Combined Hot Air and Microwave-Vacuum Drying of Cranberries: Effects of Pretreatments and Pulsed Vacuum Osmotic Dehydration on Drying Kinetics and Physicochemical Properties

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Abstract

The aim of the study was to evaluate the effect of sonication (S), microwave-vacuum (MWV), convective freezing (F), cryogenic freezing (N), and their combinations, as well as pulsed vacuum osmotic dehydration (PVOD) on the drying kinetics, bioactive compounds, texture and color of whole cranberries during combined hot air convective drying, and microwave-vacuum drying (HACD+MWVD). Drying of berries took from 20 to 493 min. Drying rate was enhanced by 23% and drying time of non-osmotically dehydrated fruits was shortened by 33% using F treatment, while MWV decreased moisture content before drying by 68% and shortened the drying time of PVOD berries by 96%. Generally, total phenolic (TP) content increased during processing, total flavonoids (TF), and total monomeric anthocyanins (TMA) contents decreased, while the values of ferric reducing antioxidant power (FRAP) of dried fruits depended on the initial pretreatment. F and HACD+MWVD yielded fruits of the highest L^* (33.8 ± 0.7), a^* (25.2 ± 1.0), and b^* (7.3 ± 0.6), inflated oval shape, and a small amount of wrinkles on the surface. PVOD and HACD+MWVD resulted in flat and wrinkled fruits.

Keywords Cranberries · Ultrasound · Microwave-vacuum treatment · Freezing · Hybrid drying · Quality attributes

Abbreviations

C	control (raw, non-treated)
S	sonication
MWV	microwave-vacuum treatment
N	cryogenic freezing
F	convective freezing
S + F	sonication and convective freezing
MWV + F	microwave-vacuum treatment and convective freezing
PVOD	pulsed vacuum osmotic dehydration

HACD+MWVD	hot air convective drying and microwave-vacuum drying
TP	total polyphenols, mg GAE/g DM
TF	total flavonoids, mg CAE/g DM
TMA	total monomeric anthocyanins, mg Cy-3G/g DM
FRAP	ferric reducing antioxidant power, mg TE/g DM
MR	moisture ratio
DR_{AVG}	average drying rate, kg H ₂ O/kg DM/min
t	drying time, min
$MC_{(t)}$	moisture content of fruits at any level and any time, dry basis (db)
MC_e	equilibrium moisture content (db)
MC_0	the initial moisture content of the material (db)

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Introduction

Cranberries (*Vaccinium macrocarpon*) contain high level of bioactive compounds, which poses health-promoting

Table 1 Parameters of initial treatments before convective and microwave-vacuum drying (HACD+MWVD) of cranberries

Initial treatment and dehydration	Parameters	Devices
Sonication S	Ultrasounds frequency: 25 ± 5 kHz; ultrasonic power input: 600 W; time: 10 min; mode: 1 s impulse and 1 s gap between impulses; medium: distilled water; volume of medium: 1 dm^3 ; sample mass: 0.2 kg.	Ultrasonic disruptor Scientz-650E (Ningbo Scientz Biotechnology Co. Ltd., China)
Sonication+convective freezing S + F	Ultrasounds frequency: 25 ± 5 kHz; ultrasonic power input: 600 W; time: 10 min; mode: 1 s impulse and 1 s gap between impulses; medium: distilled water; volume of medium: 1 dm^3 ; freezing temperature: -18°C ; freezing time: 24 h; thawing temperature: 20°C ; thawing time: 3 h; sample mass: 0.2 kg.	
Microwave-vacuum pretreatment MWV	MW power: 800 W; MW power density: 5.33 W/g ; time: 1.50 min; the maximum material temperature: 40°C ; the absolute pressure: $5 \pm 1 \text{ kPa}$; the rotational speed of the chamber: 6 rpm; sample mass: 0.2 kg.	Microwave-vacuum oven (Promis Tech, Wroclaw, Poland)
Microwave-vacuum pretreatment +convective freezing MWV + F	MW power: 800 W; MW power density: 5.33 W/g ; time: 1.50 min; the maximum material temperature: 40°C ; the absolute pressure in the chamber: $5 \pm 1 \text{ kPa}$; the rotational speed of the chamber: 6 rpm; freezing temperature: -18°C ; freezing time: 24 h; thawing temperature: 20°C ; thawing time: 3 h; sample mass: 0.2 kg.	
Convective freezing F	Freezing temperature: -18°C ; freezing time: 24 h; thawing temperature: 20°C ; thawing time: 3 h; sample mass: 0.2 kg.	Liebherr GR 4932 freezer (Liebherr-Hausgeräte GmbH, Ochsenhausen, Germany)
Cryogenic freezing N	Refrigerant: liquid nitrogen; boiling point of refrigerant: -196°C ; freezing time: 1 min (the freezing process was considered completed when the evaporation of liquid nitrogen was no longer observed); thawing temperature: 20°C ; thawing time: 3 h; sample mass: 0.2 kg.	A styrofoam container
Pulsed vacuum osmotic dehydration PVOD	Pulsed vacuum osmotic dehydration (PVOD) time: 2 h (vacuum: 0.5 h, atmospheric pressure: 1.5 h); parameters of PVOD (osmotic solution: sucrose solution; concentration of the osmotic solution: 65°Brx ; the sample to solution ratio: 1:4, temperature: $40 \pm 1^\circ\text{C}$).	Vacuum drying oven DZ ZBC II (Chemland, Stargard Szczecinski, Poland); A water bath (LWT 6/150, WSL, Poland) filled with sucrose solution.

