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Physical and chemical properties of convective and microwave dried blackberries fruits grown by organic procedure

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Abstract: This study aimed to evaluate the effect of convective and microwave drying on the content of bioactive compounds of blackberry (*Rubus fruticosus*), drying parameters and energy consumption. The fruit was dehydrated in a convective dehydrator at a temperature of 50 °C and 70 °C and a microwave oven at power levels of 90 V, 180 V and 240 V. The highest amount of anthocyanins, polyphenols and antioxidant capacity were obtained in microwave dried blackberry fruits at 90 V and 180 V. It turned out that microwave dehydration shortened the processing time and lower the energy consumption compared to the convective drying. Blackberry fruits dehydrated at 240 V showed the shortest dehydration time, minimal energy consumption and the most efficient diffusion.

Keywords: Blackberry (*Rubus fruticosus*); convective drying; microwave drying; polyphenols; antioxidant capacity

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1. Introduction

Production of blackberry fruits (*Rubus fruticosus*) constantly increases worldwide. Advantages of cultivation are reflected in its early fruit bearing, regular and high yields, and adaptation to different cultivation system. Due to their rich biochemical composition, blackberries possess nutritious and medicinal properties, which makes them an important part of the human's diet [1,2].

The demand for fresh, naturally preserved and quality products, which are physically and chemically treated as little as possible during processing, is increasing. On the other hand, blackberry fruits are extremely perishable and have a short market life, and thus various forms of processing and/or deep freezing are a necessity. Dried fruit, as concentrated form of fresh fruit, is mainly consumed as handheld snacks due to its delicate organoleptic properties and high energy content. Such image of dried fruits, including dried berry fruits, is recently being changed due to their high antioxidant capacity and beneficial influences on human health [3]. The drying process can significantly impair the sensory properties of fruits, and thus it is of essential importance to choose the proper dehydration method based on the properties of fresh fruit and the desired properties of dried products. The goal of every dehydration procedure is to reduce the negative changes in the raw material, to preserve the content of bioactive substances to the greatest extent possible and thereby enable obtaining a quality product with an extended shelf life. Regarding the energy consumption, duration of the selected dehydration method should be shortened as much as possible [4].

Unlike convective drying, where moisture is initially removed from the surface, while subsequently the remaining moisture diffuses from the inner parts towards the surface until complete dehydration, in microwave drying the heat is generated directly in the interior of the material, creating a greater heat transfer, and resulting in faster evaporation of moisture [5,6]. Microwave drying takes significantly less time compared to the convective procedure [7].

The aim of this work was to examine the possibility of applying convective and microwave dehydration of blackberry fruits of Loch Ness and Triple Crown varieties, grown by organic procedure. The drying parameters varied for both applied methods, while the energy, kinetic and control parameters were monitored.

2. Materials and Methods

2.1. Fruit sampling

Two thornless cultivars of blackberry fruits, Loch Ness and Triple Crown, were collected in July 2022 in family orchard in the village Gornji Dubac, Serbia (43°39′54″N 20°21′56″E, altitude 850 m), and stored in sealed plastic bags at −18 °C, for no longer than one month. Each sample consisted of approximately 400 blackberry samples: 10 berry fruits in full maturity stage (harvest maturity) from 40 trees, with no mechanical injuries were randomly selected. Before dehydration process, frozen blackberries were washed with cold water and allowed to stabilize for a few hours at room temperature.

The production of these two blackberry varieties were carried out according to organic principles (certificate issued by the authorized organization Ecocert Balkan).

2.2. Drying procedures

Loch Ness and Triple Crown blackberry fruits were subjected to convective and microwave drying processes. Prior to drying, the fruits were visually selected according to size and color, while damaged and moldy samples were removed. Convective drying of berry fruits was carried out in a commercial food dehydrator (Gorenje FDK 500GCW, Slovenia) at the temperatures of 50 °C and 70 °C, air flow speed of 7.9 ms^{-1}, and atmospheric pressure, until constant mass. Five drying trays were parallelly placed into the drying chamber. Berry samples were positioned onto the drying trays in a monolayer formation, while the heated air was introduced vertically across the trays, from bottom to the top. Each tray initially held approximately 100 g of berry fruits, which caused a pressure of 1.325 $kg{\cdot}m^{-2}$. Position of the trays were changed every one hour, in such a manner that the top tray was placed as the bottom one.

