Journal of Food Composition and Analysis 132 (2024) 106316

Contents lists available at ScienceDirect

Journal of Food Composition and Analysis

journal homepage: www.elsevier.com/locate/jfca

Microwave drying of black rosehip (*Rosa pimpinellifolia* L.) fruit: optimization for enhanced anthocyanin content and analysis of physicochemical properties and bioaccessibility

Hojjat Pashazadeh [a,*,1], Ali Ali Redha [b,c,**,2], Joel B. Johnson [c,3], Ilkay Koca [a,4], Mustafa Fatih Ertugay [d,5]

[a] *Department of Food Engineering, Faculty of Engineering, Ondokuz Mayis University, Samsun 55139, Turkey*
[b] *The Department of Public Health and Sport Sciences, University of Exeter Medical School, Faculty of Health and Life Sciences, University of Exeter, Exeter EX1 2 LU, United Kingdom*
[c] *Centre for Nutrition and Food Sciences, Queensland Alliance for Agriculture and Food Innovation (QAAFI), The University of Queensland, Brisbane, QLD 4072, Australia*
[d] *Department of Food Engineering, Faculty of Engineering, Erzincan Binali Yıldırım University, Yalnızbağ Campus, Erzincan, Turkey*

ARTICLE INFO

Keywords:
Anthocyanins
Black rosehip
Microwave drying
Bioaccessibility
Optimization
Microstructure

ABSTRACT

Black rosehip (*Rosa pimpinellifolia* L.) fruit is a rich source of anthocyanins and has been promoted for several bioactive properties. Drying this fruit can increase its shelf life and enhance its applications in functional food products. This study aimed to optimize the microwave drying process of black rosehip fruit. The process was optimized based on the effect of microwave power (300, 500, and 650 W) and the amount of sample per batch (50, 75, and 100 g) on the amount of total anthocyanins and individual anthocyanins (cyanin chloride, cyanidin-3-glucoside, cyanidin-3-rutinoside, pelargonidin-3-glucoside, and cyanidin chloride). The effect of different drying conditions on color, microstructure, and texture was also investigated. The bioaccessibility of anthocyanins from the dried food sample at optimum conditions was assessed by *in vitro* gastrointestinal digestion. The results showed that microwave power and the amount of sample had a significant effect on the anthocyanin content of black rosehip fruit. The optimum conditions were determined to be 350 W power and 50 g sample mass. Lower microwave power and less sample mass produced dried fruits which were slightly darker, less red and less yellow. The hardness of dried fruit was also significantly affected by the microwave drying conditions. The dried black rosehip at optimum conditions showed a high bioaccessibility of cyanidin-3-glucoside (82.6 ±4.1%) which is known for a wide range of bioactive properties.

1. Introduction

Anthocyanins are polyphenolic compounds with a wide range of bioactive properties including antioxidant, anti-inflammatory, anti-diabetic, and anti-cancer activities (Naseri et al., 2018). Fruit anthocyanins are continuously investigated for their applications in many research areas including dietetics (e.g., reduction and prevention of obesity) (Escalante-Aburto et al., 2023) and fitness (e.g., post-exercise recovery) (Prieto Martinez et al., 2024; Zare et al., 2023). One of the rich sources of anthocyanins is the black rosehip (*Rosa pimpinellifolia* L.) fruit, which is a pseudo-fruit of the rose plant, and contains about 500 mg/100 g dry weight of total anthocyanins (Pashazadeh et al.,

* Corresponding author.
** Correspondence to: The Department of Public Health and Sport Sciences, University of Exeter Medical School, Faculty of Health and Life Sciences, University of Exete, Exeter EX1 2 LU, United Kingdom.
E-mail addresses: hojjat_pashazadeh@yahoo.com (H. Pashazadeh), aa1249@exeter.ac.uk (A. Ali Redha).
[1] 0000–0001-8932–8165
[2] 0000–0002-9665–9074
[3] 0000–0002-9172–8587
[4] 0000–0001-6089–8586
[5] 0000–0002-0795–9631

https://doi.org/10.1016/j.jfca.2024.106316
Received 5 March 2024; Received in revised form 20 April 2024; Accepted 6 May 2024
Available online 17 May 2024

2021). Black rosehip comprises several anthocyanins including cyanidin-3-glucoside, cyanidin-3-rutinoside, pelargonidin-3-glucoside, and cyanidin chloride (Pashazadeh et al., 2024). *In vitro* and *in vivo* findings have reported remarkable antioxidant, anti-inflammatory, and anti-obesogenic activities in rosehip fruit (Fan et al., 2014).

Although fruit anthocyanins have a wide range of pharmacological and nutritional benefits, they are associated with low bioavailability due to their instability (Herrera-Balandrano et al., 2021). Fruit processing is one of the main factors that can influence the amount of anthocyanins present in fruit and the physicochemical properties of the fruit, thus impacting its bioavailability (Alvarez-Suarez et al., 2021). A common industrial process which has a major impact on fruit properties is drying. Drying is utilized to reduce the water content of fruit and increase their shelf-life. In addition to inactivating numerous deteriorative reactions facilitated by moisture, drying reduces the water content to a level that inhibits the growth and reproduction of microorganisms (Deng et al., 2019). Thus, drying can potentially reduce food waste and increase the range of applications for the fruits.

Different drying methods can have varying effects on the physicochemical and nutritional properties of the dried products. For example, hot-air cabinet drying is considered one of the most common and economical drying methods in the food industry due to its simplicity of construction, acceptable drying conditions for products which need long, low-intensity drying, and its low purchase and operating costs (Chojnacka et al., 2021). However, it is associated with several disadvantages such as variability in the drying process across distinct sections of the dryer, considerable heat loss during loading and unloading processes, challenges with process control, and long drying periods (Chojnacka et al., 2021). On the other hand, techniques such as microwave drying could be relatively more sustainable. Microwave drying is associated with fast volumetric heating, higher drying rate, shorter drying time, low energy consumption and reduced costs (Orsat et al., 2006). Nevertheless, microwave drying efficiency is affected by sample size and shape, and it has varying effects on the texture and sensory characteristics of the dried product. Therefore, it is crucial to optimize the microwave drying process to ensure the production of a high-quality final product.

This study aimed to investigate the use of microwave drying to dry fresh black rosehip fruits. The drying processes was optimized based on the effect of microwave power and amount of sample on the amount of total fruit anthocyanins as well as individual anthocyanins (cyanin chloride, cyanidin-3-glucoside, cyanidin-3-rutinoside, pelargonidin-3-glucoside, and cyanidin chloride). In addition, the effect of different microwave drying conditions on color, microstructure, and texture was investigated. Finally, the bioaccessibility of individual anthocyanins from the fruit sample dried under optimum conditions was assessed by *in vitro* digestion.

2. Materials and methods

2.1. Fruit sample

Fresh black rosehip fruits, harvested in the fall season of 2019 from Horasan, Erzurum, Turkey (40°02′23″N, 42°10′16″E), were utilized for the study. After transporting the samples to the lab, the fruits were washed under running water and stored at a temperature of 4–5 °C for 2 days (until the commencement of the experiment).

