significant moisture loss during drying lead to significant changes in sample texture (Zielinska et al. 2018a). Hot air drying produces brittle fruits that are difficult to store and transport and are not suitable for direct consumption. Hot air can be replaced by the alternative heat source, such as microwaves. Drying with microwaves shortens the drying time, limits oxidation and positively influences physicochemical properties of dried products (Soysal et al. 2009). However, the application of microwaves under atmospheric pressure may significantly deteriorate the quality of the final product. Microwaves cause volumetric heating, while reduced pressure eliminates the risk of excessive material temperature and degradation of bioactive compounds (Zhang et al. 2006). The application of microwaves under reduced pressure allows to produce dried snacks characterized by hard and crispy texture and considerable resistance to stress associated with manufacturing, packaging, storage, and delivery. Microwave-vacuum drying results in high retention of polyphenols and high antioxidant activity of dried cranberries (Zielinska, Zielinska 2019). Microwave-vacuum drying of cranberries at microwave power of 150 to 500 W leads to rapid evaporation of moisture from capillaries (Zielinska et al. 2019). Whole cranberries lost moisture several dozen times faster during microwave-vacuum than hot air drying. The time of microwave-vacuum drying of whole cranberries is significantly shorter than the time of hot air drying and it ranges from 8 to 91 minutes (Zielinska et al. 2019). The five-fold increase in microwave power from 100 to 500 W decreases drying time by up to 90%. Among the various variants of microwave-vacuum drying used for drying of whole cranberries, drying at low microwave powers, i.e. from 100 to 300 W is recommended as a good alternative to the hot air drying of cranberries, in terms of their phytochemicals and color (ZIELINSKA, ZIELINSKA 2019). Effective moisture diffusivities and drying rates are higher, whereas drying times are shorter for the samples dried by microwave-vacuum drying compared with the samples processed by hot air drying.

The negative effect of microwave-vacuum drying on the material properties can be minimized by the application of low microwave power and pressure in the drying chamber. Additionally, various initial treatments can be applied before drying to change material properties and speed up the drying process. Up to date, initial treatments of berries before drying processes have relied on mechanical, chemical and thermal treatments or their combinations, such as sonication, convective freezing, cryogenic freezing, osmotic dehydration, ultrasound-assisted osmotic dehydration, osmotic dehydration combined with microwave-vacuum pretreatment, etc. (GRABOWSKI et al. 2007, NOWAK et al. 2018, RENNIE, MERCER 2013, SUNJKA et al. 2004, ZIELINSKA et al. 2015, 2018a, b, 2019, ZIELINSKA, MARKOWSKI 2018, ZIELINSKA, ZIELINSKA 2019). Among mechanical pretreatments, sonication performed at frequency between 18 and 100 kHz and intensity higher than 1 $W \cdot cm^{-2}$ (typically in the range from 10 to 1000 $W \cdot cm^{-2}$) can be used as an initial treatment of different food products (MCCLEMENTS 1995). It can be used to increase e.g. the permeability of the skin of berry fruits and increase the drying rate (ZIELINSKA et al. 2015). The effect of acoustic microstreaming accelerates heat and mass transfer processes during drying (NASCIMENTO et al. 2016). Additionally, sonication prevents high losses of polyphenols and flavonoids during drying and increases the availability of vitamins B_1, B_2, B_3, and B_6 in the dried product (FERNANDES et al. 2015, RODRIGUEZ et al. 2014). Sonication represents an interesting technique for processing of raw blueberries and can be a good alternative for time and energy-consuming convective freezing of whole fruits (NOWAK et al. 2018). Also, convective and cryogenic freezing can be applied to biological materials before drying in order to change material properties and influence the drying kinetic. Nevertheless, the combination of freezing and drying adversely affects the quality of the final product, generating harder, more chewy and gummy fruits compared with those dried without initial pretreatment. Convective freezing significantly reduces time and specific energy consumption of hot air drying (ZIELINSKA et al. 2015). However, it does not significantly shorten the time of microwave-vacuum drying (ZIELINSKA, ZIELINSKA 2019). Sonication and freezing may significantly decrease particle density and increase porosity of whole blueberries. Additionally, sonication as well as freezing may produce significantly softer, less chewy and gummy blueberries compared to raw samples (NOWAK et al. 2018). Among thermal treatments, initial microwave-vacuum treatment has gained relevance in food processing (ZIELINSKA, MARKOWSKI 2018). Microwave-vacuum pretreatment at low microwave power (100 W) before osmo-microwave-vacuum drying of berries results in high retention of phenolic compounds, high antioxidant activity and attractive color, which indicates the high content of total anthocyanins and flavonoids (ZIELINSKA et al. 2018b).

Literature studies on drying of berry fruits show the need for development of innovative drying processes and pretreatments, which help to change the structure of the material, shorten the drying time, and thus obtain a high quality of dried products determined by their physical properties. There is a general scarcity of research into the possibility of using sonication (short mechanical treatment) instead of convective freezing (time and energy-consuming thermal treatment) or cryogenic freezing (a process that generates high costs due to continuous refilling of the refrigerant) of whole berries (NOWAK et al. 2018). A better understanding of changes in the physical properties of whole cranberries subjected to different initial treatments and microwave-vacuum drying could contribute to preserving the desirable characteristics of the dried products. Therefore, the aim of this study was to:

a) determine the influence of sonication (non-thermal) and freezing (thermal) treatments on the kinetic of the microwave-vacuum drying, energy consumption and physical properties of whole cranberries (*Vaccinium macrocarpon* L.);

b) evaluate the applicability of sonication instead of convective or cryogenic freezing in order to change their physical properties and thus change the drying kinetic of whole cranberries.