Fig. 1 Moisture ratios of differently pretreated and osmotically dehydrated cranberries vs. HACD+MWVD time (a); average drying rate during HACD+MWVD of whole cranberries (b)

Fig. 2 Micrographs of cross sections (magnification $\times 100$) of cranberries subjected to different initial treatments: **a** C; **b** S; **c** MWV; **d** N; **e** F; **f** MWV+F; **g** S + F

properties (Zielinska and Zielinska 2019; Grace et al. 2012). A seasonal character of production and a high moisture content of fruits make them suitable for processing. Drying can be used to reduce the moisture content, inhibit the growth of microorganisms, and prolong the shelf life of fruits (Liu et al. 2019a). Due to the waxy surface layer which is a barrier to heat and mass transfer processes, hot air drying may take up to 160 hours and negatively affect the physical properties of dried cranberries (Zielinska et al. 2018). Among various drying methods (Liu et al. 2019b; Pereira et al. 2014; Verma et al. 2014), hybrid hot air convective drying and microwave-vacuum drying (HACD+MWVD) can be considered an efficient method for drying of berries (Zielinska et al. 2019). It combines the advantages of both single-step HACD and

MWVD. Due to its low cost, HACD is the most frequently used drying method. MWVD is an increasingly popular method that uses microwave radiation to generate heat under reduced pressure. This volumetric heating reduces the drying time and performs a positive impact on the texture and nutritional value of final product (Zhang et al. 2006). Up to date, HACD+MWVD has been successfully applied for drying of e.g., cherries (Nowicka et al. 2015), blueberries (Zielinska et al. 2016), and pomegranate arils (Cano-Lamadrid et al. 2017).

Generally, agricultural materials are subjected to different pretreatments before drying with the aim of quality improvement and drying time reduction (Deng et al. 2019). Among different pretreatments, sonication (S) can be used to increase

Fig. 3 Micrographs of cross sections (magnification $\times 100$) of differently pretreated cranberries subjected to pulsed vacuum osmotic dehydration (PVOD): **a** C; **b** S; **c** MWV; **d** N; **e** F; **f** MWV+F; **g** S+F

the permeability of skin. The effect of acoustic microstreaming accelerates heat and mass transfer processes (Staniszewska et al. 2019). Microwave-vacuum pretreatment (MWV) may cause volumetric heating, so vapor generated inside the product may develop internal pressure gradients and result in water movement from the interior to the surface of the material (Zhang et al. 2006; Zielinska and Markowski 2018). Convective freezing (F) of fruits before drying may increase the moisture transfer, reduce drying time and energy consumption (Zielinska et al. 2018). Additionally, cryogenic freezing (N) may be used to minimize the formation of large ice crystals and reduce drip losses during freezing thus preserving texture and nutritional value of dehydrated products.

Pulsed vacuum osmotic dehydration (PVOD) in sucrose solution can be used to deliver sweet berries with unique texture, remove some moisture and lower energy consumption during cranberry processing (Ramaswamy and Tola 2014).