2.2. Microwave drying and optimization process

Before drying, the fruit samples were taken out of the fridge and allowed to stand at room temperature for 2 h. Black rosehip fruits were dried using a laboratory microwave oven (MD 674 20, Arçelik, Turkey) following a previous method (Yildiz and İzli, 2018). Varying amounts of samples (50, 75, and 100 g) were dried at different power levels (300, 500, and 650 W). Microwave power was administered in a pulsed mode, alternating between 30 s of activation and 30 s of inactivity. Drying experiments were conducted using a rotating glass plate situated at the base of the microwave oven measuring 210 × 450 × 420 mm in dimensions, with the plate itself having a diameter of 400 mm. The moisture losses of the samples were monitored at 1-min intervals during the drying process until reaching a moisture content of 0.10 (g water/g dry solid).

Table 1
– Actual and coded independent variables of the optimization experiment.

Coded values	Actual values	
	A	B
-1.00	350	50
0.00	500	75
1.00	650	100

A: Power (W), B: Mass (g)

For the response surface methodology (RSM), the central composite design was employed using Design-Expert software version 13.0 (Minneapolis, MN). The microwave power (A) and the amount of fruit sample in g (B) were considered as the independent variables while the dependent variables (Y) were total anthocyanins, cyanin chloride, cyanidin-3-glucoside (mg/g), cyanidin-3-rutinoside, pelargonidin-3-glucoside, and cyanidin chloride (mg/kg). The actual and coded independent variables are shown in Table 1. The RSM gave 11 experimental points, and the data were fitted according to the following quadratic polynomial model (Eq. 1):

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_{ii} + \sum_{i=1}^{k-1} \sum_{i+1}^{k} \beta_{ij} X_i X_j + \varepsilon \quad (1)$$

where Y is the response variable, β_0, β_i, β_{ii} and β_{ij} represent the regression coefficients of intercept, linear, quadric and interaction, respectively. X_i and X_j are the independent variables, k is a variable number, and ε is the random error term.

2.3. Quantification of anthocyanins

2.3.1. Total anthocyanins

The pH differential method was employed to determine the total (monomeric) anthocyanin (Lee et al., 2005). Extracts underwent dilution with buffers pH 1.0 (0.025 M KCl) and pH 4.5 (0.4 M CH_3COONa), and their absorbance was subsequently measured at 520 and 700 nm using a UV/VIS spectrophotometer (LAMBDA™ 365, Perkin Elmer, USA). Total anthocyanin content was then calculated and expressed as cyanidin-3-glucoside equivalents (CGE) per gram of dry weight (dw) in accordance with Eq. 2:

$$Total\ anthocyanins = \frac{A_t \times M_w \times D_f}{\varepsilon \times l} \quad (2)$$

where A_t = (absorbance at 520 nm – absorbance at 700 nm) pH 1.0 – (absorbance at 520 nm – absorbance at 700 nm) pH 4.5; M_w (molecular weight) = 449.2 g/mol for cyanidin-3-glucoside, D_f = dilution factor, l = pathlength (cm), and ϵ (molar extinction coefficient) = 26900 L/mol cm for cyanidin-3-glucoside.

2.3.2. Individual anthocyanins

The quantification of cyanin chloride, cyanidin-3-glucoside (mg/g), cyanidin-3-rutinoside, pelargonidin-3-glucoside, and cyanidin chloride (mg/kg) in all samples was carried out using a high-pressure liquid chromatography (HPLC) system (Agilent 1260; Agilent Technologies) coupled with a diode array detector (DAD), following a previously reported method (Pashazadeh et al., 2024). Extraction of samples was performed using HPLC grade 80% methanol containing 0.1% hydrochloric acid. Anthocyanins were separated using an Inertsil ODS-4 column (3 μm, 4.6 ×50 mm; GL Sciences), maintaining a flow rate of

Table 2
– Central composite experimental design with natural and coded microwave drying conditions and experimentally determined values of investigated responses.

Std	Run	Factor 1	Factor 2	Response 1	Response 2	Response 3	Response 4	Response 5	Response 6
		A: Power (W)	B: Mass (g)	Total anthocyanins (mg/g)	Cyanin chloride (mg/g)	Cyanidin-3-glucoside (mg/g)	Cyanidin-3-rutinoside (mg/kg)	Pelargonidin-3-glucoside (mg/kg)	Cyanidin chloride (mg/kg)
1	8	350	50	2.94	0.27	2.04	12.4	11.8	3.60
2	9	650	50	1.45	0.19	0.91	6.19	9.29	0.36
3	2	350	100	2.13	0.16	1.19	8.22	8.06	1.63
4	10	650	100	1.19	0.10	0.72	3.83	6.38	0.25
5	6	350	75	2.36	0.19	1.26	9.23	9.79	2.23
6	3	650	75	1.35	0.16	0.72	5.22	8.03	0.26
7	7	500	50	1.81	0.26	1.71	7.69	12.3	5.43
8	1	500	100	1.38	0.13	0.90	5.13	8.50	3.17
9	5	500	75	1.47	0.15	1.01	6.36	9.13	4.93
10	11	500	75	1.51	0.16	1.00	6.84	8.92	4.63
11	4	500	75	1.61	0.14	0.99	6.44	9.05	4.03

1 mL/min, and measurements were recorded at 520 nm. The mobile phases included (A) a mixture of 6% acetic acid and 94% of 2 mM sodium acetate (v/v) and (B) acetonitrile. The elution gradient, based on the concentration of solvent B, was as follows: 0–20 min, 14–23%; 20–40 min, 23–35%; 40–50 min, 40%; 50–60 min, 60%; 60–65 min, 95%; 65–80 min, 100%. The column temperature was maintained at 30 °C. Individual anthocyanins were identified by aligning their retention times with corresponding standards, and quantification was performed using a set of external standards prepared at various concentrations.

2.4. Analysis of color

The color of fresh and dried samples was measured using a colorimeter (MiniScan EZ 4500, HunterLab, USA). The L*, a*, and b* parameters were recorded for all samples. The change in lightness (ΔL) was also calculated based on the change in L* before and after the drying process.

2.5. Analysis of microstructure

The examination of the microstructure of fresh and dried black rosehip samples involved employing a scanning electron microscope (SEM) (JSM-7001 F, JEOL, Japan) (Pashazadeh et al., 2024). Each fruit was carefully prepared to ensure a uniform thickness of 1 mm, attached to the SEM stage, and then examined under consistent parameters, specifically in high vacuum mode at 0.1 kPa. Multiple images of each fruit were captured from at least three different positions within each sample, with three images taken at each specific location, all utilizing a magnification of × 200.

2.6. Analysis of texture

The assessment of black rosehip fruit texture was carried out through the utilization of Texture Profile Analysis (TPA), a commonly employed compression test, employing a texture analyzer (TA.XT.Plus, Stable Micro Systems, UK) (Pashazadeh et al., 2024). The samples experienced two successive compression events, mimicking the action of a jaw. Compression was conducted using TA-24 1/4 diameter acrylic cylinders, each with a height of 35 mm, in conjunction with a compression plate featuring a 50 kg load cell. This process generated a force-deformation curve through TPA, enabling the determination of characteristics such as hardness, springiness, stickiness, gumminess, chewiness, and elasticity.