Among thermal and non-thermal treatments, sonication, convective freezing, ultrasound-assisted convective freezing, and cryogenic freezing were used. Additionally, samples were dried without any initial treatments. Among the material properties, such properties as moisture content, water activity, moisture diffusion, lightness, redness, yellowness, total differences in color, saturation and hue, thermal conductivity, thermal diffusivity, specific heat, density, porosity, hardness, cohesiveness, springiness, and chewiness were analyzed.

The results of this study can be used in practice by producers of berries, processed cranberry fruits suppliers, and manufacturers of equipment used in cranberry processing.

Research methodology

The test material consisted of whole cranberry fruits (*Vaccinium Macrocarpon* L.) delivered by GP Klasa Sp. z o.o (Klementowice, Poland). Fruits were manually harvested several weeks before the study, sorted and packed in sealed plastic containers. Cranberries were similar in color, shape and size. Raw cranberries (R) were refrigerated (2±2°C) at 90% relative humidity for up to 2 weeks. Whole cranberries were subjected to initial treatments (sonication, convective freezing, convective freezing preceded by sonication as well as cryogenic freezing) and microwave-vacuum drying (Fig. 1). The initial moisture content of fresh fruits was about 7.49±0.02 kg $H_2O \cdot kg\ DM^{-1}$. The control sample composed of raw berries was not subjected to the drying processes. Sonication was conducted using ultrasonic disruptor Scientz-650E (Ningbo Scientz Biotechnology Co. Ltd., China) equipped with 6 mm titanium ultrasound probe. Sonication was conducted for 10 min (1 s impulse and 1 s gap between impulses) in a water bath containing 1 dm^3 of distilled water. The ultrasound frequency was 25±5 kHz, while ultrasonic power input was 600 W. Cranberries were convectively and cryogenically frozen. They were placed in a freezer operating at -18°C and left for 48 hours. Additionally, they were immersed in a liquid nitrogen (a boiling temperature of -196°C).

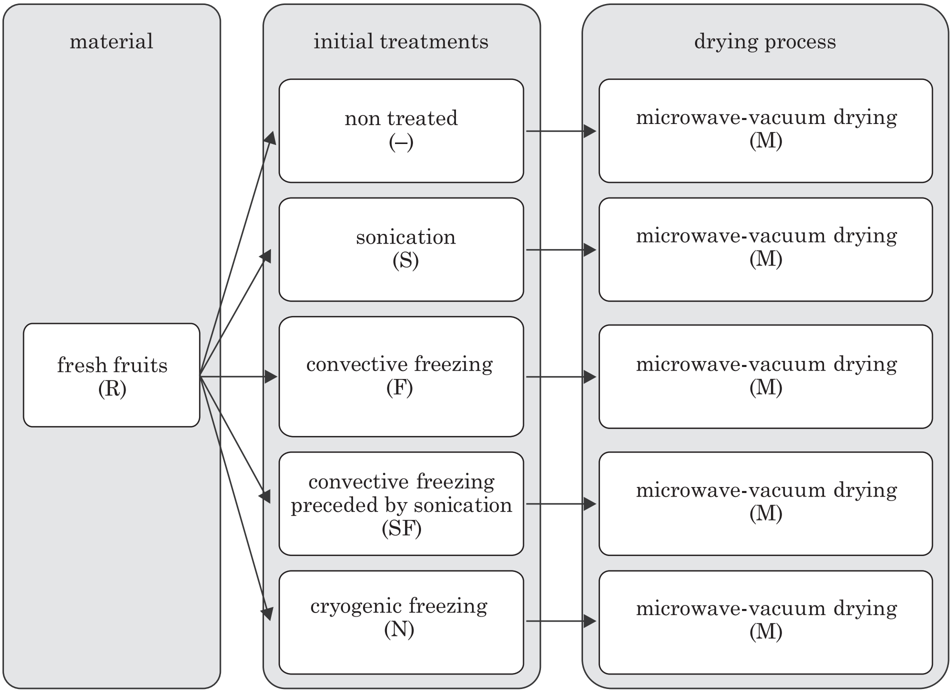

Fig. 1. Processing scheme of cranberry fruits

A microwave-vacuum dryer (PROMIS TECH, Wroclaw, Poland) was used for drying experiments (Fig. 2). System comprised a motor, a drying chamber, a regulating valve, a condensation unit, a microwave generator, a microwave circulator, a temperature measuring unit, a pressure measuring unit, a control unit. Dryer operated at a microwave power of 300 W and absolute pressure of 5± kPa. During drying, changes in sample mass, sample temperature, pressure in the drying chamber and energy consumption were recorded. To evaluate changes in sample mass, the drying time of every portion of fruits was prolonged. 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 sharply. The experiments were conducted in duplicate.

Fig. 2. Microwave-vacuum drying set up

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):

$$\mathrm{SMER} = \frac{M_{\mathrm{mr}}}{E_{\mathrm{input}}} \tag{1}$$

where:

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

E_{input} – energy input [kWh].

The moisture content of fruits was determined gravimetrically using vacuum drying oven DZ ZBC II (Chemland, Stargard Szczeciński, Poland). Cranberries were dried at 70°C for 24 h (AOAC 2002). The water activity (A_W) was measured using the Aquaspector AQS-31-TC (NAGY, Germany). The final result was the arithmetic mean of the two repetitions carried out for a given sample.

Color measurements were carried out using 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 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 the formulas presented in the literature (ZIELINSKA, MARKOWSKI 2012). The results were averaged over 32 measurements.