There is a general scarcity of research reports on the effect of various pretreatments and PVOD on the HACD+MWVD kinetics and quality of waxy fruits, particularly cranberries. Therefore, the objective of this study was to investigate the effects of sonication (S), microwave-vacuum (MWV), cryogenic freezing (N), convective freezing (F), convective freezing preceded by sonication (S + F) or convective freezing preceded by microwave-vacuum treatment (MWV + F) as well as PVOD on the HACD+MWVD drying kinetics,

Table 2 Effect of initial treatments, PVOD, and HACD+MWVD on the contents of TP, TF, TMA, and FRAP of cranberries

Initial treatment	Dehydration method	TP (mg GAE/g DM)	TF (mg CAE/g DM)	TMA (mg Cy-3G/g DM)	FRAP (mg TE/g DM)
C	-	21.45 ± 0.17 ^{aC}	4.07 ± 0.03 ^{aA}	4.31 ± 0.02 ^{bB}	38.15 ± 0.25 ^{aB}
	PVOD	18.41 ± 0.14 ^{aD}	3.78 ± 0.06 ^{aB}	4.62 ± 0.15 ^{aA}	33.58 ± 0.52 ^{aC}
	HACD+MWVD	23.90 ± 0.38 ^{abB}	3.79 ± 0.11 ^{aB}	0.75 ± 0.05 ^{aD}	37.56 ± 0.80 ^{aB}
	PVOD/HACD+MWVD	25.55 ± 0.49 ^{aA}	2.78 ± 0.05 ^{aC}	1.31 ± 0.03 ^{aC}	45.95 ± 0.62 ^{aA}
S	-	23.30 ± 0.08 ^{bA}	4.56 ± 0.02 ^{bA}	5.12 ± 0.04 ^{bA}	41.99 ± 0.31 ^{bA}
	PVOD	20.38 ± 0.18 ^{bB}	3.84 ± 0.03 ^{aB}	3.94 ± 0.09 ^{bB}	37.16 ± 0.24 ^{bB}
	HACD+MWVD	27.14 ± 0.56 ^{cA}	3.63 ± 0.10 ^{aA}	2.07 ± 0.03 ^{fA}	47.67 ± 0.39 ^{dA}
	PVOD/HACD+MWVD	23.28 ± 0.44 ^{bB}	2.93 ± 0.1 ^{aB}	0.98 ± 0.04 ^{cB}	35.65 ± 0.64 ^{cB}
S + F	-	22.24 ± 0.12 ^{cA}	3.98 ± 0.02 ^{cA}	4.64 ± 0.01 ^{cA}	39.99 ± 0.39 ^{cA}
	PVOD	21.34 ± 0.17 ^{cA}	3.74 ± 0.03 ^{aA}	4.13 ± 0.04 ^{abB}	38.10 ± 0.48 ^{bB}
	HACD+MWVD	27.51 ± 0.56 ^{cA}	3.37 ± 0.08 ^{bA}	2.22 ± 0.06 ^{gA}	46.44 ± 0.62 ^{cA}
	PVOD/HACD+MWVD	22.72 ± 0.35 ^{cB}	2.87 ± 0.09 ^{aB}	1.32 ± 0.05 ^{aB}	39.47 ± 0.47 ^{bB}
MWV	-	20.94 ± 0.09 ^{dA}	4.00 ± 0.03 ^{acA}	4.16 ± 0.04 ^{cA}	39.37 ± 0.38 ^{cA}
	PVOD	10.78 ± 0.08 ^{fB}	2.15 ± 0.04 ^{dB}	2.00 ± 0.03 ^{eB}	21.50 ± 0.20 ^{dB}
	HACD+MWVD	23.30 ± 0.28 ^{aA}	2.65 ± 0.03 ^{ea}	1.28 ± 0.01 ^{cA}	38.82 ± 0.55 ^{aA}
	PVOD/HACD+MWVD	13.01 ± 0.44 ^{fB}	1.56 ± 0.06 ^{cB}	0.63 ± 0.03 ^{eB}	17.59 ± 0.36 ^{fB}
MWV + F	-	21.42 ± 0.20 ^{adA}	3.91 ± 0.04 ^{cA}	4.32 ± 0.05 ^{aA}	42.23 ± 0.48 ^{bA}
	PVOD	10.46 ± 0.06 ^{gB}	2.10 ± 0.04 ^{dB}	1.66 ± 0.01 ^{fB}	20.52 ± 0.36 ^{eB}
	HACD+MWVD	25.85 ± 0.30 ^{bA}	3.10 ± 0.08 ^{cA}	1.93 ± 0.02 ^{ea}	46.40 ± 0.81 ^{cA}
	PVOD/HACD+MWVD	12.05 ± 0.32 ^{gB}	1.74 ± 0.07 ^{bB}	0.86 ± 0.03 ^{dB}	20.34 ± 0.55 ^{eB}
F	-	22.14 ± 0.26 ^{acA}	3.53 ± 0.05 ^{dA}	3.30 ± 0.02 ^{dA}	38.67 ± 0.42 ^{acA}
	PVOD	16.12 ± 0.11 ^{dB}	2.91 ± 0.04 ^{bB}	2.69 ± 0.02 ^{cB}	29.25 ± 0.31 ^{cB}
	HACD+MWVD	22.14 ± 0.49 ^{dA}	2.91 ± 0.07 ^{dA}	0.88 ± 0.01 ^{bB}	33.03 ± 0.72 ^{eB}
	PVOD/HACD+MWVD	22.30 ± 0.34 ^{dA}	2.79 ± 0.15 ^{aA}	1.19 ± 0.02 ^{bA}	36.75 ± 0.36 ^{cA}
N	-	21.32 ± 0.19 ^{adA}	4.08 ± 0.04 ^{aA}	4.30 ± 0.02 ^{aA}	38.02 ± 0.23 ^{aA}
	PVOD	15.21 ± 0.16 ^{eB}	2.75 ± 0.02 ^{cB}	2.90 ± 0.02 ^{dB}	30.23 ± 0.32 ^{cB}
	HACD+MWVD	24.14 ± 0.44 ^{aA}	2.93 ± 0.06 ^{dA}	1.48 ± 0.08 ^{dA}	42.41 ± 0.68 ^{bA}
	PVOD/HACD+MWVD	17.20 ± 0.38 ^{eB}	1.88 ± 0.09 ^{bB}	0.68 ± 0.03 ^{eB}	25.44 ± 0.59 ^{dB}

