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Effects of Drying Methods on Different Characteristics of Chokeberry

Cigdem Mustu Ceylan[1,2], Selma Kayacan Cakmakoglu[2], Hatice Bekiroglu[2,3], Mustafa Yaman[4], Alican Akcicek[5], Osman Sagdic[2] & Salih Karasu[2]*

[1]Department of Food Processing, Vocational School, Bilecik Seyh Edebali University, 11100, Bilecik, Turkey
[2]Department of Food Engineering, Faculty of Chemical and Metallurgical Engineering, Yildiz Technical University, Davutpasa Campus, 34210, Istanbul, Turkey
[3]Department of Food Engineering, Faculty of Agriculture, Sirnak University, Sirnak, 73300, Turkey
[4]Department of Molecular Biology and Genetics, Engineering and Natural Sciences Faculty, Istanbul Sabahattin Zaim University, 34303, Istanbul, Turkey
[5]Department of Gastronomy and Culinary Arts, Faculty of Tourism, Kocaeli University, 41080, Kocaeli, Turkey

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This research was aimed to determine effect of four different drying techniques, namely Hot Air Drying (HAD), Vacuum Drying (VD), Ultrasound-Assisted Vacuum Drying (USVD), and Freeze Drying (FD) on drying time, total bioactive content, phenolic and anthocyanin profile, surface characteristic and color change of chokeberries. The novelty of this study is the first application of USVD in chokeberry drying. The drying times were recorded as 2100, 1380, and 1200 minutes for HAD, VD, and USVD, respectively, indicating that the application of ultrasound significantly reduced the drying time. Total Phenolic Content (TPC) value of the dried samples varied between 53.15 and 81.18 GAE/g. The individual phenolic and anthocyanin content were determined by HPLC methods. The phenolic profile of the chokeberries showed that protocatechuic acid, catechin, and chlorogenic acid were the major phenolic compounds. The protocatechuic acid value changed between 707.04 and 1126.49 mg/100 and FD showed highest protocatechuic acid value. The anthocyanin profile test showed that the cyanidin-3-O-galactoside was the most prevalent anthocyanin and its value was found as 27725–198674 mcg/100g. ΔE value was used to determine effect of drying techniques on color change of the dried samples. ΔE value was found as 8.07–11.98. SEM analysis was used to determine effect of drying on surface characteristic of chokeberries. The samples dried by FD and USVD showed more porous structure. This study concluded that USVD emerged as a promising alternative to VD and HAD due to its shorter drying time, higher retention of bioactive compounds, and better color preservation.

Keywords: Anthocyanin, Bioactive compounds, Chokeberry, Phenolic compound, Ultrasound-assisted vacuum drying

Introduction

Chokeberry (*Aronia melanocarpa*), is a member of the Rosaceae family and is native to the eastern areas of North America. It is native to North America and Eastern Canada, however, it was brought to Europe approximately a century ago. It has a very high concentration of polyphenols and is a fruit with the greatest levels of antioxidants.[1] The chemical composition, health benefits and clinical effectiveness of chokeberry have attracted attention in recent years, and the fruits and their extracts have been documented to have anticarcinogenic, hepatoprotective, antimutagenic, cardioprotective, and antidiabetic properties.[2] In the food sector, chokeberries are typically processed into different food products such as juices, syrups, sauces, jams, fruit teas, and dietary supplements while they are also consumed in their fresh form.[1] There has been a growing interest in both fresh and processed products of aronia fruit. This is mostly due to the fact that aronia fruit contains a high concentration of bioactive components and has been shown to have positive implications on health. Besides the processing methods described above, there is a growing number of research projects focusing on creative products, and the variety of ways in which consumption of aronia fruit is also growing.

The limited shelf life of fresh berries has continued to be a major challenge for the agri-food sector.[3] Also, chokeberries cannot always be found fresh all year.[4] Chokeberries are extremely sensitive to microbiological and enzymatic deterioration because of the high levels of moisture, sugar, and bioactive substances that they contain. Processing can be applied to extend the shelf life of fresh fruits. This expansion mostly pertains to inhibiting bacterial proliferation, limiting the function of deleterious enzymes, and

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*Author for Correspondence
E-mail: skarasu@yildiz.edu.tr

minimizing other biochemical and physical degradation of berry products.[3] Drying is one of these processing methods. Also, drying reduces the volume of material and provides easy packaging, handling, and transportation.[5] It remains the most prevalent method because of its economic benefits. Convective dehydration based on the circulated hot air is the most studied method for fruits. It is an effective and simple method, but it is possible for heating to create changes in physical, mechanical, chemical, and nutritional properties of products. The length of drying and slow heating of the material are the other disadvantages of convective drying.[6] Freeze drying provides products with favorable sensory and nutritional attributes, together with its excellent rehydration capability while removing moisture, but it is a slow and high-cost process.[7] For these reasons, alternative drying methods that provide quick mass and heat transfer, reduce degradation of bioactive properties at low cost and are easily applicable should be tried.

