

Impact of drying technologies on polyphenols and antioxidant capacity in chokeberry pomace tea infusion

EFAISHE KAVELA, VIRÁG ORBÁN, MÓNICA MÁTÉ*  and
LILLA SZALÓKI-DORKÓ

Department of Fruits and Vegetables Processing Technology, Institute of Food Science and Technology,
Hungarian University of Agriculture and Life Sciences, H-1118, Budapest, Villányi Street 29-43, Hungary

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ABSTRACT

This study evaluated the effects of microwave vacuum drying (MVD), atmospheric drying (AD), and freeze-drying (FD) on polyphenols, antioxidant capacities, and colour of chokeberry pomace tea infusions, which were combined with market tea in various ratios for flavour enhancement: 100–0%, 50–50%, and 60–40%. 3.5 g sample was infused in 200 mL of boiled water for 5 min, and tested for total phenolic content (TPC), total anthocyanins (TA), antioxidant capacity (FRAP, TEAC, and DPPH), and colour change. Results showed significantly higher TPC and TA in the 100% samples than in the mixed samples. The FD and MVD (100%) samples had the highest TPC and TA, respectively. Antioxidant capacities (DPPH and TEAC) did not differ significantly between 100% pomace and the mixed samples. The study concludes that MVD and FD drying technologies effectively preserved high polyphenol content and colour for the tea infusion; and other fruits can enhance the flavour of the tea.

KEYWORDS

chokeberry, pomace, drying technologies, tea infusion, polyphenols

* Corresponding author. E-mail: mate.monika.zsuzsanna@uni-mate.hu

INTRODUCTION

The abundance of polyphenols in the chokeberry (*Aronia melanocarpa* (Michx) Elliot) has been extensively studied, establishing chokeberry as a rich source of polyphenols and anthocyanins, which have antioxidant effects (Kaloudi et al., 2022; Tolić et al., 2015). Antioxidants are essential for scavenging free radicals that cause oxidative stress, responsible for chronic diseases such as cancer and cardiovascular diseases (Bloch et al., 2025; Nowak et al., 2025; Ren et al., 2022). Chokeberry pomace, a residual left after juice extraction from chokeberries, has been discovered to contain a higher amount of polyphenols than the chokeberry juice (Frumuzachi et al., 2024; Gao et al., 2024; Oszmiański and Wojdyło, 2005). This discovery generated the interest among researchers to explore different ways of valorising the chokeberry pomace. The utilization of chokeberry pomace does not only improve its economic value, but it also reduces the waste, and the burden of discarding it (Hrelia et al., 2025). Additionally, chokeberry pomace has the potential to contribute to sustainable and functional ingredients in food production. In a study conducted by Esatbeyoglu et al. (2023), chokeberry pomace was used for the first time to produce a water, kefir-like beverage rich in polyphenols and antioxidants. High polyphenols in chokeberry pomace make it suitable for incorporating it into different foods, for various roles. These include acting as a natural food additive enhancing the colour, inhibiting microbial growth, and preserving the overall food quality (Babaoğlu et al., 2022; Efenberger-Szmechtyk et al., 2020).

The integration of chokeberry pomace or its extracts into food formulation provides a potential avenue for healthier, more sustainable food products with improved sensory and functional properties (Kidoń et al., 2023). However, the processing of the pomace may degrade the sensory attributes, and bioactive compounds contained in the pomace, consequently affecting its quality (Terzić et al., 2023). The colour in chokeberry pomace is a result of anthocyanins in the pomace. However, anthocyanins can be affected by many factors including light, temperature, and pH, during handling or storage, especially when the material contains high moisture content (Kassebi and Korzenszky, 2024; Somogyi et al., 2021). To effectively utilize the chokeberry pomace as an ingredient in functional foods, it is essential to use high-quality pomace. Therefore, the pomace must be prepared properly to ensure it becomes a quality, easy-to-store, and easy-to-handle ingredient, thereby preventing degradation of its quality. This preparation involves dehydrating the pomace, which is drying of the pomace. Drying of the pomace reduces the water activity in the pomace, consequently inhibiting enzymatic and microbial activities, leading to less spoilage of the pomace and extended shelf-life (Alp and Bulantekin, 2021; Wu et al., 2025). Despite the preservation benefits provided by drying technologies, the quality of the pomace after drying remains a concern. The colour, aroma, and polyphenols in the pomace can change (Nakra et al., 2025). However, the change in the quality of dried products depends on the type of drying technique used. Each drying method has its advantages and disadvantages.

Several drying technologies are employed in the food industry to dry fruits and vegetables. These technologies include atmospheric drying, freeze drying, and microwave drying (Calín-Sánchez et al., 2020; Vichakshana et al., 2023). Freeze drying, also known as lyophilization, dehydrates food by employing pressure instead of heat, sublimating solid water directly into vapour, without going through the liquid state. This is followed by adsorption of water from the dry area (Nowak and Jakubczyk, 2020), consequently retaining bioactive compounds, and

heat-sensitive nutrients (Kaur and Ghosh, 2024; Petikirige et al., 2022). However, it is expensive, has a long drying duration, and is more energy-intensive compared to other drying techniques (Guo et al., 2024; Rybak et al., 2021).