2.7. Bioaccessibility assessment

The bioaccessibility of individual anthocyanins from microwave dried black rosehip fruit at optimum conditions (350 W power and 50 g sample mass) was determined through *in vitro* digestion following a previously published protocol (Salvia-Trujillo and McClements, 2016) with some modifications (Kaba et al., 2023). An amount of 0.2 g of each sample was dissolved in 5 mL of distilled water and then was mixed with 20 mL of simulated gastric fluid containing 1.5 mL of pepsin (3.2 g/L), and the pH was adjusted to 1.7 using HCl (1 M). The mixture underwent a 2 h incubation at 37°C with continuous shaking. After 2 h, the pH was raised to 7 with NaOH (1 M). To this, 4 mL of bile salt (5 g/L) and 1 mL $CaCl_2$ (0.75 M) were added, followed by 2.5 mL of lipase (4.8 g/L). The pH of the mixture was adjusted to 7 with NaOH (1 M) and incubated for an additional 2 h at 37 °C with continuous shaking. Following this incubation, an aliquot of each sample was collected and centrifuged at 4 °C for 15 minutes at 5000×g. The amount of individual anthocyanins present in the supernatant was quantified according to Section 2.3.2. The bioaccessibility was calculated using the following equation:

$$Bioaccessibility(\%) = \frac{amount\ of\ anthocyanin\ in\ digested\ sample}{amount\ of\ anthocyanin\ in\ undigested\ sample} \times 100 \quad (3)$$

2.8. Data analysis

Every experiment was conducted in triplicate. Statistical analysis was carried out using IBM SPSS Statistics V22.0 software (International Business Machines (IBM) Corporation, Armonk, NY, USA). Analysis of variance (ANOVA) and the comparison of means were assessed using Duncan's new test ($P < 0.05$).

3. Results and discussion

3.1. Optimization of drying process

The first part of this study was the optimization of the microwave drying parameters based on the yield of anthocyanins obtained from the dried product (Table 2). The two independent variables investigated (power and sample mass) both had a significant impact on the concentration of total anthocyanins and the concentration of individual anthocyanins present in the sample. However, the effect was not consistent for all of the individual anthocyanins (Table 2). For example, the concentrations of cyanidin chloride and cyanidin-3-rutinoside varied widely depending on the drying parameters (0.25–5.43 and 3.83–12.40 mg/kg, respectively). On the other hand, pelargonidin-3-glucoside and cyanin chloride (cyanidin-3,5-di-O-glucoside) appeared to be less affected, with concentrations ranging from 6.38 to 12.31 mg/kg and 0.10–0.27 mg/g, respectively.

To investigate the influence and interaction of the independent variables, a fitted second-order polynomial model was developed, with

Table 3
– Analysis of variance (ANOVA) of the fitted second-order polynomial model for total and individual anthocyanins.

	Total anthocyanins (mg/g)			Cyanin chloride (mg/g)			Cyanidin-3-glucoside (mg/g)			Cyanidin-3-rutinoside (mg/kg)			Pelargonidin-3-glucoside (mg/kg)			Cyanidin chloride (mg/kg)		
	SS	F- value	p-value	SS	F- value	p-value	SS	F- value	p-value	SS	F- value	p-value	SS	F- value	p-value	SS	F- value	p-value
Model	2.77	93.6	< 0.0001	0.026	28.82	0.0011	1.63	31.3	0.0009	53.2	50.2	0.0003	26.4	18.9	0.0029	36.6	34.0	0.0007
A	1.97	332	< 0.0001	0.006	32.22	0.0024	0.764	73.5	0.0004	35.6	168	< 0.0001	5.83	20.9	0.0060	7.24	33.6	0.0022
B	0.378	63.9	0.0005	0.018	99.94	0.0002	0.573	55.1	0.0007	13.8	65.2	0.0005	18.1	64.8	0.0005	3.15	14.6	0.0123
AB	0.079	13.3	0.0147	0.000	0.4781	0.5201	0.110	10.6	0.0227	0.825	3.90	0.1053	0.157	0.562	0.4874	0.875	4.06	0.0999
A^2	0.276	46.6	0.0010	0.000	0.0973	0.7677	0.007	0.652	0.4560	2.43	11.5	0.0195	1.89	6.78	0.0480	23.6	110	0.0001
B^2	0.013	2.13	0.2047	0.002	11.10	0.0207	0.179	17.2	0.0089	0.066	0.312	0.6007	1.01	3.62	0.1156	0.000	0.000	0.9915
Residual	0.030			0.001			0.052			1.06			1.40			1.08		
Lack of fit	0.019	1.12	0.5029	0.001	2.01	0.3498	0.052	222	0.0045	0.923	4.56	0.1852	1.37	42.6	0.0230	0.657	1.04	0.5237
Total	2.80			0.027			1.68			54.2			27.8			37.72		
R^2	0.989			0.967			0.969			0.981			0.950			0.972		
Adj R^2	0.979			0.933			0.938			0.961			0.900			0.943		
Pred R^2	0.923			0.767			0.683			0.830			0.650			0.808		
Adeq Precision	29.0			17.3			19.3			23.3			14.0			15.0		
C.V.%	4.41			7.88			9.01			6.53			5.74			16.7		

Abbreviations: SS – sum of squares, Adj R2 – adjusted R-squared, Pred R2 – predicted R-squared, Adeq Precision – adequate precision, C.V.% - coefficient of variation in percentage. A – power, B – mass.

the ANOVA results of the reduced models shown in Table 3. The model adequacy was sufficient to allow accurate prediction of the analytes, as indicated by the low coefficient of variation (<10% for all anthocyanins except cyanidin chloride), R^2 values between 0.95 and 0.99, a $P > 0.05$ for the lack-of-fit for all anthocyanins except cyanidin-3-glucoside and pelargonidin-3-glucoside. This indicated that the assumption of constant variance for the model was generally met. However, these two exceptions indicated that the developed mathematical models did not satisfactorily fit the experimental data. Consequently, different modelling techniques or other independent variables may need to be considered in future work to fully explain the variation in these two anthocyanins.