Same letters in the same column indicate that the mean values are not significantly different at a confidence level of 95 % ($p < 0.05$). ^{ab} Significant differences between samples subjected to the same dehydration method but different initial treatments. ^{AB} Significant differences between samples subjected to the same initial treatment but different dehydration method

texture, color, and the content of bioactive compounds of cranberries.

Materials and Methods

Materials

Cranberries (*V. macrocarpon* L.) were purchased from a farm in Lublin region, Poland. To ensure the uniformity of physical characteristics, cranberries with the same size, firmness, and color were selected. The initial moisture content of raw cranberries was 7.49 ± 0.02 kg H₂O/kg DM (dry matter) determined using vacuum drying oven at the temperature of 70 °C for 24 h (AOAC 2002).

Pretreatments, Pulsed Vacuum Osmotic Dehydration, and Drying Procedures

A detailed description of pretreatments and devices used for initial pretreatments and pulsed vacuum osmotic dehydration (PVOD) is shown in Table 1. All of the pretreatments were carried out in triplicate. After pretreatments and PVOD, the whole cranberries were subjected to combined hot air convective drying and microwave-vacuum drying (HACD+MWVD). The mass of cranberries used in each drying experiment was 0.150 ± 0.001 kg. Initially, cranberries were subjected to HACD at the temperature of 80 °C. HACD was conducted in a drying oven (FED53 127 Binder, USA). The mass of samples was monitored and recorded every 10 min by a digital balance with accuracy of 0.001 g during drying.

Table 3 Effect of initial treatments and PVOD on the textural properties of raw and pretreated cranberries

Initial treatment	Dehydration method	Cutting test F (N)	Puncture test F (N)
C	-	33.06 ± 1.65 ^{aA}	6.86 ± 0.12 ^{aA}
	PVOD	25.12 ± 0.92 ^{aB}	5.47 ± 0.16 ^{aB}
S	-	30.74 ± 0.98 ^{aA}	6.86 ± 0.19 ^{aA}
	PVOD	25.92 ± 0.95 ^{aB}	5.85 ± 0.17 ^{bB}
S + F	-	27.83 ± 0.68 ^{bA}	4.90 ± 0.12 ^{bA}
	PVOD	20.73 ± 0.99 ^{bB}	4.69 ± 0.14 ^{cdA}
MWV	-	11.85 ± 0.52 ^{cA}	4.86 ± 0.24 ^{bA}
	PVOD	11.74 ± 0.74 ^{dA}	4.41 ± 0.17 ^{dB}
MWV + F	-	13.52 ± 0.85 ^{dA}	4.91 ± 0.20 ^{bA}
	PVOD	13.52 ± 0.85 ^{cA}	4.50 ± 0.17 ^{dB}
F	-	26.50 ± 1.02 ^{bA}	4.84 ± 0.11 ^{bA}
	PVOD	19.50 ± 0.70 ^{bB}	5.01 ± 0.18 ^{cA}
N	-	22.86 ± 0.76 ^{cA}	4.72 ± 0.18 ^{bA}
	PVOD	19.93 ± 0.69 ^{bB}	4.47 ± 0.14 ^{dA}