Microwave drying dries materials by rapidly evaporating moisture from within the material to its surface, using heat generated by high-frequency electromagnetic energy (González-Cavieres et al., 2021; Li et al., 2011). It involves advanced techniques such as the microwave vacuum drying, which employs microwave energy and a microwave environment to dehydrate the material at low temperature (González-Cavieres et al., 2021). This technique has been cited as time and energy-efficient compared to the traditional methods (An et al., 2024). The atmospheric drying method involves drying the material at atmospheric pressure and includes cabinet drying, rotary drying, tunnel drying, solar drying, air drying, and many others (Chibuzo et al., 2021; Monicka et al., 2024). These drying technologies have high production capacity; however, the drying duration can be too long, and the quality of the material can easily be compromised (Adeyeye et al., 2022).

The selection of an optimal drying method can be based on the type of material to be dried and the characteristics to be preserved. As far as the drying technologies have been extensively reviewed and published, there is little information regarding the drying technologies suitable for drying fruit pomace, specifically chokeberry pomace. There is also little information regarding the utilization of Aronia pomace as a tea infusion ingredient. Therefore, this study aimed to utilize Aronia pomace as a tea infusion ingredient and evaluate the effects of some common drying technologies: microwave vacuum drying (MVD), freeze-drying (FD), and atmospheric drying (AD) on the polyphenolic content, antioxidant capacity, and colour of Aronia pomace tea infusion.

MATERIALS AND METHODS

Sample preparation

Chokeberries (Galicjanka variety) provided from Harkány farm in Hungary (45° 50' 51" N, 18° 14' 12" E) in 2023 were used to prepare the pomace by pressing out the juice with laboratory-scale press equipment, under laboratory conditions. The produced pomace, a residual left after juice extraction, was collected and stored at −20 °C until drying.

Reagents and standards

Methanol, Folin-Ciocalteu phenol reagents (Sigma Aldrich, St. Louis, MO, USA), and anhydrous sodium carbonate (Na_2CO_3) (Riel-de Haen, Oberderdingen, Germany) were used for the analysis of TPC. Potassium chloride (pH 1.0) buffer, sodium acetate (pH 4.5) buffer, and hydrochloric acid (Riel-de Oberderdingen, Haen, Germany) were used for total anthocyanin analysis. Sodium acetate buffer (pH 3.6; 300 mM), iron (III) chloride hexahydrate, and 2,4,6-Tris(2-pyridyl)-s-triazine (TPTZ) were used for FRAP analysis. 125 mM potassium persulfate ($\text{K}_2\text{S}_2\text{O}_8$) and phosphate buffer (pH 7.4) were used for TEAC analysis, and 2,2-diphenyl-1-picrylhydrazyl was used for DPPH. Trolox for DPPH and TEAC method, ascorbic acid, and gallic acid were purchased from Merck KGaA (Darmstadt, Germany).

Drying methods

Chokeberry pomace, divided into different portions, was then exposed to microwave vacuum drying, freeze drying, and atmospheric drying. Microwave vacuum drying (Fructmas M04, Fructmas Ltd., Vecsés, Hungary) was carried out in two separate treatments. The first treatment (MVD1-1) exposed samples to 1 min of microwave radiation and a 1-min passive period (without microwave radiation). In this case, the drying duration was 60 min and reduced the moisture content of the pomace to 5.1%. The second treatment (MVD1-2) exposed the samples to 1 microwave radiation, alternating with 2 min passive time, making up a 30-min treatment and 60 min passive time, and a drying duration in this case was 90 min. Moisture content was reduced to 3.9%. The passive period is needed to avoid the hot spot creation in the sample to allow time for heat equalization. The pomace was placed on a rotating Teflon tray in the vacuum chamber, with the parameters: 2 pieces of 2,450 MHz magnetrons, 850 W each, 5 kPa vacuum value.

Atmospheric drying was carried out by drying samples in a drying cabinet (LabMIn LT-322A1, Labor Műszeripari Művek, Esztergom, Hungary) at 70 °C for 6.5 h. The moisture content of the pomace was reduced to 5.6%. Freeze drying was done at 100 mbar with a Leybold Heraeus Lvovac GT2 freezer dryer (Labexchanger, Burladingen, Germany). The chokeberry pomace sample was completely lyophilized, with the water activity and moisture content reduced to less than 0.221 and 4%, respectively.