Thermal conductivity (λ) and thermal diffusivity (a) of cranberries were determined using thermal analyzer (KD2 Pro meter, Decagon Devices, Pullman, USA) with the dual-needle SH-1 probe. The specific heat (C_p) of cranberries was calculated based on the measured values of Thermal conductivity (λ), thermal diffusivity (a) and apparent density (ρ_p). The measurements were performed in five replicates.

Texture profile analysis was performed using a TA-HD plus texture analyzer (Stable Micro Systems, Godalming, UK). The time between compressions was equal to 1 s, relative deformation was equal 50%, the speed of piston was equal to 2 $mm \cdot s^{-1}$. Each sample was analyzed in 15 replications. Mechanical properties of fruits were automatically computed using texture analyzer software, Texture Exponent Stable Micro Systems v.6.1.11.0. 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).

Particle density (ρ_p) was measured using hydrostatic method. The measurements were done in triplicate. It was calculated from the following formula (RAHMAN 1995):

$$\rho_p = \frac{m_p}{m_p - m_w} \cdot \rho_w \tag{2}$$

where:

ρ_p – particle density [$g \cdot cm^{-3}$],
ρ_w – water density [$g \cdot cm^{-3}$],
m_w – mass of sample immersed in water [g],
m_p – mass of sample [g].

Apparent porosity (ε_{ap}) was calculated from the following formula (NOWAK et al. 2018):

$$\varepsilon_{ap} = (1 - \frac{\rho_p}{\rho_{DM}}) \cdot 100\% \tag{3}$$

where:

ρ_p – particle density [$g \cdot cm^{-3}$],
ρ_{DM} – density of dry mass [$g \cdot cm^{-3}$].
The measurements were done in triplicate.

Density of dry mass of cranberries powder was determined by the liquid pycnometer method. Cranberries were dried at 105°C for 24 h in an air-oven (FED53 127 Binder, US) according to the standard requirements (AOAC 1975) and were ground in a laboratory mill. Samples of approximately 2 g were used in each experiment. The mass of the sample was measured to the nearest 0.001 g using an electronic balance (RADWAG, WPS 4000/C/2, Radom, Poland). Non-water miscible liquid (xylene) and a calibrated glass pycnometer with estimated volume of 50 ml (LG-3838-3658, Chemland Ltd., Poland) were used. Xylene density was determined at 864±1 kg · m^{-3}. The measurements were done in triplicate. Density of dry mass was calculated from the following equation (ZIELINSKA et al. 2015):

$$\rho_{DM} = \frac{0.864 \cdot (m_3 - m_1)}{m_2 + (m_3 - m_1) - m_4} \quad (4)$$

where:

ρ_{DM} – density of dry mass [kg · m^{-3}],
m_1 – mass of an empty pycnometer [g],
m_2 – mass of the pycnometer with the non-solvent [g],
m_3 – the total mass of the pycnometer and the powder [g],
m_4 – total mass of the pycnometer, the non-solvent liquid and the powder [g].

Volumetric shrinkage (S_v) of particle was calculated from the following formula (ZIELINSKA et al. 2015):

$$S_v = \left(1 - \frac{V_s}{V_0}\right) \cdot 100\% \quad (5)$$

where:

V_s – volume of sample after drying [cm^3],
V_0 – volume of sample before drying [cm^3].
The measurements were done in triplicate.

The coefficient of moisture diffusion was determined on the basis of the least-squares nonlinear estimation, Levenberg-Marquardt test, from equation (6) assuming constant values of the effective moisture diffusion coefficient and fruit shape as well as considering initial (7) and boundary conditions (8) (ZIELINSKA, MARKOWSKI 2018).

$$u(t = 0, x, y, z) = u_0 \quad (6)$$

$$t > 0 \rightarrow u(t, x, y, z) = u_r \quad (7)$$

$$\frac{u(\tau) - u_r}{u_0 - u_r} = \frac{6}{\pi^2} \cdot \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n^2 \cdot n^2 \cdot \frac{D_{ew} \cdot \tau}{R^2}\right) \quad (8)$$

where:

$u(\tau)$ – moisture content at the moment τ [kg H_2O·kg DM^{-1}],
u_r – equilibrium moisture content [kg H_2O · kg DM^{-1}],

u_0 – initial moisture content [kg $H_2O \cdot$ kg DM^{-1}],
n – number of measurements [-],
D_{ew} – effective moisture diffusivity [$m^2 \cdot s^{-1}$],
τ – time of drying [s],
R – radius of a sphere [m].

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

Results and discussion

To evaluate the effect of initial treatment on the kinetic of microwave-vacuum drying of whole cranberries, the changes in moisture contents (MC) vs. drying time (t) were monitored (Fig. 3). All of initial treatments significantly influenced the initial moisture contents of cranberries (Tab. 1). Even if it happened, they did not significantly shorten the drying time of cranberries. Microwave-vacuum drying of whole cranberries at 300 W, with or without initial treatments, took from 12±1 to 14.5±0.5 minutes. Also, they did not significantly change the shape of drying curve (Fig. 3). Microwave-vacuum drying allowed to obtain fruits of the final moisture contents and water activities of dried fruits in the range from 0.21±0.03 to 0.22±0.02 kg $H_2O \cdot$ kg DM^{-1} and from 0.267±0.005 to 0.314±0.002, respectively (Tab. 1). There were no significant differences between the final moisture contents of differently treated fruits. However, initial treatments significantly influenced the values of water activity of dried berries (Tab. 1). The results show that all of initial treatments allowed for the preservation of fruits and protection of biological material against the development of undesirable microorganisms. Among different treatments, sonication and ultrasound-assisted freezing before drying allowed to obtain final products of the lowest water activity.