Table shows mean values with standard deviations of the mean (the results were averaged over nine measurements). F, force; N, Same letters in the same column indicate that the mean values are not significantly different at a confidence level of 95 % ($p < 0.05$). ^{ab} Significant differences between samples subjected to the same dehydration method but different initial treatments. ^{AB} Significant differences between samples subjected to the same initial treatment but different dehydration Method

When the moisture content of cranberries was reduced to about 2.00 kg H₂O/kg DM, the samples were transferred to MWVD. MWVD was conducted at microwave power of 150 W and absolute pressure of 5 ± 1 kPa. MWVD was continued until the temperature of material increased suddenly up to 80 °C. All of the drying experiments were done in triplicate.

Drying Curves

Moisture ratios (MR) were computed based on the initial (MC_0), actual (MC_t), and equilibrium (MC_e) moisture content. MR represents the amount of moisture remaining in the samples reported to the initial moisture content. The MR of the samples during the drying process was calculated from the formula (Zielinska et al. 2016):

$$MR = \frac{MC_t - MC_e}{MC_0 - MC_e} \quad (1)$$

Mathematical differentiation of the drying curves allowed calculating the drying rates (DR) (Zielinska and Markowski 2010). DR was not constant during drying of cranberries and the average drying rate (DR_{AVG}) was calculated and presented as the mean value.

Determination of Textural Properties

Texture Analyzer TA.HD Plus (Stable Micro Systems, Godalming, UK) was used to determine the texture of cranberries. Cutting and puncture tests were applied to test every single raw and pretreated fruit. The test speed was set at 2 mm/s. Both tests were performed perpendicularly to the petiole axis. Texture of dried fruits was evaluated by texture profile analysis (TPA) using a 50 mm-diameter flat piston at 50% strain. The test speed was set at 2 mm/s. The hardness, springiness, cohesiveness, gumminess, and chewiness of dried products were obtained from the force-deformation curve (Zielinska et al. 2015). The results were averaged over 15 measurements.

Microscopic Observations

The cross-sections of raw (non-treated) and pretreated cranberries were observed using an environment scanning electron ESEM (ESEM, Quanta 200, FEI Company, Netherlands). Fruits were cut along the perpendicular axis with a scalpel and observed under ESEM without any prior preparation. The microscopic magnification was $\times 100$, while pressure was 130 Pa.

Determination of Total Phenolics, Total Flavonoids, Total Monomeric Anthocyanin Contents, and Ferric Reducing Antioxidant Power

The mass of 0.05 g of cranberries was extracted with solvent (80% aqueous methanol solution containing 0.1% HCl (v/v)) by triple sonication (30 s) and vortexing (30 s), and then the mixture centrifugation (13200 g) for 10 min. This procedure was conducted five times on the residue with the volume of 1 mL of the solvent. Extraction procedure was carried out in triplicate. The total phenolics (TP), total flavonoids (TF), total monomeric anthocyanins (TMA), and ferric reducing antioxidant power (FRAP) assay were determined according to the method of Zielinska and Zielinska (2019) with some modifications. All measurements were performed in triplicate using UV-1800 spectrophotometer (Shimadzu, Kyoto, Japan).

Color Measurement

Color of cranberries was determined by the Miniscan XE Plus spectrophotometer. A container filled with 50 g of fruits was positioned over the sample port and the color of sample surface was measured vertically through the glass bottom. A CIE standard illuminant D 65, 10° observer, and 8° diaphragm were applied to measure color parameters of cranberries in CIE $L^*a^*b^*$ space. All of the measurements were averaged over 35 measurements.