Vacuum drying is a method that takes place without oxygen and moisture is removed at mild temperature. Because of these reasons, nutritional and sensory properties of dried products could be conserved. A combination of vacuum drying with other methods may facilitate enhanced drying efficiency.[8] According to reports, USVD is a unique food drying process. By employing mechanical waves, ultrasound aids heat transmission and promotes a movement of water from the inside to the outside of the material. While vacuum drying lowers ambient pressure, ultrasonic processing boosts heat and mass transmission.[9] Ultrasonic-assisted vacuum drying has been used for many food products such as salmon and trout fillets[9], red peppers[10], carrot slices[11], nectarine[12], hawthorn fruit juices[13], raspberry fruit[14], rosehip fruit[15], Asian pear fruit.[16] Ultrasound-assisted vacuum drying of chokeberry fruit could not be found in the literature. The purpose of this research was to compare the drying kinetics, total phenolic content, antioxidant activity, phenolic profile, anthocyanin content, and colour attributes of four distinct drying methods namely, USVD, HAD, VD, and FD.

Materials and Methods

Materials

Fresh chokeberry was dried within 24 h after being brought from the local market. Until the drying process, they were stored at 4°C. During the selection of chokeberry to be dried, fruits that were of the same size and without any physical damage were selected. An infrared moisture analyzer (Rad-wag, MA 50-R) was employed to find the initial moisture content of fresh chokeberry fruits and calculated as 70.77% ± 1.22.

Drying Procedure

The HAD, VD, USVD, and FD processes were applied to the whole chokeberry fruit. Drying processes were performed at 50°C for HAD, VD, and USVD methods. HAD was carried out at constant air velocity of 1.3 m/s. A Testo 440 vane probe anemometer (Lutron, AM-4201, and Taiwan) was used to measure the air velocity. The airflow was directed horizontally through the fruits surface. The VD process was conducted in a vacuum dryer (Daihan WOV-30, Gangwondo, South Korea) at a vacuum pressure of 60 mbar. The vacuum process was performed using a vacuum pump (EVP 2XZ-2C, Zhejiang, China) with a pump speed of 2 L/s. The dryer was initially operated empty until it reached the desired drying temperature. Once the temperature was achieved, the fruits were placed in the dryer on metal drying trays, after which the air inlet and outlet of the vacuum cabinet were sealed, and the vacuum pump was activated. For USVD, chokeberries were initially placed in a beaker and subjected to an ultrasonic water bath (Daihan, WUCD10H, Gangwon-do, Republic of Korea) at 50°C for 30 min. The ultrasonic water bath (amplitude: 100%, power density: ~1 W/cm^2, volume: 10 L) was operated at a frequency of 40 kHz for sonication. Following the ultrasound treatment, the chokeberries were transferred to metal drying trays and subsequently dried using a vacuum dryer. Utilizing a freeze dryer (Martin Christ, Beta 1-8 LSC plus, Osterode am Harz, Germany) at a temperature of −55°C and a pressure of 1 hPa for duration of 72 hours, the FD technique was implemented.

Mathematical Modelling of the Drying Curve and Effective Moisture Diffusivity (D_{eff})

Drying curves were modelled using the data obtained every 60 minutes throughout the drying period with numerous models.[17–26] In these models, the moisture ratio (MR) $(M - M_e)/(M_0 - M_e)$ was shortened to M/M_0 because of the comparatively relatively low magnitude of M_e in comparison to M or M_0. M, M_0, and M_e symbolize the moisture content at the present time, the initial moisture content, and the equilibrium moisture content, respectively. Using the Statistica software (StatSoft, Tulsa, USA), the model parameters and R^2 values were calculated. The acceptability of models was determined using higher R^2 and lower Root Mean Square Error (RMSE) values. RMSE values of the models were calculated using Eq. (1).[27]

$$\mathrm{RMSE} = \left[\frac{1}{N} \sum_{i=1}^{N} \left(\mathrm{MR}_{\mathrm{pre,i}} - \mathrm{MR}_{\mathrm{exp,i}} \right)^{2} \right]^{1/2} \quad \ldots (1)$$

where, MR_{prei}, MR_{expi}, N and n represents the anticipated moisture ratio, the experimental moisture ratio, the number of observations, and the count of constants, respectively.

Effective moisture diffusivity (D_{eff}) of dried chokeberry samples was determined using Fick’s second law Eq. (2).

$$\frac{\partial M}{\partial t} = \nabla\left[D_{eff}\left(\nabla M\right)\right] \quad \ldots (2)$$

Considering the assumptions of a spherical shape and unstable diffusion conditions, Eq. (2) was altered and utilized as Eq. (3):

$$\mathrm{MR} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n} \exp\left(n^2 \pi^2 \frac{D_{\mathrm{eff}} t}{r^2} \right) \quad \ldots (3)$$

where, D_{eff}, r, and n are the diffusivity for effective moisture (m^2/s), the half-thickness of the chokeberry (m), and the positive integer, respectively. For long drying periods, this equation can be simplified to Eq. (4):

$$\ln\left(\mathrm{MR}\right) = \ln\left(\frac{6}{\pi^2} \right) - \left(\pi^2 \frac{D_{\mathrm{eff}} t}{r^2} \right) \quad \ldots (4)$$

Extraction Procedure

For the extraction of fresh and dried chokeberries, methanol-water (50:50, v/v) solution was added to the samples with 1:10 (solid:liquid) ratio. Chokeberry and methanol-water mixtures were homogenized using an ultraturrax (Daihan, HG-15D). Homogenization was performed at 10000 rpm for 2 min. After 2 h shaking of the mixtures, the mixtures underwent centrifugation at 2800 g for 10 minutes and were subsequently filtered using a 0.45 μm syringe filter.[8] The extracts were kept at –18°C until they were analyzed.