Tea infusion preparation

The tea infusion was prepared by infusing 3.5 g of sample (refer to [Table 1](#)) into 200 mL of boiled water for 5 min, then filtered through 125 mm quantitative filter paper, with a particle retention of 12–15 µm, purchased from VWR (Darmstadt, Germany). To enhance the flavour of the Aronia tea infusion, a forest fruit flavouring blend tea (BGB Interweb Kft., Budapest, Hungary) consisting of apple, 30% hibiscus flower, rosehip, buckthorn, elderberry, and 0.5% blueberry flavour was mixed with the samples (except the control) in different concentrations, as given in [Table 1](#). Different concentrations were picked to determine their influence on the total polyphenols, total anthocyanins, antioxidant activities, and colour.

The analysis of the pH level

The anthocyanins, which are the component responsible for the colour pigment, are not stable and can be affected by light, pH, temperature, etc. However, it can be stable at low pH values ([Enaru et al., 2021](#)). Therefore, the pH of tea infusion samples was measured with a TESTO 206 digital pH meter (Testo SE & Co. KGaA, Titisee, Germany).

Tea colour measurement

To determine the colour change between samples, the colour intensity of each sample was analysed with a digital colourimeter Konica Minolta, Chroma-400 (Konica Minolta Business Solutions Ltd., Mississauga, ON, Canada), based on the lightness/darkness ($+L^*/-L^*$), redness/greenness ($+a^*/-a^*$), and yellowness/blueness ($+b^*/-b^*$) of the infusion. The colour change was then calculated between the 100% Aronia pomace from different drying technologies and the mixed samples. The colour change was calculated according to [Lukács \(1982\)](#) as follows:

Table 1. The composition of the Aronia tea infusion

Samples	Dried chokeberry pomace (g)	Dried forest fruit flavouring tea (g)	Sample total (g)
FD (100%)	3.50	0.00	3.50
FD50_50%	1.75	1.75	3.50
FD60_40%	2.10	1.40	3.50
MV1-1 (100 %)	3.50	0.00	3.50
MVD1-1_50_50%	1.75	1.75	3.50
MVD1-1_60_40%	2.10	1.40	3.50
MVD1-2 (100%)	3.50	0.00	3.50
MV1-2_50_50%	1.75	1.75	3.50
MVD1-2_60_40%	2.10	1.40	3.50
AD (100%)	3.50	0.00	3.50
AD_50_50%	1.75	1.75	3.50
AD_60_40%	2.10	1.40	3.50
Tea Control	0.00	3.50	3.50

FD = Freeze dried, MVD1-1 = Microwave vacuum drying (1 min of microwave treatment, 1 min passive time), MVD1-2 = Microwave vacuum drying (1 min microwave treatment, 2 min passive time), AD = Atmospheric Drying, Tea control = forest fruit tea blend.
Own creation.

$$\Delta E * = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}}$$
 (1)

The description of the colour change (ΔE^*) was classified as 0–0.5 = not noticeable, 0.5–1.5 = slightly noticeable, 1.5–3.0 = noticeable, 3.0–6.0 = clearly visible, and 6.0–12.0 = great visibility.

The bioactive content analysis

The bioactive content was analysed by measuring the total phenolic content (TPC) and anti-oxidant activity. The TPC was analysed by measuring the absorbance of the sample against the blank sample at 760 nm, using the spectrophotometer Hitachi U-2900 (Hitachi High Technologies Europe GmbH, Krefeld, Germany). This was carried out according to the [Singleton and Rossi \(1965\)](#) method. The results are reported in mg gallic acid equivalents per 200 mL (mg GAE/200 mL).

Total anthocyanin (TA) in the tea infusion samples was measured according to the pH differential method given in the Association of Official Agricultural Chemists (AOAC) Method 2005:07, given by [Lee et al. \(2005\)](#). The absorbance was measured with a spectrophotometer at 520 and 700 nm using pH 1 and pH 4.5 buffer solutions. The results are reported as cyanidin-3-glucoside equivalents per 200 mL of the tea infusion (mg CGE/200 mL).

Antioxidant activity was measured by using the Ferric Reducing Ability of Plasma (FRAP), 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay, and Trolox equivalent antioxidant capacity (TEAC). The analysis of FRAP was carried out following the [Benzie and Strain \(1996\)](#) method. In short, a 50 µL sample was added to the FRAP solution (Na-acetate buffer (pH 3.6), iron (III)

chloride hexahydrate, and Tripyridyl-s-Triazin (TPTZ). The solution was allowed to stand for 5 min for the reaction to take place, before measuring the absorbance against the blank reagent at 593 nm. The results are reported as mg ascorbic acid equivalent per 200 mL (mg AAE/200 mL).

Antioxidant activity based on the DPPH was analysed by following the binding of the stable DPPH radicals method as given by Blois (1958). This was carried out by preparing a solution containing the sample, distilled water, and the DPPH solution, which was then left in the dark to react for 30 min. This was followed by measuring the absorbance against distilled water at 517 nm. The results are presented as mg Trolox equivalent per 200 mL (mg TE/200 mL).