Table 4 Effect of initial treatments, PVOD, and HACD+MWVD on the textural properties of dried cranberries

Initial treatment	Dehydration method	H (N)	Co (–)	S (–)	G (–)	Ch (N)	ρ_p (kg/m ³)	ε_p (–)
C	HACD+MWVD	19 ± 2 ^{efA}	0.33 ± 0.09 ^{eA}	0.62 ± 0.09 ^{fgA}	5.8 ± 2.9 ^{defgA}	3.5 ± 1.5 ^{defA}	196 ± 14 ^{fA}	86.1 ± 1.0 ^{dB}
	PVOD/HACD+MWVD	18 ± 1 ^{fA}	0.37 ± 0.01 ^{deA}	0.66 ± 0.02 ^{cdefA}	6.9 ± 0.4 ^{dA}	4.6 ± 0.3 ^{deA}	167 ± 5 ^{gB}	88.0 ± 0.3 ^{bcA}
S	HACD+MWVD	7 ± 4 ^{gA}	0.44 ± 0.05 ^{abceA}	0.63 ± 0.12 ^{efgA}	2.9 ± 1.6 ^{fB}	1.8 ± 1.0 ^{gfb}	158 ± 10 ^{gB}	88.8 ± 0.7 ^{bA}
	PVOD/HACD+MWVD	22 ± 1 ^{deA}	0.35 ± 0.01 ^{deB}	0.64 ± 0.01 ^{defgA}	7.6 ± 0.4 ^{dA}	4.9 ± 0.3 ^{dA}	194 ± 11 ^{fA}	86.2 ± 0.8 ^{dB}
S + F	HACD+MWVD	21 ± 8 ^{cdfA}	0.03 ± 0.01 ^{gB}	0.21 ± 0.21 ^{iB}	0.7 ± 0.9 ^{hB}	0.3 ± 0.5 ^{gB}	158 ± 7 ^{gB}	88.8 ± 0.5 ^{bA}
	PVOD/HACD+MWVD	29 ± 2 ^{cA}	0.22 ± 0.02 ^{fA}	0.55 ± 0.04 ^{hA}	6.5 ± 0.8 ^{deA}	3.9 ± 0.5 ^{eA}	293 ± 21 ^{dA}	79.2 ± 1.5 ^{fB}
MWV	HACD+MWVD	5 ± 2 ^{gB}	0.49 ± 0.08 ^{abceA}	0.79 ± 0.09 ^{abefA}	2.1 ± 0.8 ^{gB}	1.7 ± 0.7 ^{fB}	248 ± 12 ^{eB}	82.4 ± 0.9 ^{eA}
	PVOD/HACD+MWVD	44 ± 5 ^{bA}	0.46 ± 0.01 ^{bA}	0.68 ± 0.02 ^{bcefA}	19.1 ± 1.8 ^{bA}	12.3 ± 1.0 ^{bA}	639 ± 10 ^{bA}	54.7 ± 0.7 ^{hB}
MWV + F	HACD+MWVD	46 ± 18 ^{bcB}	0.44 ± 0.03 ^{bceA}	0.74 ± 0.05 ^{abefA}	20.2 ± 7.6 ^{bB}	14.8 ± 5.4 ^{abA}	299 ± 13 ^{dB}	78.7 ± 0.9 ^{fA}
	PVOD/HACD+MWVD	101 ± 8 ^{aA}	0.41 ± 0.01 ^{ceA}	0.51 ± 0.02 ^{hB}	41.4 ± 3.5 ^{aA}	20.3 ± 1.4 ^{aA}	689 ± 15 ^{aA}	51.1 ± 1.1 ^{iB}
F	HACD+MWVD	26 ± 3 ^{cB}	0.20 ± 0.04 ^{fA}	0.66 ± 0.04 ^{bcefA}	5.0 ± 1.1 ^{efB}	3.3 ± 0.9 ^{efB}	119 ± 9 ^{hB}	91.5 ± 0.6 ^{aA}
	PVOD/HACD+MWVD	38 ± 3 ^{bA}	0.27 ± 0.03 ^{fA}	0.60 ± 0.03 ^{gB}	10.8 ± 1.4 ^{cA}	7.0 ± 1.0 ^{eA}	170 ± 9 ^{gA}	87.9 ± 0.6 ^{bcB}
N	HACD+MWVD	9 ± 3 ^{gA}	0.50 ± 0.04 ^{abA}	0.72 ± 0.11 ^{abcdefgA}	4.7 ± 1.8 ^{efgA}	3.4 ± 1.6 ^{defA}	175 ± 8 ^{gB}	87.6 ± 0.6 ^{cdA}
	PVOD/HACD+MWVD	11 ± 1 ^{gA}	0.50 ± 0.01 ^{aA}	0.77 ± 0.02 ^{acA}	5.8 ± 0.5 ^{eA}	4.5 ± 0.4 ^{deA}	580 ± 19 ^{cA}	58.9 ± 1.4 ^{gB}