To evaluate the effect of initial treatment on the kinetic of microwave-vacuum drying of whole cranberries, also the changes in material temperatures (T) and specific moisture evaporation rates (SMER) vs. moisture content (MC) were monitored (Fig. 3). The sudden jumps and drops in surface temperature of dried berries can be observed during microwave-vacuum drying of whole (treated or non-treated) cranberries (Fig. 3). It can be explained by the fact that an increase in capillary pressure inside the dried objects increased the tensile stress and promoted microcracks in the berry skin followed by steam emission and increase in surface temperature of material. Subsequently, the sudden outflow of water

Table 1

Drying time, moisture content, water activity, specific moisture evaporation rate and moisture diffusion coefficient of cranberries subjected to different pretreatments and microwave-vacuum drying at microwave power of 300 W

Sample	t [min]	MC_i [kg $H_2O \cdot$ kg DM^{-1}]	MC_f [kg $H_2O \cdot$ kg DM^{-1}]	A_W [-]	SMER [kg $H_2O \cdot kWh^{-1}$]	$D_{ew} \cdot 10^8$ [$m^{-2} \cdot s$]
RM3	12.0 ± 1.0^b	7.50 ± 0.02^a	0.22 ± 0.02^a	0.314 ± 0.002^a	3.5 ± 0.2^b	0.76 ± 0.03^c
SM3	14.5 ± 0.5^a	7.00 ± 0.02^a	0.21 ± 0.01^a	0.267 ± 0.005^d	3.9 ± 0.2^b	0.97 ± 0.02^b
FM3	14.0 ± 0.5^a	7.00 ± 0.02^a	0.22 ± 0.01^a	0.304 ± 0.001^b	4.6 ± 0.2^a	1.60 ± 0.04^a
SFM3	14.5 ± 0.5^a	7.27 ± 0.02^a	0.21 ± 0.03^a	0.270 ± 0.001^d	3.8 ± 0.2^b	1.52 ± 0.04^a
NM3	14.5 ± 0.5^a	7.32 ± 0.02^a	0.22 ± 0.01^a	0.287 ± 0.002^c	3.6 ± 0.2^b	0.58 ± 0.03^d

Table contains mean values ± standard errors.
$^{a, b, c, d, e}$ – the same letters in columns mean no statistical differences between samples ($p \leq 0.05$).
Symbols: RM3, SM3, FM3, SFM3, NM3 – raw (non-treated), sonicated, convectively frozen, sonicated and convectively frozen as well as cryogenically frozen fruits subjected to microwave-vacuum drying at microwave power of 300 W, t – drying time [min], MC_i – initial moisture content [kg $H_2O \cdot$ kg DM^{-1}], MC_f – final moisture content [kg $H_2O \cdot$ kg DM^{-1}], A_W – water activity [–], SMER – specific moisture evaporation rate during microwave-vacuum drying at microwave power of 300 W [kg $H_2O \cdot kWh^{-1}$], D_{ew} – coefficient of effective moisture diffusion [$m^{-2} \cdot s$].

vapor from the surface of berries reduced pressure inside the dried particles. It allowed to close the microcracks that occurred on the surface of dried fruits and thus reduced surface temperature of dried fruits (ZIELINSKA et al. 2019).

Initial treatments increased SMER values during microwave-vacuum drying of whole cranberries and lowered (even ≈ 10%) the surface temperature of dried material (Tab. 1). The changes in local temperatures of material can explain the changes in the values of local SMER (Fig. 3). The highest values of local material temperature and the lowest SMER values were noted during drying of non-treated berries (Fig. 3*a*). In this case, average SMER value reached 3.5±0.2 kg $H_2O \cdot kWh^{-1}$. On the other hand, the lowest values of local material temperature and the highest SMER values were noted during drying of convectively frozen berries (Fig. 3*c*). In this case, average SMER value reached 4.6±0.2 kg $H_2O \cdot kWh^{-1}$. Compared to non-treated samples, much lower energy input registered during microwave-vacuum drying of treated berries was enough to reach quite high material temperature that allowed to evaporate comparable amount of moisture as in case of non-treated berries (Fig. 2). It should be mentioned that the average surface temperature of initially treated berries was higher than 50°C. Regarding energy consumption, the effectiveness of initial treatments was presented as follows: convective freezing (Fig. 3*c*), sonication (Fig. 3*b*), ultrasound-assisted convective freezing (Fig. 3*d*) and cryogenic freezing (Fig. 3*e*).

Compared to non-treated samples, sonication slightly increased the values of $D_{ew.}$ The study demonstrates that initial freezing had a significant effect on the moisture diffusion coefficient. The highest values of D_{ew} ($1.60\pm0.04 \cdot 10^{-8}$ and 1.52 ± 0.04 $m^{-2} \cdot s$) were noted for convectively frozen cranberries and those