The TEAC was analysed according to Müller et al. (2010) method with some modifications. In brief, an ABTS radical solution containing 125 µL of 7 mM ABTS solution and 39.2 µL of 125 mM potassium persulfate ($K_2S_2O_8$) was left in the dark overnight. It was then used to prepare the stock solution by diluting it with phosphate buffer (pH 7.4) to an absorbance of 700 (± 2). A 1950 µL of the diluted working stock solution was then mixed with 40 µL sample (10 µL infusion sample + 30 µL phosphate buffer). This solution was shaken for 5 min, then its absorbance was measured against the blank (pH 7.4 phosphate buffer). Trolox standard solution (1 mM) was used to generate the standard curve. The results are given as mg Trolox Equivalent per 200 mL (mg TE/200 mL).

STATISTICAL ANALYSIS

The statistical analysis of TPC, TA, FRAP, DPPH, TEAC, and colour change between samples was done with the IBM SPSS Statistics software, version 29 (IBM Corp., New York, NY 10022, USA, 2020). The mean variances between infusion samples were tested with the One-way analysis of variance (ANOVA) using post-hoc tests (Tukey's and Games-Howell). The normality of error was proven by Kolmogorov-Smirnov ($P > 0.05$), as well as by Skewness and Kurtosis (Absolute value of Skewness = 2 and Kurtosis = 4). Levene's test was used to test the homogeneity of variances between the mean values of infusion samples. The homogeneity was confirmed not violated where the P -value > 0.05 . The severity of homogeneity violation, where $P < 0.05$, was measured with the maximum/minimum variance test. The significant differences between the mean values of infusion samples were determined at the interval level of $P < 0.05$.

RESULTS

The pH and colour change between the infusion samples

The pH values of the infusion samples are indicated in Table 2. Based on the results, all samples showed an acidic level, ranging between pH 3.35 and pH 4.70. The freeze-dried (FD) control had the highest pH value (4.70), and the atmospheric dried (AD) sample with 60% Aronia pomace and 40% flavouring tea had the lowest pH value of 3.35.

The colour was evaluated based on the visibility of colour change between the 100% samples of each drying technology and their mixed samples, to determine the change in colour intensity of the infusion when Aronia pomace samples are mixed with other tea ingredients. Based on the results in Table 2, the visibility of colour ranged from slightly noticeable to great visibility.

Table 2. The pH and colour change of the infusion samples

	PH	L*	a*	b*	ΔE*	Evaluation
Tea control	3.40	26.48 ^e	18.05 ^d	10.51 ^d		
MVD1-1 (100%)	3.60	20.03 ^a	4.48 ^a	2.67 ^a		
MVD1-1_50_50	3.60	21.66 ^d	11.89 ^c	4.57 ^c	4.31	Clearly visible
MVD1-1_60_40	3.50	21.71 ^d	11.68 ^c	4.19 ^{bc}	7.55	Great visibility
MVD1-2 (100%)	3.60	20.53 ^{ab}	6.05 ^a	2.58 ^a		
MVD1-2_50_50	3.60	21.42 ^d	11.01 ^c	4.31 ^{bc}	5.33	Clearly visible
MVD1-2_60_40	3.50	22.50 ^d	12.34 ^c	4.69 ^c	6.91	Great visibility
FD (100%)	4.70	21.02 ^{bc}	9.02 ^b	3.92 ^{bc}		
FD50_50	3.60	21.67 ^d	9.25 ^b	4.38 ^{bc}	0.82	Slightly noticeable
FD60_40	3.50	22.62 ^{bc}	10.23 ^{bc}	4.27 ^{bc}	2.03	Noticeable
AD (100%)	3.60	20.39 ^a	9.13 ^b	3.35 ^{ab}		
AD_50_50	3.49	21.78 ^d	11.76 ^c	4.72 ^c	3.28	Clearly visible
AD_60_40	3.40	21.49 ^c	10.91 ^{bc}	4.25 ^{bc}	2.28	Noticeable

FD = Freeze dried, MVD1-1 = Microwave vacuum drying (1 min of microwave treatment, 1 min passive time), MVD1-2 = Microwave vacuum drying (1 min microwave treatment, 2 min passive time), AD = Atmospheric Drying, Tea control = Forest fruit tea blend. Different superscript letters (a, b, c) indicate the significant differences in colours between samples.
Own creation.

The forest tea blend mixed showed a significantly lighter colour (L*) compared to all 100% Aronia samples, as clearly seen in Fig. 1. This resulted in the reduction of the colour intensity of the Aronia pomace infusion samples mixed with the forest tea blend (Fig. 2). The 100% Aronia pomace infusion samples were darker compared to all other samples, with 100% MVD1-1 and MVD1-2 drying giving the redder colour than 100% FD and AD (Figs 1 and 2).