The microwave power (variable A) significantly affected the concentration of all anthocyanins ($P < 0.01$ for all); as did the sample mass used (variable B; $P < 0.05$ for all). However, a significant interaction ($P < 0.05$) between power and sample mass only occurred for cyanidin-3-glucoside and the total anthocyanin content. Similarly, the quadratic term for power (A^2) was significant for total anthocyanin content, cyanidin-3-rutinoside, pelargonidin-3-glucoside and cyanidin chloride; while the quadratic term for sample mass (B^2) was only significant for cyanin chloride and cyanidin-3-glucoside. The regression equations of total anthocyanins (Eq. 4) and individuals anthocyanins (Eqs. 5–9) are shown below:

$$\text{Total anthocyanins} = 1.53 - 0.5729\,A - 0.2511B + 0.\,1405AB + 0.3300\,A^2 + 0.0705B^2 \quad (4)$$

$$\text{Cyanin chloride} = 0.1561 - 0.0310\,A - 0.0547B + 0.0046AB - 0.0026\,A^2 + 0.0280B^2 \quad (5)$$

$$\text{Cyanidin-3-glucoside} = 1.02 - 0.3570\,A - 0.3091B + 0.1657AB - 0.0517\,A^2 + 0.2658B^2 \quad (6)$$

$$\text{Cyanidin-3-rutinoside} = 6.43 - 2.44\,A - 1.52B + 0.4543AB + 0.9799\,A^2 + 0.1614B^2 \quad (7)$$

$$\text{Pelargonidin-3-glucoside} = 9.33 - 0.9860\,A - 1.74B + 0.1980AB - 0.8645\,A^2 + 0.6314B^2 \quad (8)$$

$$\text{Cyanidin chloride} = 4.44 - 1.10\,A - 0.7245B + 0.4678AB - 3.05\,A^2 + 0.0033B^2 \quad (9)$$

Further investigation of the coded equations for each regression model revealed that both lower power and lower sample mass were associated with a higher concentration of all anthocyanins. In other words, the highest anthocyanin concentrations were typically found using the lowest power setting (350 W) and lowest sample mass tested (50 g). Nevertheless, there was a wide variation in the response of individual anthocyanins to these two independent variables, as can be seen in the response surface area plots in Fig. 1. Notably, the highest concentrations of cyanidin chloride were actually found at an intermediate microwave power setting, with the sample mass having less influence on this analyte. However, most other anthocyanins – including cyanidin-3-glucoside, cyanin chloride and the total anthocyanin content – displayed fairly consistent trends in their response to microwave power and sample mass (Fig. 1).

The increased microwave power likely increases the degradation of anthocyanins via the cleavage of covalent bonds and oxidation processes (Zorić et al., 2014). Previous studies have found a reduction in the anthocyanin content of rosehip fruit during convective drying (Pashazadeh et al., 2021), vacuum drying and microwave drying (Özkan-Karabacak, 2023). Compared to convective drying, microwave-assisted drying allows the drying process to occur at a lower temperature, as the irradiation wavelength specifically targets water molecules. Consequently, at lower power, the main effect on anthocyanins is the hydrolysis of anthocyanin glycosides into their aglycones (Duan et al., 2015). However, at higher power, further degradation of the anthocyanin structure may occur. Similarly, using a larger sample mass may take longer for the entire product to dry, providing an

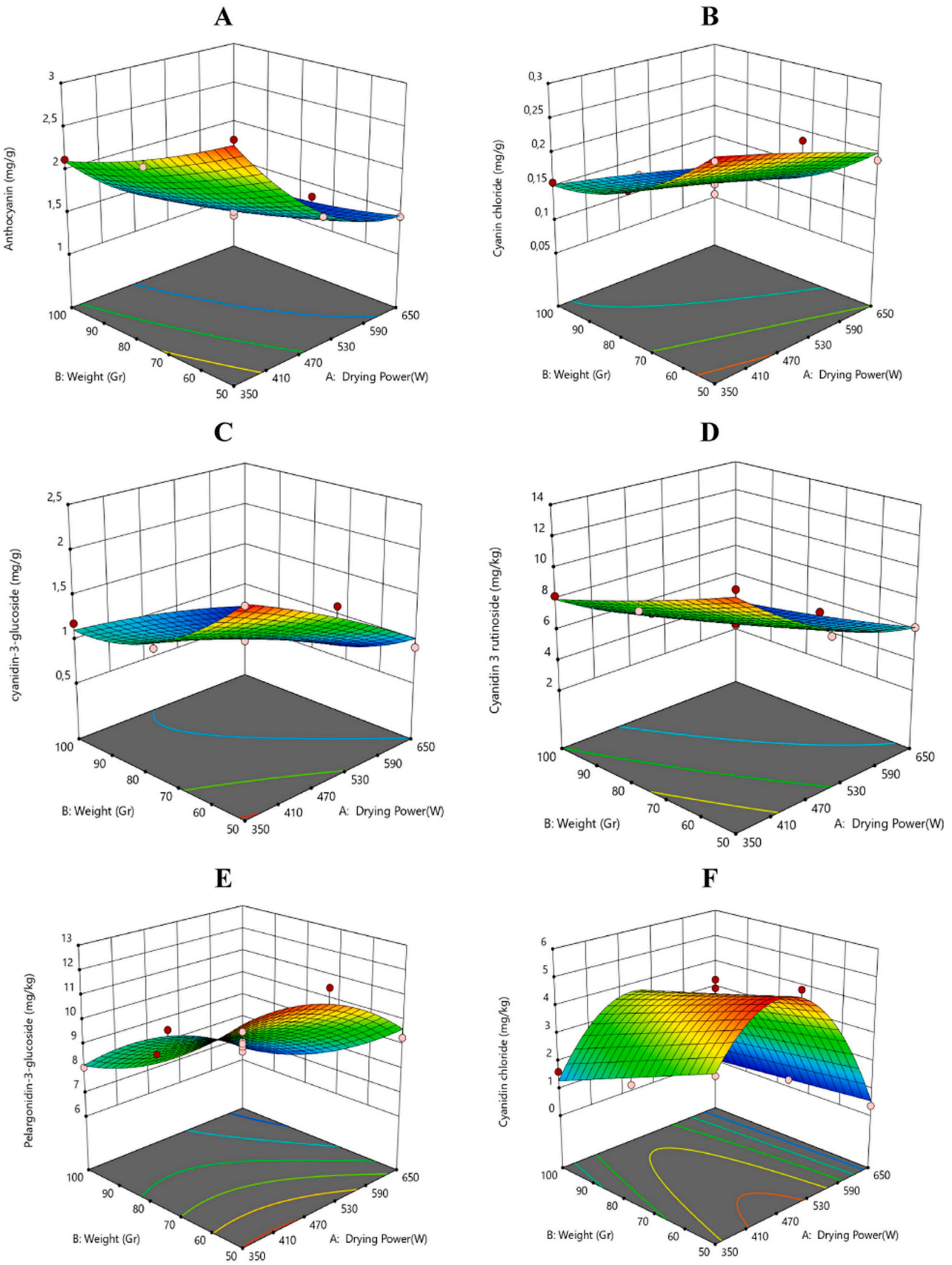

Fig. 1. – Three-dimensional response surface contour plots (3D-RSCP) showing the effect of the independent factors: drying power and weight on A) total anthocyanins, B) cyanin chloride, C) cyanidin-3-glucoside (mg/g), D) cyanidin-3-rutinoside, E) pelargonidin-3-glucoside, and F) cyanidin chloride.

Table 4
- Color properties of microwave-dried black rosehip fruits.