Total Phenolic Content

A modified version of the method proposed by Singleton and Rossi was utilized in order to ascertain the composition of TPC (1965).[28] In a tube, the following components were mixed: 7.5 g/100 g Na_2CO_3, 2.5 mL of tenfold Folin Ciocalteu's phenol reagent, and 0.5 mL of diluted methanolic chokeberry extracts. The combination was kept in dark environment for 30 min. The absorbance at 760 nm was accurately measured using a UV-Vis spectrophotometer. The concentration of phenolics was quantified as milligrams of gallic acid equivalents (GAE) per gram of Dry Matter (DM) (mg GAE/g DM).

Antioxidant Capacity

In order to determine the effective antioxidant capacity of chokeberry extracts, the DPPH and CUPRAC techniques were utilized. The DPPH (1, 1-diphenyl-2-picrylhydrazyl) method is used for assessing the radical scavenging activity of extracts, thereby estimating their antioxidant properties against free radicals. This method relies on the spectrophotometric measurement of changes in DPPH concentration, which occur as a result of the reaction between antioxidant compounds present in the extract and the DPPH radical. The CUPRAC (Cupric Reducing Antioxidant Capacity) method is based on the reduction of copper(II)–neocuproine to copper(I)–neocuproine upon the addition of an antioxidant solution to the reaction medium. For DPPH, 0.1 mL from the extracts and 4.9 mL of 0.1 mmol/L DPPH• in methanol were included in the tube. After a 30-minute incubation time in the dark, the absorbance at 517 nm was measured.[29] The CUPRAC test was conducted in accordance with the guidelines established in a previously published study.[30] For CUPRAC, 0.1 mL of extract, 1 mL of distilled water, 1 mL of neocuproine (7.5 mmol/L), 1 mL of $CuCl_2$ (10 mmol/L), and 1 mL of NH_4Ac (1 mol/L) were all added together. The samples were examined for absorbance at 450 nm following an hour of dark incubation. The findings were presented in the form of milligrams of Trolox Equivalents (TE) per gram of dry matter (mg TE/g DM).

Phenolics and Anthocyanin Profiles

An Agilent 1200 HPLC system with photodiode array detector, column oven, quaternary pump, and autosampler was employed for analysis of extracted phenolic substances from fresh and dried chokeberry extracts. The extracts were filtered employing 0.22 m filter. Phenolic substances were isolated on a Waters Atlantis C18 column (250 mm × 4.6 mm, 5 μm) using linear gradient elution. The solvent gradient program, the chromatography parameters and quantification procedures were conducted according to the method described by Ucar and Karadag.[31]

SEM Images

The scanning electron microscope (SEM) was utilized by the Yildiz Technical University Central Laboratory to examine the microscopic structure and surface characteristic of the dried samples slices. On the stub of the scanning electron microscope, the dried chokeberry samples were placed. Gold was applied to the samples in order to produce a reflecting surface that would be suitable for the electron beam. Images of the gold-plated samples were taken with the SEM at a voltage of 10 kV.

Color Properties

A colorimeter was utilized in order to ascertain the colour parameters of both fresh and dried chokeberry samples (CR-400 Konica, Minolta, Tokyo, Japan). The colorimeter was calibrated at a standard illuminant D65 (representing daylight) before measurement. Measurements were obtained from various surfaces of the aronia fruit in order to generate a homogenous colour measurement. Measurement in triplicate was taken and average was recorded. The colour values were represented as L*, a*, and b*. The overall colour change (ΔE) was determined using L*, a*, b* as in Eq. (5):

$$\Delta E = \sqrt{(\Delta L^{*})^{2} + (\Delta a^{*})^{2} + (\Delta b^{*})^{2}} \quad \dots (5)$$

Statistical Analysis

The data acquired in this study underwent statistical analysis utilizing JMP 9 software (SAS, NC, USA). The arithmetic mean and standard deviations of the relevant parameters were computed and analyzed. For the purpose of determining whether or not there were any significant differences between the variables, a one-way analysis of variance (ANOVA) with the Tukey test was utilized. The data analysis of findings indicated a statistically significant distinction among the variables at a significance level of $p < 0.05$, which is typically regarded as meaningful.

Results and Discussion

Effect of Drying Methods on Drying Time

The moisture content of chokeberries prior to the drying procedure level was found to be 70.77%. The drying curves of HAD, VD and USVD are shown in Fig. 1. Fresh chokeberries were dried until they had a moisture content of 20%. The drying process period was 1200, 1380 and 2100 minutes for USVD, VD and HAD at 50°C, respectively. HAD had the longest drying period compared to VD and USVD. The longer drying time of HAD could be explained by the fact that the temperature of the product increases slowly due to external heat flux and moisture migration occurs slowly from the interior.[32] The drying times of VD and USVD were approximately 1.52 times and 1.75 times less than HAD. The evaporation rate increases in a vacuum because of decreasing the boiling point.[15] USVD was 1.15 times faster than VD. Ultrasound creates cavitation effects. Moisture in the products expands suddenly and forcefully due to cavitation. The releasing explosive force generates microchannels and reduces moisture diffusion resistance. Therefore, drying time decreases.[13] Studies have indicated that ultrasound assisting increases the drying rate for drying red peppers[10], garlic slices[33], and pomegranate.[34]