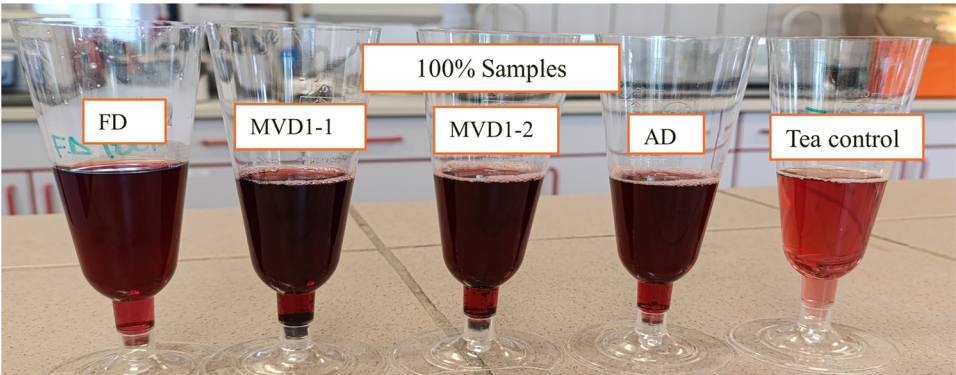


Fig. 1. The infusions from the 100% samples of Aronia pomace dried with different technologies, and a forest tea blend used in this study. FD = Freeze dried Aronia pomace, MVD1-1 = Microwave vacuum drying (1 min of microwave treatment, 1 min passive time), MVD1-2 = Microwave vacuum drying (1 min microwave treatment, 2 min passive time), AD = Atmospheric Drying, Tea control = forest fruit flavouring tea. Own source

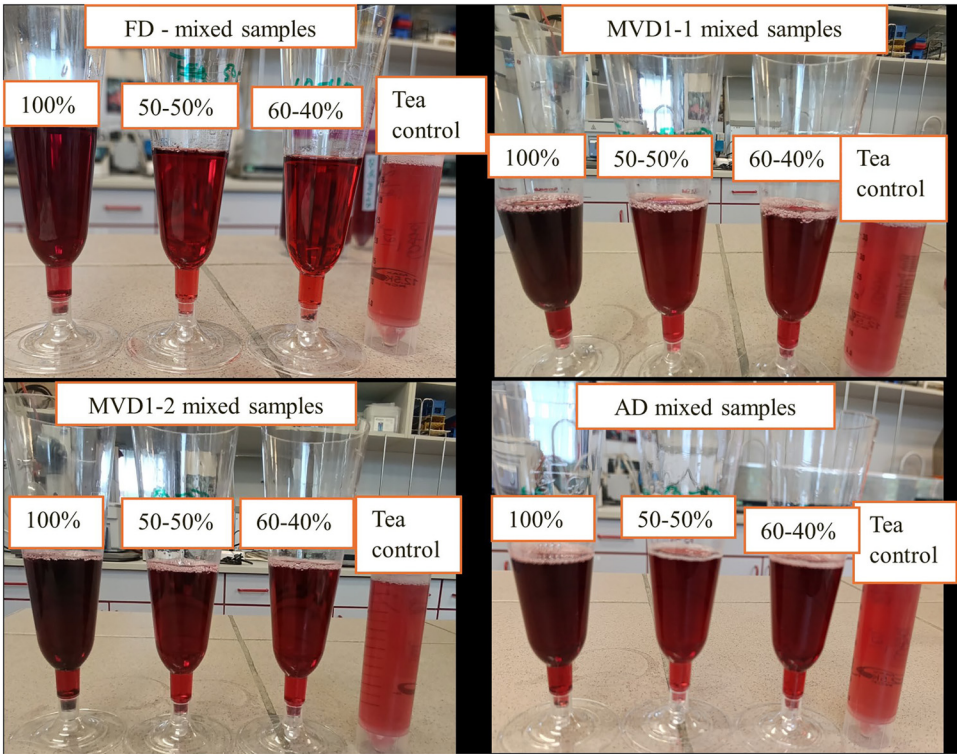


Fig. 2. The infusions from the 100% samples of Aronia pomace mixed with the forest tea blend in different concentrations. FD = Freeze dried Aronia pomace, MVD1-1 = Microwave vacuum drying (1 min of microwave treatment, 1 min passive time), MVD1-2 = Microwave vacuum drying (1 min microwave treatment, 2 min passive time), AD = Atmospheric Drying, Tea control = forest fruit flavouring tea. Own source

Total phenolic content

The TPC results indicated in Fig. 3 show high TPC levels in the control samples, significantly higher than those incorporated with flavouring tea. The flavouring tea indicated significantly lower TPC (32.18 ± 2.97 mg GAE/200 mL) than Aronia infusion control samples, ranging from 89.37 ± 7.08 and 98.98 ± 6.05 mg GAE/200 mL. The FD indicated the highest TPC (98.98 ± 6.05 mg GAE/200 mL); however, it was not significantly different from that of MVD1-1, MVD1-2, and the AD. The results also indicate that the lower the concentration of the Aronia pomace percentage in the tea, the lower the TPC.