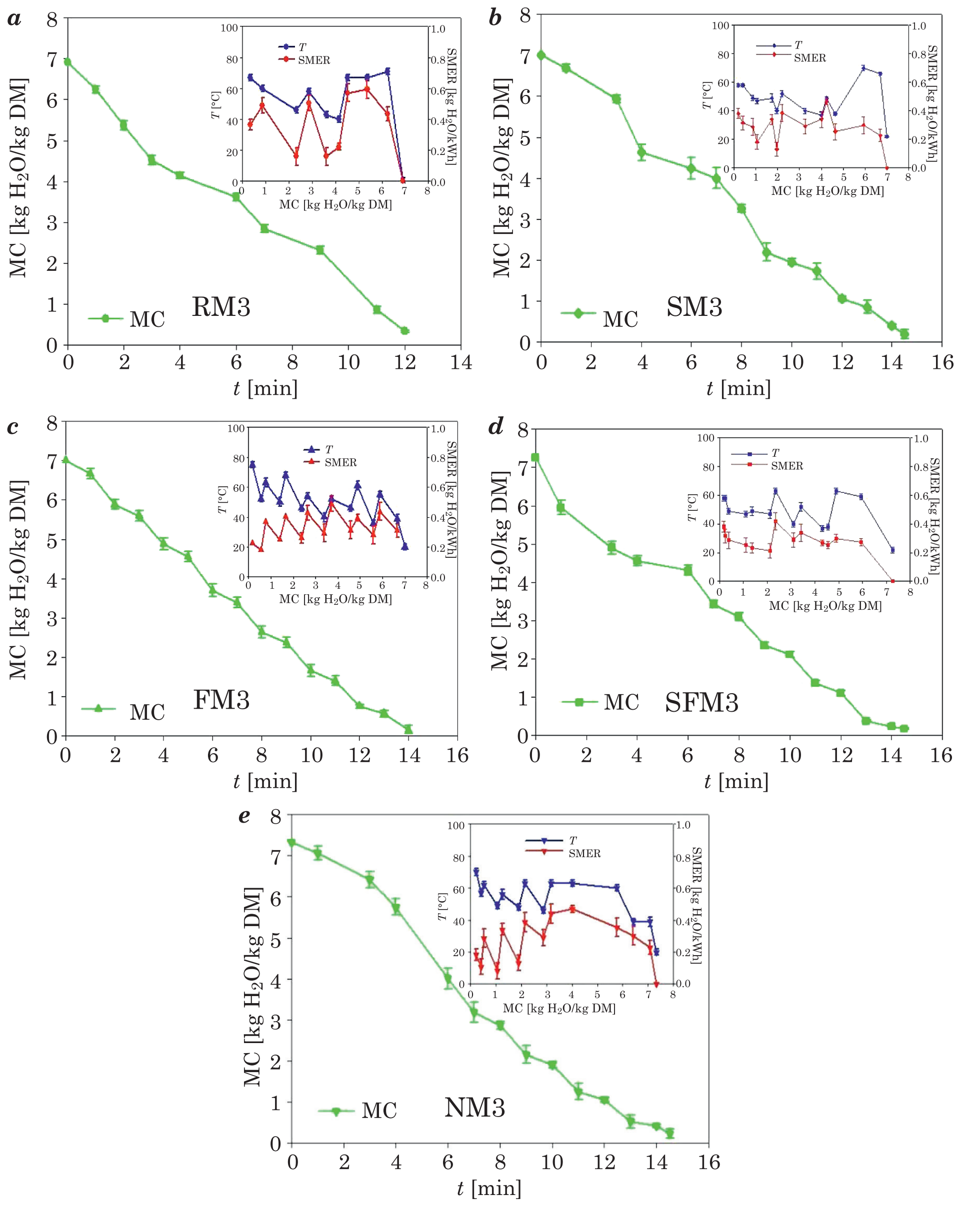

Fig. 3. Changes in moisture contents (MC) vs. drying time (t) as well as changes in material temperatures (T) and specific moisture evaporation rates (SMER) vs. moisture contents (MC) of whole cranberries subjected to different initial treatments and microwave – vacuum drying at microwave power of 300 W: a – RM3 – non-treated fruits subjected to drying, b – SM3 – fruits subjected to sonication and drying, c – FM3 – fruits subjected to convective freezing and drying, d – SFM3 – fruits subjected to convective freezing preceded by sonication and then subjected to drying, e – NM3 – fruits subjected to cryogenic freezing and drying

subjected to ultrasound-assisted convective freezing, whereas the lowest values of D_{ew} ($0.58 \pm 0.03 \cdot 10^{-8}$ $m^{-2} \cdot s$) were observed for cryogenically frozen fruits (Tab. 1). The freeze-cracking that occurred during cryogenic freezing caused significant structure damage and thus difficulties in moisture diffusion and low values of D_{ew} during drying of cryogenically frozen fruits. The freeze-cracking was not observed during convective freezing, and thus much higher values of D_{ew} could be obtained (ZIELINSKA et al. 2019). In terms of D_{ew}, ultrasound-assisted convective freezing was even less effective than sonication alone. Regarding the values of D_{ew}, the effectiveness of initial treatments was presented as follows: convective freezing, ultrasound-assisted convective freezing, and sonication (Tab. 1).

Table 2 shows the values of color parameters as well as indices of total difference in color, saturation and hue of cranberries subjected to different pretreatments and microwave-vacuum drying at microwave power of 300 W. Fruits subjected to microwave-vacuum drying without any initial treatments were characterized by the lowest values of lightness (29.1±0.3), redness (21.4±1.0) and yellowness (4.6±0.5). Sonication did not significantly influence the lightness of dried fruits. However, it significantly increased redness (25.1±1.0) and yellowness (7.0±0.5) of dried berries. Its efficiency in color change was comparable to cryogenic freezing and much lower than convective freezing. Among different treatments, the highest values of lightness (32.2±0.7), redness (32.6±0.8), and yellowness (11.1±0.7) of dried fruits as well as the greatest changes in color (13.7±1.1), saturation (1.5±0.1) and hue (13.0±1.0) were found for fruits subjected to initial convective freezing before drying. Also ultrasound-assisted convective freezing can be recommended for cranberries processing, when the color of dried fruits is considered. However, this method was found to be less effective than sonication alone.