Modeling Drying Behavior and D_{eff} Values

Drying models to simulate chokeberry drying behavior are displayed in Table 1. Model parameters, $R^{2,}$ and RMSE values of models are presented in

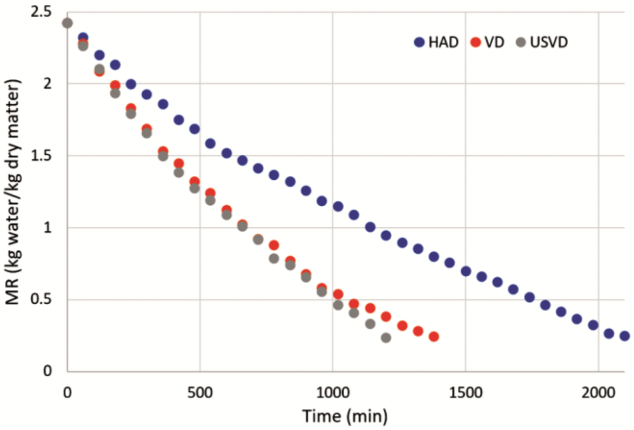

Fig. 1 — Drying kinetics of HAD, VD and USVD at 50°C

Table 1 — Mathematical models for the drying curves

Models	Equation
Newton[17]	$MR=\exp(-k\times t)$
Page[18]	$MR=\exp(-k\times t^{n})$
Henderson and Pabis[19]	$MR=a\times\exp(-k\times t^{n})$
Logarithmic[20]	$MR=a\times\exp(-k\times t^{n})+c$
Wang and Singh[21]	$MR=1+a\times t+b\times t^{2}$
Two terms[22]	$MR=a\times\exp(-k_{0}\times t)+b\times\exp(-k_{1}\times t)$
Two terms exponential[23]	$MR=a\times\exp(-k\times t)+(1-a)\times\exp(-k\times a\times t)$
Parabolic[24]	$MR=a+b\times t+c\times t^{2}$
Agbashlo[25]	$MR=\exp((-k_{1}\times t)/(1+k_{2}\times t))$
Verma[26]	$MR=a\times\exp(-k\times t)+(1-a)\times\exp(-g\times t)$

Table 2. R^2 values of the models were changed from 0.9920 to 0.9997. These values indicate that all drying models were applied successfully to describe the drying behaviour of chokeberry samples. From the perspective of maximizing R^2 and minimizing RMSE the mathematical model for fitting experimental data was selected. Taking R^2 and RMSE into account, logarithmic model were chosen as the most suitable dehydration mathematical models to characterize the drying characteristics of chokeberries for HAD and USVD while two-term exponential models was selected as most suitable models for VD. D_{eff} values were calculated as 9.17×10^{-10}, 1.54×10^{-9}, and 1.73×10^{-9} for HAD, VD, and USVD, respectively.

Table 2 — Statistical analysis of models

Models	Parameters	Drying methods		
		HAD	VD	USVD
Newton	k	0.000815	0.001372	0.001429
	R^2	0.9920	0.9940	0.9924
	RMSE	0.1948	0.1455	0.1503
Page	k	0.000266	0.000410	0.000429
	n	1.158737	1.183640	1.400806
	R^2	0.9960	0.9990	0.9974
	RMSE	0.1382	0.0600	0.0877
Henderson and Pabis	k	0.000847	0.001443	0.001498
	a	1.031573	1.044400	1.039997
	R^2	0.9930	0.9959	0.9940
	RMSE	0.1818	0.1217	0.1332
Logarithmic	k	0.000432	0.000964	0.000830
	a	1.460608	1.243775	1.400806
	c	–0.479432	–0.236498	–0.404859
	R^2	0.9992	0.9996	0.9995
	RMSE	0.0611	0.0365	0.0392
Wang and Singh	b	0.000000	0.000000	0.000000
	a	–0.000639	–0.001087	–0.001115
	R^2	0.9982	0.9997	0.9990
	RMSE	0.0918	0.0353	0.0541
Two term	a	6.24961	2.97834	1.060301
	k_0	0.00028	0.00071	0.001533
	k_1	0.00022	0.00048	1.157066
	b	–5.26973	–1.97237	–0.060301
	R^2	0.9992	0.9997	0.9949
	RMSE	0.0630	0.0352	0.1239
Two term exponential	a	0.000276	1.713817	1.710884
	k	2.955126	0.001879	0.001967
	R^2	0.9920	0.9990	0.9975
	RMSE	0.1950	0.0575	0.0860
Parabolic	a	0.973106	0.996383	0.987556
	b	–0.000587	–0.001077	–0.001075
	c	0.000001	0.000001	0.000001
	R^2	0.9990	0.9997	0.9992
	RMSE	0.0721	0.0348	0.0499
Agbashlo	a	0.00649	0.001103	0.001124
	b	–0.00159	–0.000242	–0.000290
	R^2	0.9982	0.9997	0.9989
	RMSE	0.0939	0.0335	0.0563
Verma	a	–0.003646	–0.065119	–0.010769
	k	–0.001699	–0.001850	–0.002105
	g	0.000723	0.001475	0.001220
	R^2	0.9996	0.9967	0.9997
	RMSE	0.0441	0.1092	0.0288

HAD, hot air drying; VD, vacuum drying; USVD, ultrasound assisted vacuum drying; FD, freeze drying

According to the results, drying methods affected the D_{eff} values. USVD had higher D_{eff} value than VD and HAD.