Microwave power (W)	Amount of sample (g)	L*	a*	b*	ΔL
350	50	21.3 ±0.0 ^{f}	1.87 ±0.01^{e}	3.13 ±0.01^{dcb}	9.60 ±0.01^{a}
	75	22.4 ±0.0^{ed}	1.74 ±0.02 ^{f}	3.21 ±0.01^{b}	8.56 ±0.03^{d}
	100	22.1 ±0.1^{e}	1.72 ±0.04 ^{f}	3.14 ±0.03 ^{cd}	8.72 ±0.07^{dc}
500	50	22.7 ±0.0 ^{cd}	1.56 ±0.02 ^{g}	3.05 ±0.07^{dc}	8.23 ±0.02^{e}
	75	23.0 ±0.0^{c}	2.44 ±0.01^{b}	3.60 ±0.03^{a}	7.95 ±0.05 ^{f}
	100	23.7 ±0.0^{b}	2.65 ±0.07^{a}	3.04 ±0.06^{d}	7.20 ±0.04 ^{g}
650	50	22.5 ±0.6^{d}	1.24 ±0.06 ^{h}	3.54 ±0.01^{a}	8.88 ±0.02bc
	75	21.5 ±0.0 ^{f}	1.60 ±0.02 ^{g}	3.63 ±0.05^{a}	9.47 ±0.03^{a}
	100	22.0 ±0.1^{e}	2.35 ±0.01^{c}	3.22 ±0.01^{b}	9.00 ±0.10^{b}
Fresh fruit		29.7 ±0.4^{a}	1.97 ±0.47^{d}	2.17 ±0.11^{e}	-

Data are expressed as mean ± standard deviation of triplicate measurements. Mean superscript with different alphabets in the same column differ significantly ($P < 0.05$) according to Duncan's new test.

extended period during which anthocyanin degradation can take place. Studies on other analytes suggest that the optimum drying process is a trade-off between maintaining a low microwave power and reducing the drying duration (Gunaydin and Alibas, 2023).

Although several studies have previously investigated the impact of microwave drying on the quality of rosehip fruit (Gunaydin and Alibas, 2023; Özkan-Karabacak, 2023; Taşova et al., 2020); none appear to have focused on the influence of this drying technique on the anthocyanins present. Goztepe et al. (2022) did note a loss of colour quality in rosehip fruit dried using hot-air drying, which would most likely be attributable to anthocyanin degradation. Overall, microwave drying appears to be better at retaining anthocyanins compared to other drying techniques. Zhang et al. (2023) reported that microwave vacuum drying, microwave freeze drying and freeze drying all retained higher levels of anthocyanins in blueberry pomace (approximately 18%, 21% and 60% loss of anthocyanins, respectively) compared to hot-air drying (around 81–91% anthocyanin loss, depending on the oven temperature). Additionally, microwave vacuum drying afforded the best natural colour and antioxidant capacity. Similarly, Parveez Zia and Alibas (2021) reported less loss of anthocyanins in cornelian cherry when using microwave drying compared to convective drying (42–52% anthocyanin loss compared to 71–82%, respectively), while Wojdyło et al. (2014) also found that microwave drying outperformed convective drying for anthocyanin retention in sour cherries (0–30% anthocyanin loss compared to 38–45% loss, respectively). Consequently, this study provides crucial insight into the degradation dynamics of individual rosehip anthocyanins when subjected to microwave drying.

3.2. Color

The color of food products holds significant importance as a quality attribute, playing a crucial role in influencing consumer acceptance of food products (Deng et al., 2019). The drying parameters had small but significant impacts on the color of the resultant dried rosehip product (Table 4). Upon drying, the lightness (L*) of the product significantly decreased, while the yellowness (b*) of the product increased ($P < 0.05$). The degree of redness varied between samples depending on the drying power and amount of sample used. In general, lower microwave power and less sample mass gave a color which was slightly darker (lower L* value), less red (lower a* value) and less yellow (lower b* value). The conditions yielding the reddest coloration (highest a* value) tended to be a combination of an intermediate/high sample mass (75 g) and higher microwave power (500–650 W). The highest ΔL values were seen for the combinations of the lowest microwave power and sample mass (350 W and 50 g), and the combinations of the highest power and a high sample mass (650 W, 75–100 g). Wojdyło et al. (2014) noted that sour cherries dried by vacuum microwave drying were redder than those dried using convective drying, which was attributed to a loss of anthocyanins.

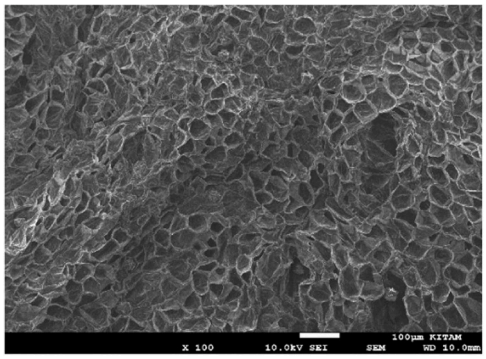

Fig. 2. – Scanning electron microscopy image of fresh black rosehip fruit.

The lack of a direct correlation between the a* value (red coloration) and anthocyanin content mirrors previous research, which reported that the total anthocyanin content was only correlated with color parameters in plums (Usenik et al., 2009). Individual anthocyanins range in color from red to purple and blue (Khoo et al., 2017), but their color can also be influenced by various interactions (Tindal et al., 2024). Additionally, the matrix pH has a strong influence on the color of specific anthocyanins (Fossen et al., 1998) and microwave drying can impact the pH in strawberry (de Bruijn et al., 2016). Consequently, the degree of red coloration (a* value) would not be expected to correlate closely with the total anthocyanin content but result from the relative amounts of the individual anthocyanins present after each treatment condition, as well as other potential matrix effects.

3.3. Microstructure

SEM analysis of fresh black rosehip (Fig. 2) shows regular cellular cavities that become wrinkled and irregularly compacted upon drying (Fig. 3). SEM images of the dried product from each combination of conditions highlighted changes in the microstructure of the rosehip (Fig. 3). The SEM images show the cellular cavities and interstitial spaces in the dried rosehip. In general, a higher microwave power seemed to produce a greater number of smaller cavities, while increasing the sample mass appeared to produce larger cavities. Previous research has highlighted that these cavities form from the collapse of structural components of the cell walls, particularly polysaccharides (Giri and Prasad, 2007). Combined with the observations in Fig. 3, this suggests that microwave irradiation plays a major role in initiating this structural collapse and the formation of small cavities/pores; while extended drying times (used for the trials with a higher sample mass) caused these cavities to expand and coalesce into larger cavities. Similarly, it has previously been noted that rosehip fruit dried for shorter time periods (albeit at higher temperatures) suffered less damage to the cell walls, compared to fruit dried for longer periods at lower temperatures (Pashazadeh et al., 2024).