Microwave drying was processed in a commercial microwave oven (Tesla MW2390MB 1250 W, Czech Republic), applying the power of 90, 180 and 240 W. Berries (~ 100 g) were processed into the single mono-layer formation, until constant mass.

The consumption of energy and the amount of emitted CO_2 in the atmosphere were monitored by the consumption meter (Prosto PM 001, Ningbo Huading, China). The mathematical relation between energy consumption and oxidation is 1 kWh = 0.998 kg CO_2.

2.3. Extraction and determination of total anthocyanins, total phenolics and antioxidant capacity

Dried blackberry samples (50 g) were powdered and mixed with 250 mL of 96% ethanol and ultrasonicated. After 30 min of extraction at 25 °C, the mixture was centrifuged in two sequential times for 15 min at 3500 rpm, and supernatant was filtered through a 0.45 mm Minisart filter before analysis. The obtained extracts were used for the determination of total polyphenolic contents and antioxidant capacity. The identical extraction procedure was repeated, but with 25 mL of 96% ethanol/HCl (85:15 v/v), in order to obtain extract for anthocyanin content. All these determinations were performed in triplicate, and results were presented as mean value of three measurements ± standard deviation.

2.4. Determination of total soluble solids content, dry matter content, pH and ash content

The soluble solid content of the fresh blackberries was determined on a manual refractometer (3828, Carl Zeiss, Germany), while dry matter content was determined by drying ~10 g of berries at 105°C, until constant mass. The ash content was measured on a 5 g sub-sample by a muffle furnace at 550 °C, until constant mass.

2.5. Statistical analysis

All assays were carried out in triplicate. Data were analyzed by one-way analysis of variance (ANOVA), using CoStat software. The pairwise comparisons between different parameters were performed using Tukey's test ($p < 0.05$). To evaluate and distinguish all examined parameters of blackberries (drying time, effective moisture diffusivity, energy consumption / emission of CO_2, total anthocyanins, total phenolics and antioxidant activity), a covariance matrix was employed for comparison through Principal Component Analysis (PCA) [8]. Pearson correlation was computed, and a significance level of $p < 0.05$ was applied. The color correlation diagram between the derived mass transfer rate parameters, drying time, effective moisture diffusivity, energy consumption / emission of CO_2, total anthocyanins, total phenolics and antioxidant activity was generated using the R Studio 1.4.1106 program [9].

3. Results and Discussion

3.1. Chemical properties of fresh and dried blackberry fruits

Basic physico-chemical properties of fresh blackberry samples were determined (Table 1). There are no significantly statistical differences among the two varieties. The obtained results for dry matter content, total soluble content, acidity (pH) and mineral content are either slightly lower or comparable to the previously published data [10–12].

Table 1. The physico-chemical parameters of fresh blackberry fruits.

Cultivar	Dry matter content (%)	Soluble solid content (%)	pH	Ash content (%)
Loch Ness	15.3 ± 0.1	9.7 ± 0.1	3.40 ± 0.15	0.34± 0.04
Triple Crown	15.2 ± 0.1	9.8 ± 0.1	3.61 ± 0.10	0.30 ± 0.05
ANOVA	ns	ns	ns	ns

There are no statistically significant differences between two varieties (Tukey's test, $p < 0.05$).
ns: not significant.

The chemical composition of fresh and dried blackberry fruits were analyzed and presented in Table 2. Fresh fruits of Loch Ness contained significantly higher amount of bioactive compounds, such as total anthocyanins and total phenolics, compared to the fresh fruits of Triple Crown variety. Consequently the higher level of antioxidativity was performed by the Loch Ness samples.

Any kind of dehydration process resulted in a loss in content of bioactive compounds. Applying high temperatures certainly causes degradation, due to the high thermolability of polyphenolics, especially anthocyanins [13]. Regarding our results, one can conclude that level of preservation of bioactive compounds is higher if higher temperature was applied, which is related to the duration of convective drying (Table 2). Namely, convective drying of Loch Ness fruits at 50 °C and 70 °C lasted 9,629 min and 3,086 min, respectively, while drying of Triple Crown samples at the same temperatures lasted 9,903 min and 3,255 min, respectively. Although the sensitivity of polyphenolics increases with temperatures, duration of the processes at 50 °C is ~3 times longer, which prompted degradation to a greater extent at this thermal level.