Effect of Drying Methods on Total Phenolic and Antioxidant Activity of Chokeberries

The TPC and antioxidant capacity values before and after dehydration process are shown in Table 3. TPC values of fresh chokeberry samples were found to be 84.54 mg GAE/g DM and TPC value was found as 24.71 mg GAE/g fresh weight. The four different cultivars of chokeberry were analyzed and found that the total polyphenol content of the cultivars varies between 1845–2340 mg GAE/100 g.[35] Wangensteen found the total phenolic content of three cultivars of chokeberry to vary between 1079–1921 mg GAE/100 g fresh weight. It has been stated that chokeberry fruit composition and health value rely on many factors including variety, maturity, environmental circumstances, and climatic conditions.[1] In this study, the TPC value of fresh chokeberry (84.54 mg GAE/g DM) was also affected by VD (63.54 mg GAE/g DM) and USVD (68.53 mg GAE/g DM), with HAD (53.15 mg GAE/g DM) being the most affected ($p < 0.05$). No significant differences between fresh and FD TPC results were detected ($p > 0.05$). Similar results for FD were found in other studies.[4,36] Phenolic compounds are sensitive to heat and oxidation.[8] The higher retention of phenolic compound in FD samples can be attributed to the drying process occurring at an extremely low temperature and within a vacuum environment during freeze-drying.[15]

On the other hand, long drying (2100 min) time and heat treatment can cause degradation of phenolic compounds during HAD. Among the thermal treatments, USVD provided higher retention for TPC compared to HAD and VD. The cavitation caused by ultrasound application can increase the phenolic extraction rate by causing the plant cell to break down.[8] The development of capillaries in the microstructure through the use of ultrasound made mass transfer easier, and the extraction efficiency of phenolic compounds was improved. A number of studies indicate that ultrasound-assisted drying lead to less deterioration e.g., Asian pear[16], red peppers[10], nectarine[12], and papaya.[37] Another study also reported that extraction using ultrasound improves phenolics.[38] The antioxidant capacity values of the chokeberries were determined as 67.11–95.52 mg TE/ 100 g DM and 22.05–96.12 mg TE/ 100 g DM by the DPPH and CUPRAC methods, respectively. As in TPC results, the highest DPPH and CUPRAC values belonged to FD. HAD caused a significant decrease in DPPH (67.11 mg TE/g DM) and CUPRAC (22.05 mg TE/g DM) values ($p < 0.05$). Chokeberries from USVD had higher Antioxidant Activity (AA) values than HAD and VD samples. The comparable finding for USVD raspberries[14] and Asian pear[16] were reported. The relation between CUPRAC and TPC (0.9924) was higher than that between TPC and DPHH (0.9888). Additionally, there was a substantial relationship between DPPH and CUPRAC (0.9777). Considering the results, it seems that USVD is an alternative method for drying chokeberry because it provides less heat treatment and high retention of phenolics.

Effects of Drying Methods on Individual Phenolic Compounds and Anthocyanin Composition

The effects of HAD, VD, USVD and FD techniques on individual phenolic compounds are given in Table 4. It shows that protocatechuic acid, catechin and chlorogenic acid are the major phenolic compounds of chokeberry.[39] Catechuic acid is the primary bonded phenolic component in chokeberry.[40] The catechin values of the dried chokeberries were higher than the catechin values of the fresh sample, indicating that bound phenolics, which are covalently attached to the cell wall, maintain their stability during all drying processes.[40] A similar result was reported by Zhu *et al.* (2023)[40] for chokeberry. In this study, chlorogenic acid was found to be 290.93 mg/

Table 3 — TPC, DPPH and CUPRAC results of fresh and chokeberry samples

Bioactive properties	Fresh chokeberry	Dried chokeberry				*r*	
		HAD	VD	USVD	FD	DPPH	CUPRAC
TPC$_1$	84.54±3.67^a	53.15±0.55^d	63.54±1.00^c	68.53±1.20^b	81.18±3.43^a	0.9888	0.9924
DPPH$_2$	89.71±2.01^{ab}	67.11±4.30^d	77.96±6.67^c	86.43±2.73^b	95.52±5.62^a	1	0.9777
CUPRAC$_3$	96.12±6.49^a	22.05±2.63^d	51.67±7.92^c	56.49±0.93^c	84.22±9.23^b		1

HAD, hot air drying; VD, vacuum drying; USVD, ultrasound assisted vacuum drying; FD, freeze drying; different lowercase letters in the same line indicates differences between samples subjected to different drying methods ($p < 0.05$). TPC expressed as mg GAE/g DM; DPPH expressed as mg TE/g DM; CUPRAC expressed as mg TE/g DM