3.4. Texture

The hardness of the dried samples was significantly impacted by the drying parameters (Table 5); however, there were no clear trends across both independent variables. In comparison to the fresh fruit, the

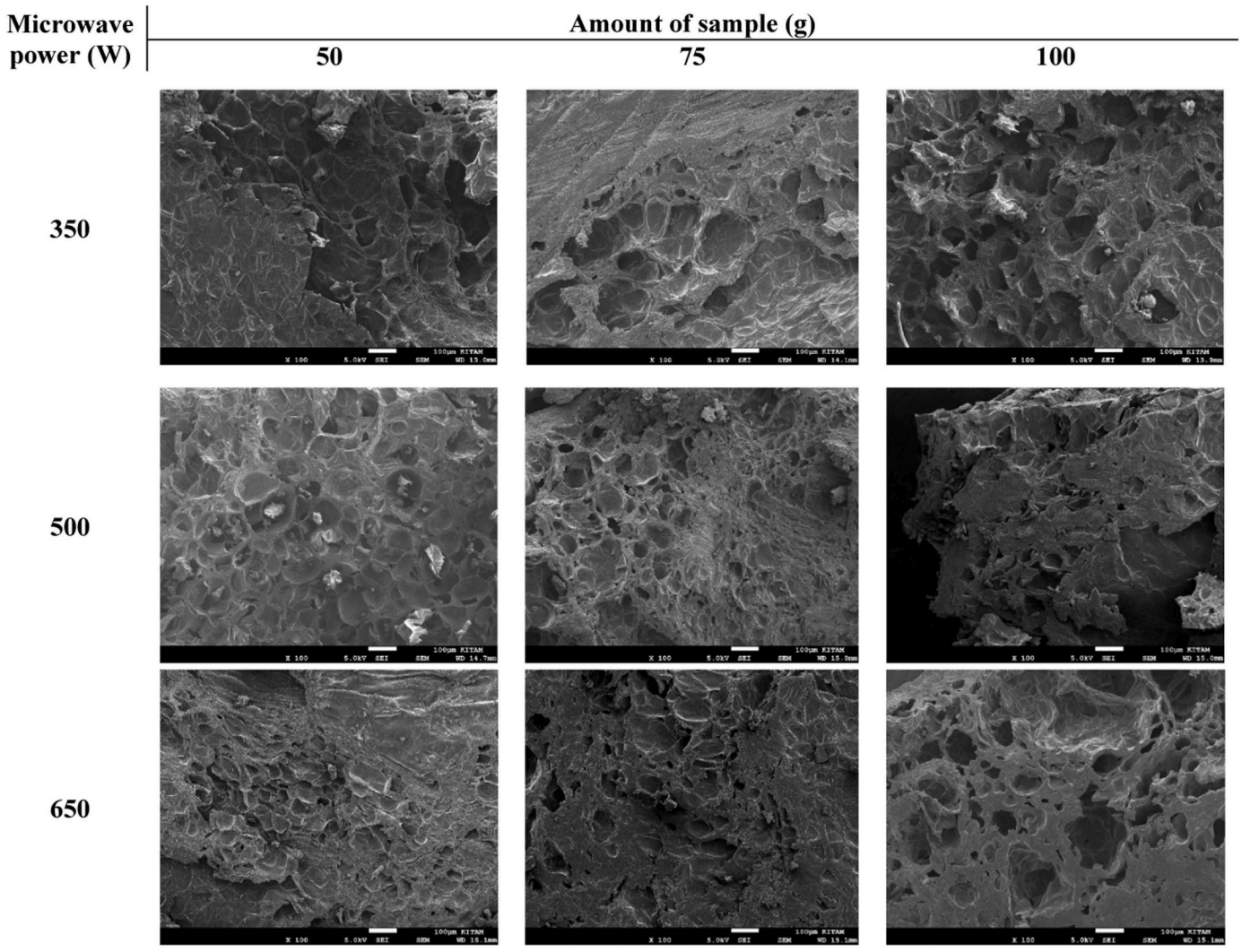

Fig. 3. – Scanning electron microscopy images of black rosehip fruits dried using microwave oven at different conditions (microwave power and amounts).

Table 5
- Texture properties of microwave-dried black rosehip fruits.

Microwave power (W)	Amount of sample (g)	Hardness (N)	Springiness	Cohesiveness	Gumminess	Chewiness	Resilience
350	50	30.33 ±0.27^{e}	0.78 ±0.70^{abc}	0.63 ±0.04^{ab}	19.3 ±1.6^{bcdef}	15.1 ±2.5^{abc}	0.31 ±0.01^{abc}
	75	20.73 ±1.39 ^{f}	0.80 ±0.02^{abc}	0.52 ±0.18^{ab}	10.8 ±1.1 ^{f}	8.7 ±2.7^{c}	0.22 ±0.06^{c}
	100	23.10 ±1.94 ^{f}	0.89 ±0.03^{ab}	0.52 ±0.02^{ab}	12.1 ±1.4^{ef}	10.8 ±1.7^{bc}	0.24 ±0.00^{bc}
500	50	50.88 ±2.03^{b}	0.72 ±0.01^{bc}	0.47 ±0.12^{ab}	24.3 ±1.3^{abc}	17.5 ±1.2^{ab}	0.24 ±0.05^{bc}
	75	40.98 ±0.09^{d}	0.74 ±0.01^{abc}	0.52 ±0.01^{ab}	21.5 ±0.2^{bcd}	15.9 ±0.2^{abc}	0.24 ±0.00^{bc}
	100	45.94 ±1.40^{c}	0.70 ±0.12^{bc}	0.36 ±0.17^{c}	16.6 ±1.8^{cdef}	12.2 ±1.5^{bc}	0.19 ±0.01^{c}
650	50	32.19 ±0.10^{e}	0.88 ±.0.01^{a}	0.61 ±0.01^{ab}	19.9 ±0.2^{bcde}	17.5 ±0.2^{ab}	0.27 ±0.00^{abc}
	75	45.24 ±3.81^{c}	0.66 ±0.08^{b}	0.58 ±0.04^{abc}	26.5 ±0.9^{ab}	17.5 ±1.7^{ab}	0.36 ±0.01^{ab}
	100	56.76 ±2.38^{a}	0.72 ±0.17^{bc}	0.57 ±0.06^{abc}	32.6 ±1.9^{a}	23.4 ±2.2^{a}	0.30 ±0.10^{abc}
Fresh fruit		42.1 ±0.1^{dc}	0.91 ±0.01^{a}	0.75 ±0.33^{a}	15.0 ±0.2^{def}	12.1 ±0.3^{bc}	0.40 ±0.01^{a}

Data are expressed as mean ± standard deviation of triplicate measurements. Mean superscript with different alphabets in the same column differ significantly ($P < 0.05$) according to Duncan's new test.

hardness of the dried fruit produced at low microwave power (350 W) was significantly lower ($P < 0.05$), yet the springiness of the dried product at the power was not significantly different than the fresh sample. The resilience of most samples dried at 350 and 500 W was significantly lower than fresh fruit ($P < 0.05$). On the other hand, the cohesiveness of the dried product did not significantly differ in comparison to the fresh fruit in most cases. The lowest microwave power (350 W) gave the lowest hardness values; however, the intermediate and high powers gave mixed results – depending on the amount of sample used. The hardest samples were found using 650 W power and 100 g sample mass. This condition also yielded the gummiest and chewiest sample (significantly higher for both parameters than any other combination of drying conditions). In general, low microwave power reduced the gumminess and chewiness of the dried product, while sample mass did not have a major impact on texture. A previous study found that the drying temperature was positively correlated with hardness during the convective drying of black rosehip fruit, which was attributed to initial evaporation from the fruit surface leading to

Table 6
- Bioaccessibility of fresh and optimized microwave-dried black rosehip fruits anthocyanins.