Table shows mean values with standard deviations of the mean (the results were averaged over twenty five measurements). Mechanical and physical properties of raw sample (before drying): H: 63.7 ± 2.5 N; Co: 0.23 ± 0.01, –; S: 0.71 ± 0.01, –; G: 14.4 ± 0.9, –; Ch: 10.2 ± 0.8, N; ρ_p : 683 ± 6, kg/m³; ε_p : 51.2 ± 0.4, –. Same letters in the same column indicate that the mean values are not significantly different at a confidence level of 95 % ($p < 0.05$). ^{ab} Significant differences between samples subjected to the same dehydration method but different initial treatments. ^{AB} Significant differences between samples subjected to the same initial treatment but different dehydration method. Symbols: H: hardness, N; Co: cohesiveness, –; S: springiness, –; G: gumminess, –; Ch: chewiness, N; ρ_p : particle density, kg/m³; ε_p : particle porosity, –

Statistical Analysis

Statistical analyses were done using the STATISTICA 12.0 software (StatSoft Inc., Tulsa, OK, USA). One-way analysis of variance was used for testing the differences between samples. Significant differences were determined using Mann Whitney *U* test ($p < 0.05$).

Results and Discussion

Effect of Pretreatments and PVOD on HACD+MWVD Drying Kinetics of Whole Cranberries

Drying of non-osmotically dehydrated fruits took from 243 to 374 min, while DR_{AVG} was from 0.047 ± 0.002 to 0.064 ± 0.003 kg H₂O/kg DM/min (Figs. 1a and 1b). Figure 1a presents two stages of drying process. The first stage is hot air convective drying process. HACD curves decreased gently due to the relatively low drying rate. When the moisture content of HACD materials reached around 2.00 kg H₂O/kg DM, partially dried fruit was transferred to the second MWVD stage. Thus, the drying rate increased rapidly and steeply

decreased in the final stage of drying. The fruits subjected to MWV and PVOD did not require HACD stage, and MWVD took in this case only 20 min. The changes in drying kinetics are related to the changes in the microstructure of processed fruits (Figs. 2 and 3).

Effect of Pretreatments, PVOD, and HACD+MWVD on the Content of Bioactive Compounds and Antioxidant Activity of Cranberries

The TP content of dried fruits without any pretreatment was 23.90 ± 0.38 mg GAE/g DM, while non-treated fruits subjected to combined PVOD and HACD+MWVD were characterized by higher TP content, i.e., 25.55 ± 0.49 mg GAE/g DM (Table 2). In terms of TF content, no treatment or sonication (S or S + F) can be applied to produce high value-added dried sour snacks or sweet cranberries. TMA content of fruits decreased dramatically during HACD+MWVD or combined PVOD and HACD+MWVD. Anthocyanins were particularly sensitive to thermal degradation and losses during osmotic dehydration due to leaching into osmotic solution (Mundada et al. 2010).

Effect of Pretreatments and PVOD on the Texture of Cranberries

Various pretreatments except sonication (S) significantly decreased, i.e., from 16 to 64%, the resistance of cranberry skin in cutting test, while decrease in puncture force was from 28 to 31% (Table 3). Compared with non-treated cranberries, MWV resulted in a number of microfissures and cracks on the fruit surface layer and thus less springy and resistant fruit's skin in cutting test (Fig. 2). Cryogenic freezing (N) significantly reduced hardness of fruits, while convective freezing (F) or other techniques combined with F (S + F or MWV + F)

significantly increased hardness of dried fruits (Table 4). Low hardness of cryogenically frozen fruits could result from freeze-cracking that appeared under high freezing rate of whole cranberries (Zielinska et al. 2019).