Total anthocyanins

The total anthocyanin results are given in Fig. 4. The results indicated MVD1-1 control with significantly ($P < 0.05$) higher anthocyanins (47.09 ± 0.51 TA mg/200 mL) compared to all FD, AD, and the flavouring tea samples. The flavouring tea indicated the lowest total anthocyanins

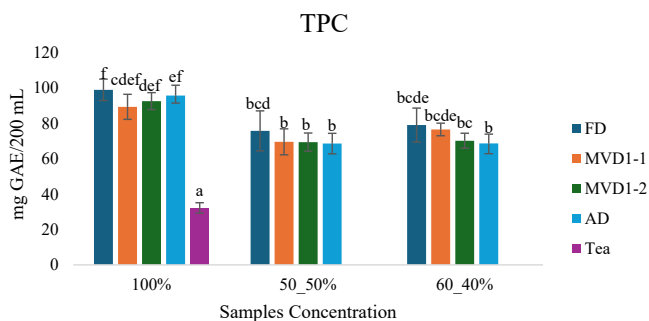


Fig. 3. Total phenolic content (TPC) of different tea infusion samples. FD = Freeze dried, MVD1-1 = Microwave vacuum drying (1 min of microwave treatment, 1 min passive time), MVD1-2 = Microwave vacuum drying (1 min microwave treatment, 2 min passive time), AD = Atmospheric Drying, Tea control = forest fruit tea blend. Different superscript letters (a, b, c) indicate the significant differences between samples. Own creation

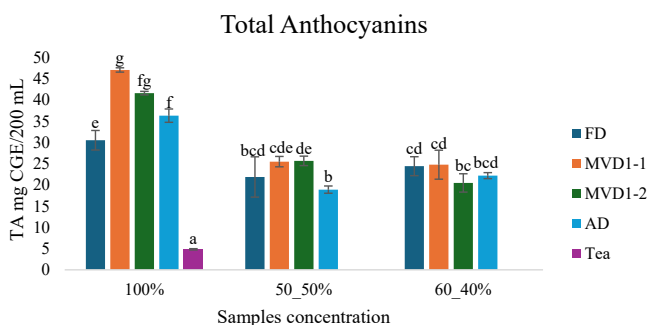


Fig. 4. Total anthocyanins between different infusion samples. FD = Freeze dried, MVD1-1 = Microwave vacuum drying (1 min of microwave treatment, 1 min passive time), MVD1-2 = Microwave vacuum drying (1 min microwave treatment, 2 min passive time), AD = Atmospheric Drying, Tea control = forest fruit flavouring tea. Different superscript letters (a, b, c) indicate the significant differences between samples. Own creation

(4.83 ± 0.16 TA mg/200 mL) significantly ($P < 0.05$) lower than all other samples. When the Aronia pomace was mixed with 50 and 40% flavouring tea, the total anthocyanins dropped to nearly 50%.

The antioxidant capacity of the Aronia pomace tea infusion

The antioxidant capacity results are indicated in Fig. 5 (A, B, and C). Based on FRAP results (Fig. 5A), the antioxidant capacity between the control samples was the highest in the AD (110.37 ± 9.92 mg/200 mL), however, not significantly different from the MVD1-1 (106.92 ± 11.11 mg/200 mL) and MVD1-2 (99.66 ± 5.24 mg/200 mL). The FD control showed significantly lower antioxidant capacity compared to all other Aronia tea infusion control