Anthocyanins	Bioaccessibility (%)	
	Fresh fruit	Dried fruit at optimum conditions
Cyanin chloride	53.1 ±2.1[a]	58.5 ±0.9[b]
Cyanidin-3-glucoside	56.8 ±6.6[a]	82.6 ±4.1[a]
Cyanidin-3-rutinoside	6.11 ±0.98[b]	9.1 ±0.2[c]
Pelargonidin-3-glucoside	6.98 ±0.88[b]	8.4 ±1.2[c]
Cyanidin chloride	1.87 ±0.08[c]	3.1 ±0.1[d]

Data are expressed as mean ± standard deviation of triplicate measurements. Mean superscript with different alphabets in the same column differ significantly ($P < 0.05$) according to Duncan's new test.

shrinkage the collapse of the fruit surface (Pashazadeh et al., 2024). However, gumminess and chewiness were not clearly correlated with drying temperature under those conditions.

The drying conditions had minimal impact on the springiness, resilience or cohesiveness of the samples (Table 5). Generally, springiness was inversely correlated with hardness, similar to observations reported by Chong et al. (2008). Springiness is influenced by pectin and other gelling agents in the fruit (Pashazadeh et al., 2024), which can be broken down by elevated temperatures (Chong et al., 2008).

3.5. Bioaccessibility

The bioaccessibility of each of the anthocyanins was determined under the optimal drying conditions (350 W power and 50 g sample mass). Cyanidin-3-glucoside showed the highest bioaccessibility (82.6%); significantly higher than any other anthocyanin (Table 6). It was followed by cyanin chloride (58.5% bioaccessible). Cyanidin-3-rutinoside, pelargonidin-3-glucoside and cyanidin chloride all showed very low bioaccessibility (9.1, 8.4 and 3.1%, respectively). Victoria-Campos et al. (2022) also reported that the gastrointestinal bioaccessibility of most common anthocyanins (including cyanidin-3-glucoside, cyanidin-3-rutinoside, and pelargonidin-3-glucoside) was very low in unprocessed fruits, ranging from 0.1% to 3.5%. Both, the fresh and dried fruit, had a similar trend in terms of bioaccessibility of different anthocyanins, with exception to cyanidin-3-glucoside. The remarkable difference can only be seen with the bioaccessibility of cyanidin-3-glucoside, which had a bioaccessibility of 56.8 ±6.6% from fresh fruit, while 82.6 ±4.1% from the dry fruit. This suggests that drying at optimum conditions can improve the bioaccessibility of black rosehip cyanidin-3-glucoside.

While there are limited studies on the effects of drying methods on the bioaccessibility of anthocyanins, Zhao et al. (2017) reported 52.3% bioaccessibility in the total phenolic content of *Rhodomyrtus tomentosa* berries following microwave drying; moderately higher than the bioaccessibility following combined microwave-hot-air-drying (45.2%). On the other hand, Ozay-Arancioglu et al. (2022) showed that the gastric bioaccessibility of cyanidin-3-glucoside in pomegranate fruit varied significantly depending on the drying method – from 4.2% for oven-drying to 65.2% for freeze-drying. The extreme variability in bioaccessibility may be due to several reasons, including anthocyanin degradation from elevated temperatures, matrix effects between anthocyanins and the cell structural components, and the physical availability of the anthocyanins for diffusion (relating to the structural collapse of the fruit structure mentioned above). Nevertheless, the high bioaccessibility observed in the present study indicates that microwave drying is a suitable method for preserving the content and bioaccessibility of cyanidin-3-glucoside in rosehip fruit.

4. Conclusions

Microwave drying can be utilized to produce dried black rosehip at optimum conditions of 350 W power and 50 g sample mass. In general, power and sample mass had a significant impact on the anthocyanin content in black rosehip and the fruit hardness. It was noted that lower microwave power and less sample mass gave a color which was slightly darker, less red, and less yellow. The dried fruit sample at optimum conditions showed a high bioaccessibility of cyanidin-3-glucoside, which has been previously reported to have high anti-inflammatory, antimicrobial, anti-viral, neuroprotective, anti-thrombotic activities.

Funding

Not applicable.

Author Statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process. He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs

CRediT authorship contribution statement

Hojjat Pashazadeh: Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ali Ali Redha:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Joel B. Johnson:** Writing – review & editing, Writing – original draft. **Ilkay Koca:** Supervision, Project administration. **Mustafa Fatih Ertugay:** Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. For the purpose of open access, the author, Ali Ali Redha, has applied a "Creative Commons Attribution (CC BY) license to any Author Accepted Manuscript version arising.".

Data availability

All data has been included in the manuscript (tables and figures)

References

Alvarez-Suarez, J.M., Cuadrado, C., Redondo, I.B., Giampieri, F., González-Paramás, A. M., Santos-Buelga, C., 2021. Novel approaches in anthocyanin research - Plant fortification and bioavailability issues. Trends Food Sci. Technol. 117, 92–105.

Chojnacka, K., Mikula, K., Izydorczyk, G., Skrzypczak, D., Witek-Krowiak, A., Moustakas, K., Ludwig, W., Kułażyński, M., 2021. Improvements in drying technologies - Efficient solutions for cleaner production with higher energy efficiency and reduced emission. J. Clean. Prod. 320.

Chong, C.H., Law, C.L., Cloke, M., Abdullah, L.C., Daud, W.R.W., 2008. Drying Kinetics, Texture, Color, and Determination of Effective Diffusivities During Sun Drying of Chempedak. Dry. Technol. 26 (10), 1286–1293.

de Bruijn, J., Rivas, F., Rodriguez, Y., Loyola, C., Flores, A., Melin, P., Borquez, R., 2016. Effect of Vacuum Microwave Drying on the Quality and Storage Stability of Strawberries. J. Food Process. 40, 1104–1115. https://doi.org/10.1111/jfpp.12691.

Deng, L.Z., Mujumdar, A.S., Zhang, Q., Yang, X.H., Wang, J., Zheng, Z.A., Gao, Z.J., Xiao, H.W., 2019. Chemical and physical pretreatments of fruits and vegetables: Effects on drying characteristics and quality attributes - a comprehensive review. Crit. Rev. Food Sci. Nutr. 59 (9), 1408–1432.

Duan, W., Jin, S., Zhao, G., Sun, P., 2015. Microwave-assisted extraction of anthocyanin from Chinese bayberry and its effects on anthocyanin stability. Food Sci. Technol. 35, 524–530.