Table 2. Chemical composition of fresh and dried blackberries.

		Total anthocyanins (mg/100 g dm)		Total phenolics (mg/100 g dm)		Antioxidant capacity (mmol TE/100 g dm)	
		Loch Ness	**Triple Crown**	**Loch Ness**	**Triple Crown**	**Loch Ness**	**Triple Crown**
Fresh		503.9 ± 16.7^{a}	331.0 ± 9.4^{b}	1280.0 ± 150.5^{a}	796.0 ± 151.7^{b}	7.49 ± 0.94^{a}	4.86 ± 0.84^{b}
CD*	50 °C	1.3 ± 0.2^{g}	0.9 ± 0.1^{g}	149.8 ± 18.0^{h}	79.3 ± 3.0^{i}	0.64 ± 0.03^{fg}	0.43 ± 0.08^{g}
	70 °C	16.7 ± 1.7^{ef}	5.8 ± 0.3^{fg}	229.6 ± 0.6^{f}	53.1 ± 6.2^{i}	0.95 ± 0.00^{ef}	0.82 ± 0.07^{efg}
MD*	90 W	46.3 ± 1.9^{d}	52.5 ± 2.5^{d}	296.3 ± 25.7^{e}	255.8 ± 0.1^{f}	1.51 ± 0.13^{d}	1.20 ± 0.09^{de}
	180W	51.8 ± 1.6^{d}	83.5 ± 4.4^{c}	418.4 ± 6.6^{d}	502.2 ± 25.7^{c}	1.45 ± 0.06^{d}	2.35 ± 0.19^{c}
	240 W	17.2 ± 1.4^{ef}	19.9 ± 1.5^{e}	196.0 ± 19.4^{g}	246.1 ± 2.4^{f}	0.95 ± 0.01^{ef}	1.48 ± 0.10^{d}
ANOVA		***		***		***	

*CD and MD stand for conductive drying and microwave drying, respectively.
Values with different letters within analyzed trait (total anthocyanins, total phenolics, antioxidant capacity) and both varieties (Loch Ness, Triple Crown) denote statistically significant differences (Tukey's test, $p < 0.05$). ns, *, **, *: not significant or significant at $p < 0.05$, 0.01, 0.001, respectively.

In microwave drying, the highest level of bioactive compounds and antioxidativity were achieved at 180 W, while the most dominant degradation occurred during drying at 240 W, in both cultivars. Again, the duration of dehydration process played an important role in preservation of bioactive compounds, and thus the level of degradation was higher at the drying power of 90 W, compared to the 180 W. Namely, drying both blackberry varieties at 90 W and 180 W lasted 197 min and 71 min, respectively. Three times prolonged drying process, albeit at half the power, led to the higher level of degradation. Comparison between two drying methods led to the conclusion that microwave drying preserves the anthocyanins and polyphenols to a greater extent than convective drying. Such conclusion is supported by the previously published works [7,14].

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Table 3. Drying parameters, energy usage and CO_2 emission of CD and MD.