Table 2

The values of color parameters as well as indices of total difference in color, saturation and hue of cranberries subjected to different pretreatments and microwave-vacuum drying at microwave power of 300 W

Sample	L^* [-]	a^* [-]	b^* [-]	ΔE^* [-]	ΔC^* [-]	ΔH^* [-]
RM3	29.1 ± 0.3^{c}	21.4 ± 1.0^{c}	4.6 ± 0.5^{d}	–	–	–
SM3	29.2 ± 0.5^{c}	25.1 ± 1.0^{b}	7.0 ± 0.5^{c}	6.9 ± 0.7^{c}	0.5 ± 0.1^{c}	6.4 ± 0.7^{c}
FM3	32.2 ± 0.7^{a}	32.6 ± 0.8^{a}	11.1 ± 0.7^{a}	13.7 ± 1.1^{a}	1.5 ± 0.1^{a}	13.0 ± 1.0^{a}
SFM3	31.0 ± 0.5^{ab}	31.0 ± 0.8^{a}	9.1 ± 0.4^{b}	11.3 ± 0.8^{b}	1.2 ± 0.1^{b}	10.9 ± 0.7^{b}
NM3	30.3 ± 0.4^{b}	26.5 ± 0.8^{b}	6.7 ± 0.4^{c}	6.7 ± 0.7^{c}	0.6 ± 0.1^{c}	6.2 ± 0.7^{c}

Table contains mean values ± standard errors.
$^{a, b, c, d}$ – the same letters in columns mean no statistical differences between samples ($p \leq 0.05$).
Symbols: RM3, SM3, FM3, SFM3, NM3 – raw (non-treated), sonicated, convectively frozen, sonicated and convectively frozen as well as cryogenically frozen fruits subjected to microwave-vacuum drying at microwave power of 300 W, L^* – lightness [-], a^* – redness [-], b^* – yellowness [-], ΔE^* – total color difference [-], ΔC^* -–total saturation difference [-], ΔH^* – total hue difference [-].

The overall appearance of cranberries subjected to different initial treatments and microwave-vacuum drying at microwave power of 300 W is shown in Figure 4. Figure 4 proves that fruits subjected to initial convective freezing as well as ultrasound-assisted freezing and then drying were apparently brighter and more red then other fruits. It can be explained by the fact that the texture of berries was considerably altered by the ice crystals formed during freezing. It promoted greater leakage of natural juice from frozen fruits during drying than from other treated or untreated fruits and the presence of juice on the surface of berries increased the redness, yellowness and glossiness of dried berries (ZIELINSKA, ZIELINSKA 2019).

Fig. 4. The overall appearance of cranberries subjected to different initial treatments and microwave-vacuum drying at microwave power of 300 W: *a* – RM3 – non-treated fruits subjected to microwave-vacuum drying, *b* – SM3 – fruits subjected to sonication and microwave-vacuum drying, *c* – FM3 – fruits subjected to convective freezing and microwave-vacuum drying, *d* – SFM3 – fruits subjected to convective freezing preceded by sonication and then dried by microwave-vacuum drying, *e* – NM3 – fruits subjected to cryogenic freezing and microwave-vacuum drying

The effect of initial treatments on the values of hardness, cohesiveness, springiness and chewiness of microwave-vacuum dried cranberries was evaluated and the values are shown in Table 3. Sonication and microwave-vacuum drying at 300 W allowed to obtain dried berries characterized by the lowest values of cohesiveness, springiness and chewiness and can be recommended for the production of dried crispy snacks. It did not significantly influence the hardness of dried fruits. Hardness, cohesiveness, springiness and chewiness of fruits subjected to microwave-vacuum drying without any initial treatments were 20±4 N, 0.42±0.02, 0.73±0.02, and 6.2±0.5 N, while the hardness, cohesiveness, springiness and chewiness of fruits subjected to sonication and microwave-vacuum drying were 25±4 N, 0.19±0.02, 0.62±0.02, 3.4±0.8 N, respectively.

Table 3

Hardness, cohesiveness, springiness and chewiness of cranberries subjected to different pretreatment methods and microwave-vacuum drying at microwave power of 300 W

Sample	H [N]	C [-]	S [-]	Ch [N]
RM3	20 ± 4^b	0.42 ± 0.02^a	0.73 ± 0.02^a	6.2 ± 0.5^b
SM3	25 ± 4^b	0.19 ± 0.02^d	0.62 ± 0.02^b	3.4 ± 0.8^c
FM3	20 ± 1^b	0.43 ± 0.01^a	0.73 ± 0.02^a	6.2 ± 0.5^b
SFM3	32 ± 2^a	0.37 ± 0.01^b	0.70 ± 0.02^a	8.0 ± 0.4^a
NM3	15 ± 2^c	0.29 ± 0.01^c	0.75 ± 0.03^a	3.3 ± 0.5^c

Table contains mean values ± standard errors.
$^{a, b, c}$ – the same letters in columns mean no statistical differences between samples ($p \leq 0.05$).
Symbols: RM3, SM3, FM3, SFM3, NM3 – raw (non-treated), sonicated, convectively frozen, sonicated and convectively frozen as well as cryogenically frozen fruits subjected to microwave-vacuum drying at microwave power of 300 W, H – hardness [N], C – cohesiveness [-], S – springiness [-], Ch – chewiness [N].

Cryogenic freezing and microwave-vacuum drying at 300 W allowed to obtain dried fruits characterized by the highest values of springiness and low values of chewiness and can be recommended for the production of soft dried fruits used in breakfast mixes. Hardness, cohesiveness, springiness and chewiness of fruits subjected to microwave-vacuum drying preceded by cryogenic freezing were 15±2 N, 0.29±0.01, 0.75±0.03, and 3.3±0.5 N, respectively. Convective freezing did not significantly influence the hardness, cohesiveness, springiness and chewiness of dried fruits. In terms of texture changes, ultrasound-assisted sonication was more effective than sonication alone.