100 g DM for fresh chokeberry samples. Similar to the results in this study, Oszmiański and Wojdylo (2005)[41] detected chlorogenic acid in chokeberry samples at 301.85 mg/ 100 g DM.[35] and also analyzed four different cultivars of chokeberry and found a range of chlorogenic acid between 72 and 96.6 mg/100 g. Among the HAD, VD, USVD and FD, chlorogenic acid was found to have the highest amount for FD samples. HAD, VD, and USVD caused a significant decrease in chlorogenic acid amount ($p < 0.05$). Chlorogenic acid content was analyzed for sun-dried, freeze-dried, and oven-dried chokeberries and found that the highest amount of chlorogenic acid belonged to freeze-dried chokeberries.[4] Additionally, chlorogenic acid was found to be 293.26 and 259.03 mg/100g for freeze drying and convective drying, respectively.[42] Also, it was stated that chokeberry can contain p-coumaric acid, caffeic acid protocatechuic, ferulic, syringic, 4-hydroxybenzoic, and ellagic acids[43], rutin, and quercetin.[2] These compounds were detected in this study.

The anthocyanin profiles of fresh and dried chokeberry samples are given in Table 5. Cyanidin-3-O-galactoside was identified as the major anthocyanin for chokeberry berries. This result is in agreement with previously published studies.[44,45] The cyanidin-3-O-galactoside content of chokeberry samples ranged from 27725 to 198674 mcg/100 g. This finding demonstrated that chokeberry has a significant amount of anthocyanin. Except for the sample dried with HAD, all dried samples had higher anthocyanin concentrations than fresh ones. Among the dried samples, the sample dried with FD had the largest quantity of anthocyanin, followed by the samples dried with USVD and VD, respectively. Due to the low thermal stability of anthocyanins, it may have caused thermal degradation of anthocyanins during hot air drying.[46] The long drying time during HAD caused high thermal load on the anthocyanins and thus significant losses were observed. The fact that the other three drying methods were carried out under vacuum may have caused anthocyanins not to be exposed to oxidation and to undergo less degradation.

Table 4 — Individual phenolic compounds

Phenolic compounds (mg/100 g)	Fresh	HAD	VD	USVD	FD
Gallic acid	25.57±1.3^{a}	23.00±0.87^{b}	25.88±1.87^{a}	18.31±0.63^{d}	20.68±1.06^{c}
Protocatechuic acid	856.37±43.2^{b}	707.04±27.6^{c}	721.45±34.4^{c}	807.57±38.2^{b}	1126.49±89.7^{a}
Catechin	572.47±26.3^{c}	652.42±29.5^{b}	652.50±20.1^{b}	676.57±24.2^{b}	952.51±30.8^{a}
4-Hydroxybenzioc acid	6.52±0.43^{d}	23.87±1.26^{b}	23.94±1.43^{b}	21.05±1.19^{c}	28.46±1.87^{a}
Syringic acid	2.68±0.12^{d}	10.18±0.82^{b}	12.47±0.98^{a}	7.28±0.45^{c}	10.46±0.65^{b}
Ellagic acid	65.90±3.45^{d}	101.52±4.39^{c}	112.33±6.19^{bc}	101.39±6.92^{c}	138.32±6.63^{a}
Caffeic acid	5.31±0.32^{a}	3.48±0.14^{c}	3.53±0.12^{c}	3.48±0.11^{c}	4.05±0.17^{b}
p-Coumaric acid	6.00±0.34^{d}	6.85±0.39^{c}	7.73± 0.43^{b}	7.16±0.49^{bc}	8.85±0.56^{a}
Ferulic acid	1.31±0.12^{c}	1.54±0.10^{b}	2.00±0.15^{a}	1.87±0.08^{a}	0.52±0.02^{d}
Myricetin	29.77±1.48^{a}	10.66±0.54^{b}	10.51±0.39^{b}	10.51±0.48^{b}	9.98±0.43^{bc}
Quercetin	16.46±0.97^{a}	7.87±0.18^{c}	8.20±0.12^{b}	7.93±0.46^{bc}	8.56±0.3^{b}
Kaempferol	0.00±0	1.94±0.1^{a}	1.91±0.08^{a}	1.91±0.09^{a}	1.81±0.11^{a}
Chlorogenic acid	290.93±17.2^{a}	106.66±5.63^{d}	105.03±6.43^{d}	116.97±4.01^{c}	159.35±9.27^{b}
Rutin	33.14±1.87^{d}	39.05±1.64^{c}	44.18±2.34^{b}	40.87±2.92^{bc}	50.67±2.69^{a}
Sinapic acid	18.12±0.72^{a}	1.20±0.14^{c}	1.69±0.11^{b}	19.65±1.14^{a}	0.13±0.01^{d}

HAD, hot air drying; VD, vacuum drying; USVD, ultrasound assisted vacuum drying; FD, freeze drying; different lowercase letters in the same line indicates differences between samples subjected to different drying methods ($p < 0.05$)