Effect of Pretreatments, PVOD, and HACD+MWVD on Color Parameters and Overall Appearance of Cranberries

No treatment or sonication (S) resulted in quite high L^* values of HACD+MWVD fruits (Table 5). The L^* values of HACD+MWVD samples pretreated other way were lower than that of

Table 5 Effect of initial treatments, PVOD, and HACD+MWVD on the color parameters and overall appearance of whole cranberries

Initial Treatment	Dehydration Method	Color Parameters			Overall Appearance
		L^* [-]	a^* [-]	b^* [-]	
C	HACD+MWVD	31.8 ± 0.5 ^{bcA}	25.5 ± 1.0 ^{aA}	7.3 ± 0.5 ^{aA}
	PVOD/HACD+MWVD	32.2 ± 0.5 ^{ba}	19.0 ± 1.2 ^{cdB}	4.6 ± 0.5 ^{bcB}
S	HACD+MWVD	31.7 ± 0.7 ^{bcA}	21.2 ± 1.1 ^{bcA}	5.4 ± 0.4 ^{ba}
	PVOD/HACD+MWVD	27.4 ± 0.5 ^{fb}	16.1 ± 0.9 ^{eb}	4.4 ± 0.5 ^{cb}
S+F	HACD+MWVD	29.7 ± 0.5 ^{deA}	16.1 ± 1.2 ^{eb}	4.1 ± 0.6 ^{ca}
	PVOD/HACD+MWVD	30.8 ± 0.5 ^{cdA}	18.4 ± 1.0 ^{dA}	4.5 ± 0.5 ^{bcA}
MWV	HACD+MWVD	27.8 ± 0.5 ^{fb}	16.4 ± 0.9 ^{eb}	4.6 ± 0.4 ^{bcB}
	PVOD/HACD+MWVD	29.0 ± 0.6 ^{eA}	22.5 ± 1.5 ^{ba}	7.4 ± 0.8 ^{aA}
MWV+F	HACD+MWVD	27.9 ± 0.7 ^{fa}	16.6 ± 1.3 ^{deA}	4.3 ± 0.7 ^{bcA}
	PVOD/HACD+MWVD	26.9 ± 0.4 ^{fb}	18.2 ± 1.0 ^{dA}	4.5 ± 0.4 ^{ca}
F	HACD+MWVD	33.8 ± 0.7 ^{aA}	25.2 ± 1.0 ^{aA}	7.3 ± 0.6 ^{aA}
	PVOD/HACD+MWVD	30.4 ± 0.5 ^{dB}	20.9 ± 1.0 ^{bcB}	6.4 ± 0.4 ^{aA}
N	HACD+MWVD	32.0 ± 0.6 ^{ba}	26.3 ± 1.0 ^{aA}	7.6 ± 0.8 ^{aA}
	PVOD/HACD+MWVD	27.4 ± 0.6 ^{fb}	15.3 ± 1.1 ^{eb}	4.1 ± 0.4 ^{ca}

Table shows mean values with standard deviations of the mean (the results were averaged over thirty five measurements). Same letters in the same column indicate that the mean values are not significantly different at a confidence level of 95 % ($p < 0.05$). ^{ab} – Significant differences between samples subjected to different initial treatments. ^{AB} – significant differences between osmotically dehydrated and non-dehydrated samples. Color parameters of raw sample: L^* : 31.1 ± 0.2, –; a^* : 22.5 ± 0.6, –; b^* : 8.4 ± 0.4, –. L^* : lightness, –; a^* : redness, –; b^* : yellowness

raw fruits. Dried fruits pretreated by MWV were characterized by the lowest L^* values. Initial treatment decreased lightness of osmotically dehydrated and HACD+MWVD fruits. Pretreatments and PVOD influenced the drying time and the surface structure of HACD+MWVD of cranberries. In the case of PVOD and dried fruits, MWV pretreatment produced berries of the most intensive red and yellow color, but the overall appearance was less attractive and fruits appeared to be flattened and wrinkled (Table 5).

Conclusions

Results showed that drying time of cranberries varied from 20 to 493 min. HACD+MWVD produced high value added products, i.e., crispy sour berries of attractive color and high TP content and FRAP values. MWV, S, and N resulted in low hardness of HACD+MWVD fruits. PVOD and HACD+MWVD yielded sweet fruits of flat and wrinkled appearance and much lower nutritional value. It increased hardness of dried berries, while MWV caused significant hardening of their surface. PVOD resulted in high losses of bioactive compounds. HACD+MWVD seems to be good alternative for single-step HACD and single-step MWVD as well as PVOD and HACD+MWVD of cranberries. The results of this study provide useful data for manufacturers, suppliers, and consumers of waxy fruits and vegetables.

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