The effect of initial treatments on the values of particle density, porosity and volumetric shrinkage of microwave-vacuum dried cranberries was evaluated and the values are shown in Table 4. Initial treatments did not significantly influence the particle density, apparent porosity and the shrinkage of whole cranberries subjected to microwave-vacuum drying at 300 W. The values of particle density, porosity and volumetric shrinkage for microwave-vacuum dried fruits with or without initial treatment were in the range from 157±15 $kg \cdot m^{-3}$ to 198±52 $kg \cdot m^{-3}$, from 86±4 to 89±1% and from 46±3 to 52±5%, respectively.

The effect of initial treatments on the values of thermal conductivity, thermal diffusivity and specific heat of microwave-vacuum dried cranberries was evaluated and the values are shown in Table 5. Cranberries subjected to microwave-vacuum drying without any initial treatment were characterized by the lowest values of thermal conductivity λ ($0.056 \pm 0.004\ W \cdot m^{-1} \cdot K^{-1}$) and thermal diffusivity a ($1.19 \pm 0.10\ m^2 \cdot s^{-1}$). All of initial treatments increased thermal conductivity and thermal diffusivity of dried cranberries. However, some differences were not statistically different ($p \leq 0.05$). Most of initial treatments did not significantly influence specific heat of dried berries.

Table 4

Particle density, porosity and volumetric shrinkage of cranberries subjected to different pretreatments and microwave-vacuum drying at microwave power of 300 W

Sample	ρ_p [kg · m-3]	ε_p [%]	S_v [%]
RM3	177 ± 24^a	87 ± 2^a	46 ± 3^a
SM3	198 ± 52^a	86 ± 4^a	52 ± 5^a
FM3	162 ± 15^a	89 ± 1^a	47 ± 7^a
SFM3	157 ± 15^a	89 ± 1^a	48 ± 3^a
NM3	177 ± 33^a	87 ± 2^a	52 ± 5^a

Table contains mean values ± standard errors.
$^{a, b, c, d, e}$ – the same letters in columns mean no statistical differences between samples ($p \leq 0.05$).
Symbols: RM3, SM3, FM3, SFM3, NM3 – raw (non-treated), sonicated, convectively frozen, sonicated and convectively frozen as well as cryogenically frozen fruits subjected to microwave-vacuum drying at microwave power of 300 W, ρ_p – density of the particle [kg · m-3], ε_p – porosity of the particle [%], S_v – volumetric shrinkage [%].

Table 5

Thermal conductivity, thermal diffusivity and specific heat of cranberries subjected to different pretreatments and microwave-vacuum drying at microwave power of 300W

Sample	λ [W · m-1 · K-1]	$a \cdot 10^9$ [m2 · s-1]	C_p [J · kg-1 · K-1]
RM3	0.056 ± 0.004^a	1.19 ± 0.10^b	2878 ± 201^a
SM3	0.063 ± 0.003^a	1.40 ± 0.07^a	2122 ± 37^b
FM3	0.064 ± 0.004^a	1.26 ± 0.02^b	2946 ± 122^a
SFM3	0.064 ± 0.006^a	1.48 ± 0.08^a	2876 ± 261^a
NM3	0.076 ± 0.004^b	1.40 ± 0.14^a	3257 ± 209^a

Table contains mean values ± standard errors.
$^{a, b, c, d, e}$ – the same letters in columns mean no statistical differences between samples ($p \leq 0.05$).
Symbols: RM3, SM3, FM3, SFM3, NM3 – raw (non-treated), sonicated, convectively frozen, sonicated and convectively frozen as well as cryogenically frozen fruits subjected to microwave-vacuum drying at microwave power of 300 W, λ – thermal conductivity [W · m-1 · K-1], a – thermal diffusivity [m2 · s-1], C_p – specific heat [J · kg-1 · K-1].

Summary and Conclusions

Microwave-vacuum drying of whole cranberries with or without initial treatments took from 12±1 to 14.5±0.5 minutes. All of treatments did not significantly shorten the drying time of cranberries. However, they reduced the average material temperature during drying and significantly increased SMER values. Regarding energy consumption, the effectiveness of initial treatments was presented as follows: convective freezing, sonication, convective freezing preceded by sonication and cryogenic freezing. Despite of cryogenic freezing, all of treatments significantly increased the values of D_{ew}. Regarding the values of D_{ew}, the effectiveness of initial treatments was presented as follows: convective freezing, ultrasound-assisted convective freezing, and sonication. Initial treatments significantly influenced the color as well as the mechanical and thermal properties of dried fruits. Sonication significantly increased the redness and yellowness of dried fruits. Its efficiency in color change was comparable to cryogenic freezing and much lower than convective freezing. All of treatments increased such thermal properties of dried cranberries as thermal conductivity and thermal diffusivity. Sonication combined with microwave-vacuum drying at 300 W allowed to obtain dried berries characterized by the lowest values of cohesiveness, springiness and chewiness and can be recommended for the production of dried crispy snacks. Cryogenic freezing combined with microwave-vacuum drying at 300 W allowed to obtain dried fruits characterized by highest values of springiness and low values of chewiness and can be recommended for the production of soft dried fruits used in breakfast mixes. Initial treatments did not significantly influence such physical properties of dried cranberries, as density, porosity and volumetric shrinkage.

As it is expected that the effect of sonication on the microwave-vacuum drying kinetic and material properties could be more visible in case of mechanically treated samples, i.e. sliced or cutted in half cranberries, further studies should be conducted in this specific area. Also, most consumers would characterize cranberries as sour. Therefore, it would be interesting to combine the initial treatments with osmotic dehydration and evaluate their effect on the drying kinetic and material properties.

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 kinetic 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).