Table 5 — Anthocyanin profiles of the fresh and dried chokeberry samples

Samples	cyanidin-3-O-galactoside	cyanidin-3-O-glucoside	cyanidin-3-O-arabinoside	cyanidin-3-O-xyloside
	mcg/100g	mcg/100g	mcg/100g	mcg/100g
Fresh	43087±2765^{d}	1334±83^{d}	10294±864^{d}	1715±142^{d}
HAD	27725±1873^{e}	1063±47^{e}	6740±374^{e}	1316±68^{e}
VD	87314±4897^{c}	3103±163^{c}	20649±1356^{c}	4011±203^{c}
USVD	134743±7562^{b}	3715±189^{b}	25237±1173^{b}	4628±195^{b}
FD	198674±9764^{a}	5639±477^{a}	39353±2743^{a}	6839±302^{a}

HAD, hot air drying; VD, vacuum drying; USVD, ultrasound assisted vacuum drying; FD, freeze drying; different lowercase letters in the same line indicates differences between samples subjected to different drying methods ($p < 0.05$)

FD, VD, and USVD showed higher anthocyanins compared to the wet sample, deterioration of fruit matrix, and increased extraction efficiency of anthocyanins. This was more evident in USVD. The augmentation of anthocyanin extraction is attributable resulting in improved mass transfer caused by cavitation effects of ultrasound treatment. Furthermore, cell walls can be damaged allowing for a extraction of anthocyanins to the solvent, and the formation of micro-jetting is caused by the collapse of cavitation bubbles.[47] These outcomes indicated that USVD, FD and VD dried chokeberry samples could be an important alternative in terms of anthocyanin.

Effect of Drying Methods on Colour Parameters and Surface Morphology (SEM images)

The images of the fresh and dried chokeberry samples were given in Fig. 2. Colour is one of the primary indicators of food quality and frequently is a good indicator of the chemical, biochemical, and microbiological characteristics of food stuffs. It can also have a significant impact on the market value of item. The effects of drying methods on colour parameters of chokeberries are shown in Table 6. The L^*, a^* and b^* values of fresh chokeberry samples were found to be 17.69, 1.63 and –1.27, respectively. L^* values of all dried chokeberries increased significantly ($p < 0.05$). The highest increase was found in FD and the lowest increase was found in HAD for L^* values. Similar results were found for raspberries.[14] a^* values decreased in HAD and increased in VD, USVD, and FD. The fact that the FD chokeberry samples had the highest L^* and a^* values are because thermal degradation and browning reactions do not occur during low temperature FD. In addition, the increase in the anthocyanin concentration may be the reason for the high a^* because of the removal of water.[36] Probably, VD and USVD provided more anthocyanin retention like FD than HAD, a^* values of VD and USVD were found higher than HAD. Also, drying occurred in VD and USVD without oxygen, and drying periods were shorter than in HAD. HAD had the longest drying time among the drying methods. This could cause high degradation of pigment and non-enzymatic browning.[36] The lowest color change (minimum ΔE value) was determined for HAD (8.07), while the highest ΔE value was found for FD (11.98). With ΔE values of 5, it was noted that there were significant changes in color after the drying process.[34] For all drying methods, ΔE was higher than 5. The findings indicated that all drying techniques would induce a noticeable alteration in the color of aronia fruit. Various factors contributed to the elevated ΔE value in the samples subjected to FD treatment. The FD approach, by not degrading anthocyanins, led to an enhanced concentration of anthocyanins in the samples dried using FD. This resulted in an augmentation of the A value. The L value of the samples dried with FD increased significantly. The FD approach induced the creation of surface pores, hence enhancing reflection. The alterations were beneficial in the samples dehydrated using FD. Consequently, it is essential to analyze the direction of change in both the ΔE value and the L^*, a^* and b^* values of the samples subjected to FD. In the samples dried with HAD, despite a low ΔE value, it was seen that the L^*, a^* and b^* values exhibited variations in