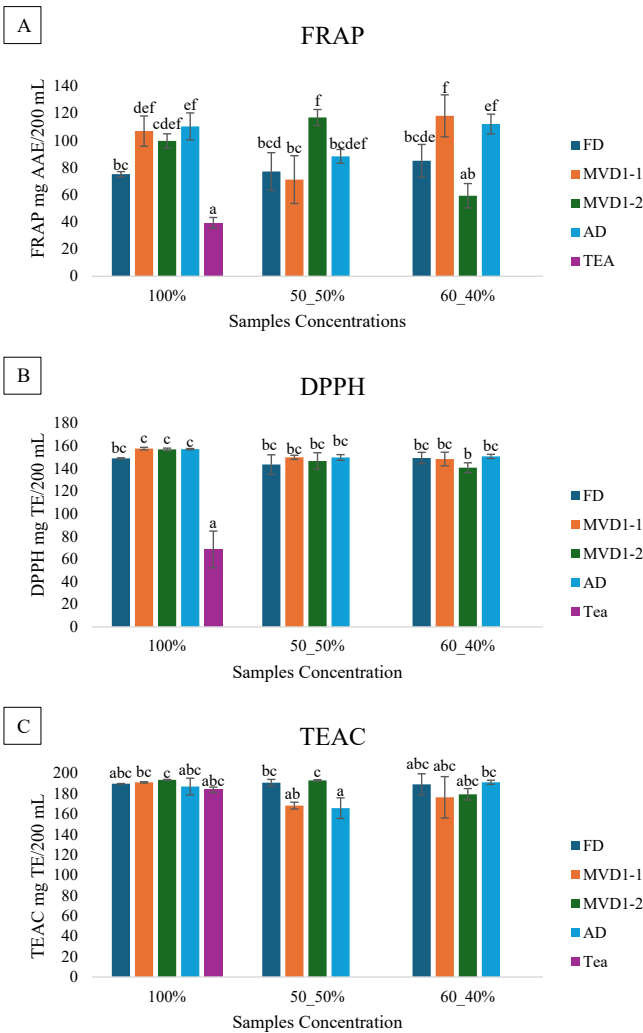


Fig. 5. Antioxidant activities based on FRAP (A), DPPH (B), and TEAC (C). between different infusion samples. FD = Freeze dried, MVD1-1 = Microwave vacuum drying (1 min of microwave treatment, 1 min passive time), MVD1-2 = Microwave vacuum drying (1 min microwave treatment, 2 min passive time), AD = Atmospheric Drying, Tea control = forest fruit flavouring tea. Different superscript letters (a, b, c) indicate the significant differences between samples. Own creation

samples. The flavouring tea indicated significantly lower antioxidant capacity (39.32 ± 3.98 mg/200 mL) than all other samples.

The antioxidant capacity results based on DPPH shown in Fig. 5B indicate no significant difference ($P > 0.05$) between the Aronia control infusion results, which ranged from 157.53 ± 1.13 and 148.91 ± 0.50 mg/200 mL. However, MVD1-1, MVD1-2, and AD control had the highest compared to FD. The flavouring tea indicated the lowest like in all other tests; however,

with DPPH, it did not reduce the antioxidant capacity when it was added to the Aronia pomace samples.

The antioxidant capacity in the Aronia pomace tea infusion incorporated with the flavouring tea indicates no significant difference to the antioxidant capacity from the 100% Aronia pomace tea infusion.

The TEAC results (Fig. 5C) indicated no significant difference ($P > 0.05$) between the control samples and the Aronia tea infusion samples containing the flavouring tea. The MVD1-2 control samples indicated the highest antioxidant capacity (193.51 ± 0.5 mg/200 mL). Unlike other results, the flavouring tea control with TEAC has indicated high antioxidant activity (183.81 ± 2.56 mg/200 mL), significantly lower than the MVD1-2, which had the highest of all.

DISCUSSION

This study evaluated the level of polyphenols in the tea infusion samples prepared from Aronia pomace dried with different technologies, intending to determine the effects of the drying technologies on the level of polyphenols. Due to the abundance of polyphenols in the Aronia pomace, there is a great possibility to utilize the pomace as a functional tea ingredient (Gao et al., 2024). However, the colour and the flavour are some of the important quality attributes to be considered. Aronia fruits in general have a flavour, which may not attract consumers that much (Kaloudi et al., 2022). Thus, in this study, the forest fruit tea blend was incorporated in the Aronia pomace tea infusion samples at different concentrations to enhance the flavour of the Aronia pomace tea infusion. The 100% Aronia tea infusion samples in this study served as indicators of the effects of drying technologies on polyphenols.

Anthocyanins are the components responsible for the pigmentation in the fruits, and it has been reported to be abundant in Aronia (Gerasimov et al., 2023). However, it is also known that they are not stable but can be maintained at low pH (Enaru et al., 2021). In this study, the pH of all samples was lower than pH 5, with 92% ranging between pH 3.30 and pH 3.60; only freeze-dried indicated a low acidity, pH 4.70. The mechanism of freeze-drying involves freezing the water in the food material before lyophilization (Bhatta et al., 2020). This prevents the biochemical, chemical, and microbial processes (Vagiri and Jensen, 2017). Thereby, retaining the organoleptic properties, the quality, and the biological properties of the dried product (Bhatta et al., 2020). MVD and AD use high temperatures compared to the freeze-drying method, allowing the biochemical and chemical reactions, and the loss of organic acids to take place (Li et al., 2024). Hence lowering the acidity in the dried product. This means that, freeze-drying can maintain the original pH level of the product. These make it easier to use the Aronia pomace without adding an acid needed to maintain the anthocyanins, consequently, maintaining the colour in the samples throughout the analysis. Additionally, it serves as indication that the dried Aronia pomace can be utilized for the intended purpose such as the tea ingredient with a stable colour throughout, although other factors other than the pH level must be considered.