References

Chong Ch.H., Figiel A., Chung L.L., Wojdylo A. 2014. *Combined Drying of Apple Cubes by Using of Heat Pump, Vacuum-Microwave, and Intermittent Techniques*. Food Bioprocess Technology, 7: 975–989.

Fernandes F.A.N., Rodrigues S., Cárcel J.A., García-Pérez J.V. 2015. *Ultrasound-assisted air-drying of apple (malus domestica L.) and its effects on the vitamin of the dried product*. Food Bioprocess Technology, 8(7): 1503–1511.

GRABOWSKI S., MARCOTTE M., QUAN D., TAHERIAN A.R., ZAREIFARD M.R., POIRIER M., KUDRA T. 2007. *Kinetics and quality aspects of Canadian blueberries and cranberries dried by osmo-convective method*. Drying Technology, 25(2): 367–374.

MCCLEMENTS D.J. 1995. *Advances in the application of ultrasound in food analysis and processing*. Trends in Food Science and Technology, 6: 293-299.

MCKAY D.L., BLUMBERG J.B. 2007. *Cranberries (Vaccinium macrocarpon) and cardiovascular disease risk factors*. Nutrition Reviews, 65(11): 490–502.

NASCIMENTO E.M.G.C., MULET A., RAMÍREZ ASCHERI J.L., PILER DE CARVALHO C.W., CARCEL J.A. 2016. *Effects of high-intensity ultrasound on drying kinetics and antioxidant properties of passion fruit peel*. Journal of Food Engineering, 170: 108-118.

NOWAK K.W., ZIELINSKA M., WASZKIELIS K.M. 2018. *The effect of ultrasound and freezing/thawing treatment on the physical properties of blueberries*. Food Science and Biotechnology, 28(3): 741–749. doi: 10.1007/s10068-018-0528-5.

RAHMAN S. 1995. *Food Properties Handbook*. CRC Press Inc, Boca Raton.

RENNIE T.J., MERCER D.G. 2013. *Effect of blanching on convective drying and osmotic dehydration of cranberries*. Transactions of ASABE, 56(5): 1863–1870.

RODRIGUEZ Ó., SANTACATALINA J.V., SIMAL S., GARCÍA-PÉREZ J.V., FEMENIA A., ROSSELLO C. 2014. *Influence of power ultrasound application on drying kinetics of apple and its antioxidant and microstructural properties*. Journal of Food Engineering, 129: 21–29.

SCHMIDT E.L., KLOCKER K., FLACKE N., STEIMLE F. 1998. *Applying the transcritical CO_2 process to a drying heat pump*. International Journal of Refrigeration, 21(3): 202–211.

SKROVANKOVA S., SUMCZYNSKI D., MLCEK J., JURIKOVA T., SOCHOR J. 2015. *Bioactive compounds and antioxidant activity indifferent types of berries*. International Journal of Molecular Sciences, 16(10): 24673–24706.

SOYSAL Y., AYHAN Z., ESTURK O., ARIKAN M.F. 2009. *Intermittent microwave–convective drying of red pepper: drying kinetics, physical (color and texture) and sensory quality*. Biosystem Engineering, 103: 455–463.

SUNJKA P.S., RENNIE T.J., BEAUDRY C., RAGHAVAN V.G.S. 2004. *Microwave-Convective and Microwave-Vacuum Drying of Cranberries: A Comparative Study*. Drying Technology, 22(5): 1217-1231.

ZHANG M., TANG J.M., MUJUMDAR A.S., WANG S. 2006. *Trends in microwave related drying of fruits and vegetables*. Trends in Food Science and Technology, 17: 524–534.

ZIELINSKA M., MARKOWSKI M. 2018. *Effect of microwave-vacuum, ultrasonication, and freezing on mass transfer kinetics and diffusivity during osmotic dehydration of cranberries*. Drying Technology, 36(10): 1158–1169.

ZIELINSKA M., MARKOWSKI M. 2012. *Color Characteristics of Carrots: Effect of Drying and Rehydration*. International Journal of Food Properties, 15: 450-466.

ZIELINSKA M., MARKOWSKI M. ZIELINSKA D. *2019. The effect of freezing on the hot air and microwave vacuum drying kinetics and texture of whole cranberries*. Drying Technology, doi: 10.1080/07373937.2018.1543317.

ZIELINSKA M., ROPOLEWSKA E., MARKOWSKI M. 2017. *Thermophysical properties of raw, hot-air and microwave-vacuum dried cranberry fruits (Vaccinium macrocarpon)*. LWT – Food Science and Technology, 85: 204–211.

ZIELINSKA M., ROPOLEWSKA E., ZAPOTOCZNY P. 2018a. *Efffects of freezing and hot air drying on thephysical, morphological and thermal properties ofcranberries (Vaccinium macrocarpon)*. Food and Bioproducts Processing, 110: 40–49.

ZIELINSKA M., SADOWSKI P., BŁASZCZAK W. 2015. *Freezing/thawing and microwave assisted drying of blueberries (Vaccinium corymbosum L.)*. LWT-Food Science and Technology, 62(1, 2): 555–563.

ZIELINSKA M., ZIELINSKA D. 2019. *Effects of freezing, convective and microwave-vacuum drying on the content of bioactive compounds and color of cranberries*. LWT – Food Science and Technology, 104: 202-209. doi: 10.1016/j.lwt.2019.01.041.

ZIELINSKA M., ZIELINSKA D., MARKOWSKI M. 2018b. *The effect of microwave-vacuum pretreatment on the drying kinetics, color and the content of bioactive compounds in osmo-microwave-vacuum dried cranberries (Vaccinium macrocarpon)*. Food and Bioprocess Technology, 11: 585–602.