Escalante-Aburto, A., Mendoza-Córdova, M.Y., Mahady, G.B., Luna-Vital, D.A., Gutiérrez-Uribe, J.A., Chuck-Hernández, C., 2023. Consumption of dietary

anthocyanins and their association with a reduction in obesity biomarkers and the prevention of obesity. Trends Food Sci. Technol. 140.
Fan, C., Pacier, C., Martirosyan, D.M., 2014. Rosehip (*Rosa canina L*): A functional food perspective. Funct. Foods Health Dis. 4 (11), 493–509.
Fossen, T., Cabrita, L., Andersen, O.M., 1998. Colour and stability of pure anthocyanins influenced by pH including the alkaline region. Food Chemistry 63, 435–440. https://doi.org/10.1016/S0308-8146(98)00065-X.
Giri, S.K., Prasad, S., 2007. Drying kinetics and rehydration characteristics of microwave-vacuum and convective hot-air dried mushrooms. J. Food Eng. 78 (2), 512–521.
Goztepe, B., Kayacan, S., Bozkurt, F., Tomas, M., Sagdic, O., Karasu, S., 2022. Drying kinetics, total bioactive compounds, antioxidant activity, phenolic profile, lycopene and β-carotene content and color quality of Rosehip dehydrated by different methods. LWT 153, 112476.
Gunaydin, S., Alibas, I., 2023. The influence of short, medium, and long duration common dehydration methods on total protein, nutrients, vitamins, and carotenoids of rosehip fruit (*Rosa canina* L.). J. Food Compos. Anal. 124, 105631.
Herrera-Balandrano, D.D., Chai, Z., Beta, T., Feng, J., Huang, W., 2021. Blueberry anthocyanins: An updated review on approaches to enhancing their bioavailability. Trends Food Sci. Technol. 118, 808–821.
Kaba, B., Yıkılkan, Y., Pashazadeh, H., Ali Redha, A., Koca, I., (2023). Production of cornelian cherry (Cornus mas L.) pulp powder by foam-mat drying: analysis of physicochemical and antioxidant properties. Biomass Conversion and Biorefinery.
Khoo, H.E., Azlan, A., Tang, S.T., Lim, S.M., 2017. Anthocyanidins and anthocyanins: colored pigments as food, pharmaceutical ingredients, and the potential health benefits. Food & Nutrition Research 61.
Lee, J., Durst, R.W., Wrolstad, R.E., 2005. Determination of Total Monomeric Anthocyanin Pigment Content of Fruit Juices, Beverages, Natural Colorants, and Wines by the pH Differential Method: Collaborative Study. J. AOAC Int. 88 (5), 1269–1278.
Naseri, R., Farzaei, F., Haratipour, P., Nabavi, S.F., Habtemariam, S., Farzaei, M.H., Khodarahmi, R., Tewari, D., Momtaz, S., 2018. Anthocyanins in the Management of Metabolic Syndrome: A Pharmacological and Biopharmaceutical Review. Front. Pharmacol. 9.
Orsat, V., Changrue, V., Raghavan, G.V., 2006. Microwave drying of fruits and vegetables Stewart. Postharvest Rev. 6 (4).
Ozay-Arancioglu, I., Bekiroglu, H., Karadag, A., Saroglu, O., Tekin-ÇAkmak, Z.H., Karasu, S., 2022. Effect of different drying methods on the bioactive, microstructural, and in-vitro bioaccessibility of bioactive compounds of the pomegranate arils. Food Sci. Technol. 42.
Özkan-Karabacak, A., 2023. Evaluation of drying kinetics and quality parameters of rosehip pestils dried by three different methods. J. Berry Res. 13, 261–283.
Parveez Zia, M., Alibas, I., 2021. The effect of different drying techniques on color parameters, ascorbic acid content, anthocyanin and antioxidant capacities of cornelian cherry. Food Chem. 364, 130358.
Pashazadeh, H., Ali Redha, A., Koca, I., 2024. Effect of convective drying on phenolic acid, flavonoid and anthocyanin content, texture and microstructure of black rosehip fruit. J. Food Compos. Anal. 125.
Pashazadeh, H., Zannou, O., Galanakis, C.M., Aldawoud, T.M.S., Ibrahim, S.A., Koca, I., 2021. Optimization of drying process for *Rosa pimpinellifolia* L. fruit (black rose hips) based on bioactive compounds and modeling of drying process. Int. J. Food Prop. 24 (1), 1367–1386.
Prieto Martinez, A., Coutino Diaz, M., Anaya Romero, L., Ali Redha, A., Zare, R., Ventura Hernandez, S., Prokopidis, K., Clifford, T., 2024. Effects of Vaccinium berries (blueberries, cranberries and bilberries) on oxidative stress, inflammation, exercise performance, and recovery - a systematic review. Food Funct. 15 (2), 444–459.
Salvia-Trujillo, L., McClements, D.J., 2016. Enhancement of lycopene bioaccessibility from tomato juice using excipient emulsions: Influence of lipid droplet size. Food Chem. 210, 295–304.
Taşova, M., Ergüneş, G., Gerçekcioğlu, R., Karagül, Ş., 2020. Quality changes in rosehip (*Rosa montana* Chaix subsp. *woronovii* (Lonacz) Ö. Nilsson) fruits dryed by convective and microwave methods. Anadolu Tarim. Bilim. Derg. 34 (3), 312–318.
Tindal, R.A., Jeffery, D.W., Muhlack, R.A., 2024. Nonlinearity and anthocyanin colour expression: A mathematical analysis of anthocyanin association kinetics and equilibria. Food Research International 183, 114195. https://doi.org/10.1016/j.foodres.2024.114195.
Usenik, V., Štampar, F., Veberič, R., 2009. Anthocyanins and fruit colour in plums (Prunus domestica L.) during ripening. Food Chemistry 114, 529–534. https://doi.org/10.1016/j.foodchem.2008.09.083.
Victoria-Campos, C.I., Ornelas-Paz, Jd.J., Rocha-Guzmán, N.E., Gallegos-Infante, J.A., Failla, M.L., Pérez-Martínez, J.D., Rios-Velasco, C., Ibarra-Junquera, V., 2022. Gastrointestinal metabolism and bioaccessibility of selected anthocyanins isolated from commonly consumed fruits. Food Chem. 383, 132451.
Wojdyło, A., Figiel, A., Lech, K., Nowicka, P., Oszmiański, J., 2014. Effect of Convective and Vacuum–Microwave Drying on the Bioactive Compounds, Color, and Antioxidant Capacity of Sour Cherries. Food Bioprocess Technol. 7 (3), 829–841.
Yildiz, G., İzli, G., 2018. Influence of microwave and microwave-convective drying on the drying kinetics and quality characteristics of pomelo. J. Food Process. Preserv. 43 (6).
Zare, R., Kimble, R., Ali Redha, A., Cerullo, G., Clifford, T., 2023. How can chokeberry (Aronia) (poly)phenol-rich supplementation help athletes? A systematic review of human clinical trials. Food Funct. 14 (12), 5478–5491.
Zhang, L., Zhang, C., Wei, Z., Huang, W., Yan, Z., Luo, Z., Beta, T., Xu, X., 2023. Effects of four drying methods on the quality, antioxidant activity and anthocyanin components of blueberry pomace. Food Prod., Process. Nutr. 5 (1), 35.
Zhao, G., Zhang, R., Liu, L., Deng, Y., Wei, Z., Zhang, Y., Ma, Y., Zhang, M., 2017. Different thermal drying methods affect the phenolic profiles, their bioaccessibility and antioxidant activity in *Rhodomyrtus tomentosa* (Ait.) Hassk berries. LWT - Food Sci. Technol. 79, 260–266.
Zorić, Z., Dragović-Uzelac, V., Pedisić, S., Kurtanjek, Ž., Elez Garofulić, I., 2014. Kinetics of the degradation of anthocyanins, phenolic acids and flavonols during heat treatments of freeze-dried sour cherry Marasca paste. Food Technol. Biotechnol. 52 (1), 101–108.