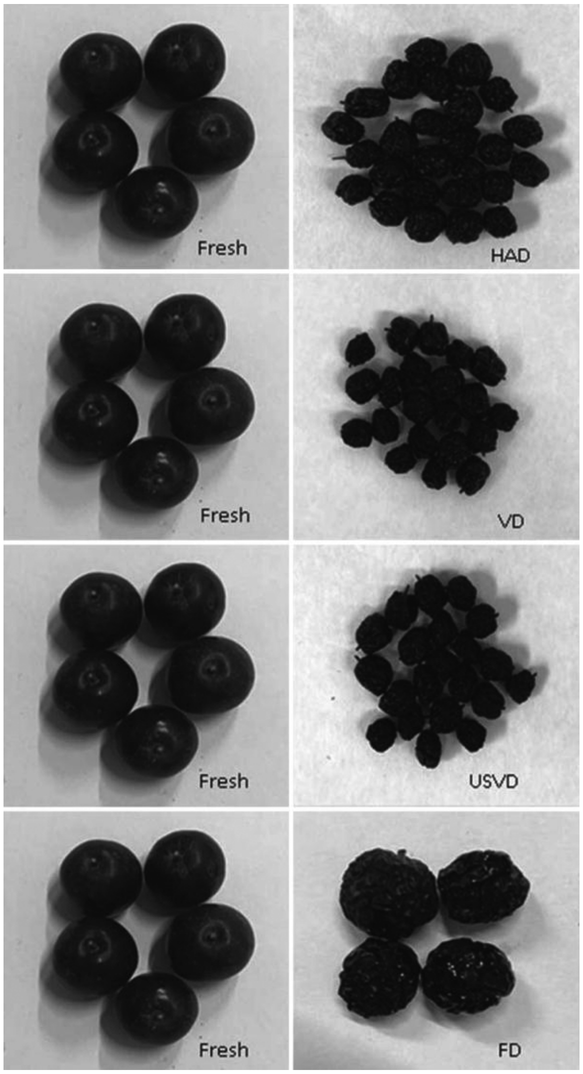

Fig. 2 — The Images of the fresh and dried chokeberry samples

Table 6 — Color results of fresh and driedchokeberry

Color parameters	Fresh chokeberry	Dried chokeberry			
		HAD	VD	USVD	FD
L^*	17.69±0.17^d	24.64±0.29^c	27.27±0.63^b	26.99±1.16^b	29.29±0.14^a
a^*	1.63±0.10^c	1.57±0.37^d	2.31±0.10^b	2.93±0.06^b	3.59±0.14^a
b^*	–1.27±0.28^a	3.85±0.15^{bc}	–3.72±0.19^{bc}	–4.00±0.29^c	–3.53±0.18^b
ΔE	—	8.07^d	10.91^b	9.78^c	11.98^a

HAD, hot air drying; VD, vacuum drying; USVD, ultrasound-assisted vacuum drying; FD, freeze drying; different lowercase letters in the same line indicates differences between samples subjected to different drying methods (p <0.05)

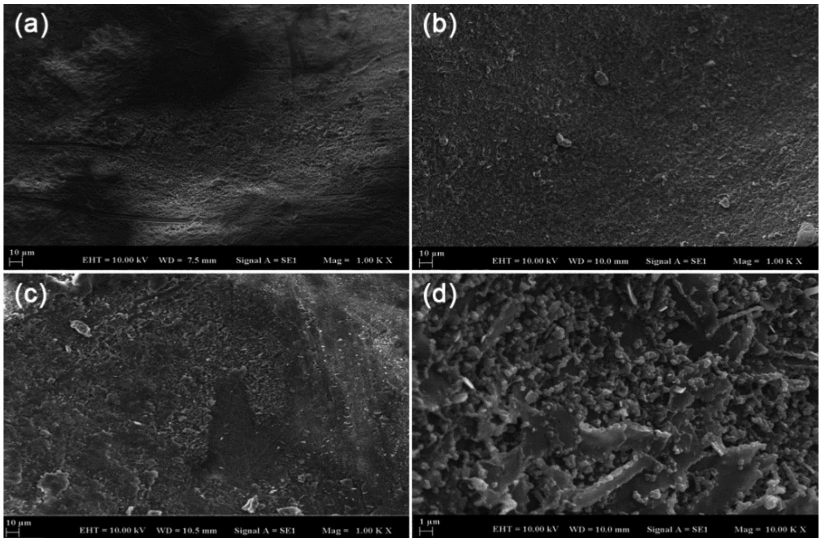

Fig. 3 — SEM images of the dried chokeberry by: (a) HAD, (b) VD, (c) USVD, and (d) FD

opposite directions. In the samples dried using HAD, a reduction in a* value and an elevation in the b* value were noted, in contrast to conventional drying techniques. A favorable alteration in the b* value was noted. Upon examining the alterations in the ΔE value alongside the L^*, a^* and b^* values, it was determined that the color values of the samples dried using FD and USVD were more favorable.

Microscopy (SEM) images are depicted in Fig. 3. There is a definite observation of the impact of HAD on distortion and shrinking. The observed phenomenon could potentially be attributed to the extended duration of temperature exposure experienced by chokeberry fruits. The findings align with the data presented in Fig. 3. For VD, it is noted that the surface morphology exhibits substantially less damage and a uniform surface structure is present. USVD reveals partial alterations in the surface morphology, with the presence of porous structures in specific areas. The presence of a porous structure can be attributed to the cavitation effect that occurs during the ultrasonic process. Post-HAD drying, the deterioration of the porous structure and significant surface shrinkage are unfavorable surface attributes. In USVD, the porosity structure is maintained while achieving a reduced degree of shrinking. The FD drying procedure attains the most optimal surface characteristic. The low drying temperature and vacuum drying procedure facilitated the development of a more porous surface structure without shrinking. USVD has superior quality features relative to HAD concerning surface properties. Consequently, similar to the depicted images in Fig. 3, the samples dried with VD exhibit a smoother and more uniform surface structure. Conversely, the samples dried with HAD display noticeable shrinkage, while the samples dried with USVD have a specific porosity structure.

Conclusions

This study aimed to investigate the impact of HAD, VD, USVD, and FD drying methods on the bioactive compounds, phenolic and anthocyanin profiles, and colour properties of chokeberries. It can be stem from this study that the utilization of ultrasound markedly decreased the drying duration of chokeberry. It can be inferred from modelling results that the logarithmic and two-term exponential drying models should be used for modelling of the drying behaviour of chokeberry. Total bioactive content, anthocyanin and phenolic profile analysis concluded that USVD showed higher bioactive retention than HAD and VD. The surface characteristic and colour quality of the dried chokeberries was affected from different drying techniques. It was concluded that USVD and FD could be evaluated as more porous structure and less shrinkage. Based on the findings, the study concluded that USVD should be applied as a viable alternative to VD and HAD due to its shorter drying time and improved retention of bioactive compounds compared to HAD.

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