Based on the results of this study, 100% Aronia tea infusion samples were redder compared to samples mixed with the forest fruit tea blend. This is because the forest fruit tea blend consists of some ingredients that are not red, like apple, hence, the forest tea samples were significantly lighter ($P < 0.05$) than all Aronia samples. Therefore, when mixed with Aronia pomace, the dark red colour reduces to light. This correlates with the pH levels; the forest fruit tea blend pH was

3.40. At the pH level around 3.00, the red colour is expected to be lighter than dark or purplish. Whereas at pH 4, the colour is expected to be darker/purplish than red or light (Ghareaghajlou et al., 2021), which is the pH level and the colour indicated by the freeze-dried tea infusion samples in this study. The colour of the 100% Aronia and the mixed tea infusions samples differed. Hence, the colour changes were evaluated between the 100% Aronia samples and the mixed samples from the same drying technology. This was done to determine the level of noticeability in the colour change between samples when other tea ingredients are added to the Aronia pomace tea ingredient.

The anthocyanin in this study was found to be highest in the MVD1-1 tea infusion, which was dried using microwave vacuum drying for 1 min of microwave treatment and 1 min of passive time. Whereas freeze-dried (FD) Aronia pomace tea infusion samples indicated the highest TPC retention. The highest antioxidant capacity was given by MVD1-2, which is microwave vacuum drying at 1 min microwave treatment, 2 min passive time. The findings of this study are not far from the literature findings; however, in most studies, Freeze-drying has been reported with high polyphenols and antioxidant capacity retention. A study conducted by Akcicek et al. (2023) used “hot air drying (HAD), vacuum drying (VD), ultrasound-assisted vacuum drying (UAVD), and freeze drying (FD)” to dry blueberries. Their results indicated higher bioactive retention on blueberries dried with FD than all three other methods. Similar drying technologies: HAD, FD, VD, and UAVD, were used by Goztepe et al. (2022) to rosehip, and based on their findings, freeze-dried samples presented the highest bioactive compounds, followed by vacuum-dried samples, and HAD presented the lowest. Nemzer et al. (2018) also dried different berries with HAD, Refractance Window drying (RWD), and FD, and found freeze-dried berries containing higher TA and TPC than those dried with the other two methods. Similar results have also been reported in a study conducted by Samoticha et al. (2016), where the highest TPC, TA, and antioxidant activities were obtained in freeze-dried samples. On the contrary, Zielinska et al. (2018) reported higher retention of polyphenols and antioxidant activity from cranberries with microwave vacuum drying compared to freeze-drying cranberries. Zielinska et al. (2018) also reported microwave drying at low power, suitable for producing high-quality cranberries.

Based on the literature, high processing temperatures can degrade heat-labile polyphenols, including anthocyanins (Bustos et al., 2018; Enaru et al., 2021; Ghafoor et al., 2019). This explains why, in most studies, freeze-drying and vacuum drying exhibited higher polyphenols and antioxidant activity than the hot air-drying method. In this study, the highest temperature used was 70 °C in the atmospheric drying. However, the TPC and antioxidant capacities results between the FD samples, and the AD drying are not significantly different, and the total anthocyanins were recorded significantly higher in AD than in FD. The AD has also retained higher total phenolic content compared to MV1-1 and MV1-2. This means that atmospheric drying can also be used to retain a product containing high bioactive compounds and antioxidant activity. During heating, polyphenols go through different mechanisms, including polymerization, isomerization, oxidative polymerization, and hydrolysis, influencing the amount of polyphenols to be recovered from the product (Zhang and Liu, 2022). In a study done by Martini et al. (2021) frying has been reported to have increased the main polyphenols. Polyphenols are found in the matrix and bound to other components, and they can be released through hydrolysis methods, which can be assisted by heating, especially during extraction

methods (Li et al., 2020). However, regarding the drying of fruits and vegetables, there is limited information about the positive impacts of applied heat.

CONCLUSION

This study assessed the effects of drying technologies on the level of total phenolic content and the antioxidant activities of Aronia pomace tea infusion. It also tried to improve the quality of the Aronia pomace infusion with the forest fruit tea blend. The tea infusion colour differed between samples, and the pH of the tea infusion ranged between pH 3.40 and pH 4.70 without the addition of an acid. Based on the analysis of the results, freeze-dried Aronia pomace tea infusion has given the highest polyphenols, however, the highest antioxidant activities were obtained from microwave-dried and atmospheric-dried samples. The enhancement of Aronia pomace tea infusion with the flavouring tea has lowered the level of total phenolic content and anthocyanins in the sample, this was simply because the flavouring tea had the lowest total phenolic content and anthocyanins compared to the Aronia pomace samples. The findings of this study offer valuable insights into optimal drying methods for preserving the polyphenols and quality of Aronia pomace, which can be utilized as a tea ingredient or for other food applications. The findings highlight freeze-drying as effective for maintaining total phenolic content (TPC), and microwave vacuum drying as advantageous for retaining high levels of anthocyanins and antioxidant activity. These insights may assist future researchers in developing efficient processing techniques and enhancing the valorisation of Aronia pomace within the food or pharmaceutical industries. However, the drying parameters must be carefully selected.

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