		Drying time (min)		D_{eff} (m^2s^{-1})		E_a**		E (kWh)		CO_2 (kg)	
		Loch Ness	Triple Crown	Loch Ness	Triple Crown	Loch Ness	Triple Crown	Loch Ness	Triple Crown	Loch Ness	Triple Crown
CD	50 °C	9629 ± 41^b	10156 ± 94^a	7.09×10^{-11} ± 6.02×10$^{-12\ e}$	7.77×10^{-11} ± 5.83×10$^{-12\ e}$	54.45 ± 2.54^a	54.45 ± 1.94^a	6.75 ± 0.21^b	7.36± 0.26^a	6.74 ± 0.30^b	7.34 ± 0.26^a
	70 °C	3086 ± 37^d	3255 ± 47^c	2.36×10^{-10} ± 2.32×10^{-11e}	2.59×10^{-10} ± 2.16×10$^{-11\ e}$			5.61 ± 0.28^d	6.11 ± 0.18^c	5.59 ± 0.28^d	6.1 ±0.18^c
MD	90 W	252 ± 13^e	197 ± 11^e	3.98×10^{-9} ± 2.94×10$^{-10\ d}$	5.94×10^{-9} ± 1.88×10$^{-10\ c}$	16.66 ±1.63^{a*}	12.06 ± 0.71^{a*}	0.38 ± 0.02^e	0.30 ±0.02^e	0.38 ± 0.02^e	0.29 ± 0.02^e
	180W	75 ± 8^f	71 ± 7^f	1.42×10^{-8} ± 6.86×10$^{-10\ b}$	1.43×10^{-8} ± 4.05×10$^{-10\ b}$			0.23 ± 0.01^e	0.19 ±0.01^e	0.23 ± 0.01^e	0.19 ± 0.02^e
	240 W	67 ± 7^f	59 ± 5^f	1.48×10^{-8} ± 1.10×10$^{-9\ b}$	1.66×10^{-8} ± 9.48× 10$^{-10\ a}$			0.23 ± 0.02^e	0.21 ± 0.01^e	0.23 ± 0.02^e	0.21 ± 0.01^e
ANOVA		***		***		***		***		***	

**CD and MD stand for conductive drying and microwave drying, respectively.
**E_a: CD, kJmol^{-1}; MD, Wg^{-1}.
***Values with different letters within trait (drying time, D_{eff}, energy consumption, CO_2 emission) and both varieties (Loch Ness, Triple Crown) denote statistically significant differences (Tukey's test, $p < 0.05$).ns, *, **, ***: not significant or significant at p< 0.05, 0.01, 0.001, respectively. Activation energy (E_a) was separately compared for conductive drying and microwave drying, within both varieties, due to the different energy unit (kJmol^{-1}and MD, Wg^{-1}, respectively).

foods MDPI

3.2. Thin-layer convective and microwave drying of blackberries

The fresh Loch Ness blackberries fruits' initial moisture content was 5.53 ± 0.31 kg H_2O kg^{-1} dm, and Triple Crown 5.57 ± 0.31 kg H_2O kg^{-1} dm [15]. During dehydration of fruits, moisture ratio (MR) over time was followed and the results are presented in Figure 1. *MR* is defined as the following ratio: $[(M_t - M_e) / (M_0 - M_e)]$, where M_0 is initial moisture content, M_e is equilibrium moisture content and M_t is the moisture content at a given time on the dry basis. With increasing the temperature or power, the curves are steeper, which indicates a shorter time of fruit dehydration. If the drying temperature increases, the partial pressure of water vapor on the surface of the fruit also increases, resulting in a faster diffusion of moisture from the interior to the surface of the fruit. All dehydration curves had the same shape with different drying times to constant mass. Loch Ness fruits had the longest drying time at a temperature of 50 ^{0}C (9,629 min), while drying at a microwave power of 240 W took the least time (59 min, for both varieties). The drying curves of the Triple Crown fruits using the microwave method were steeper compared to the Loch Ness curves and the drying processes were shorter. Irrespective of the dehydration technique employed, a swift reduction in water content was observed in the initial phase of the drying process. The dehydration time from the initial to the final moisture contents in *Eminoğlu*`s at all. results were measured as 2040, 1350, 1050, and 930 min for air-drying temperatures of 54, 61, 68, and 75 °C, respectively [16]. The drying experiments for blackberries using microwave and convective dehydration methods indicate a significantly reduced drying time of 92–99% with microwave dehydration. Similar results could be observed in the work of Pantelić, where the savings in microwave drying of raspberries were 86 – 96% [17].

The *MR* gauges the moisture level in a food item undergoing drying through a microwave and convective energy. This parameter plays a crucial role in the drying process as it dictates both the speed at which moisture is extracted from the product and the ultimate moisture content. A reduced MR leads to quicker drying and lower ultimate moisture content, whereas an elevated MR leads to a slower drying process and higher final moisture content [18]. Typically, using a microwave with higher wattage and employing convective dehydration at a higher temperature range statistically significantly ($p < 0.05$) will result in a quicker dehydration rate compared to the slower rate achieved with a lower-wattage microwave (Table 3, Figure 1).

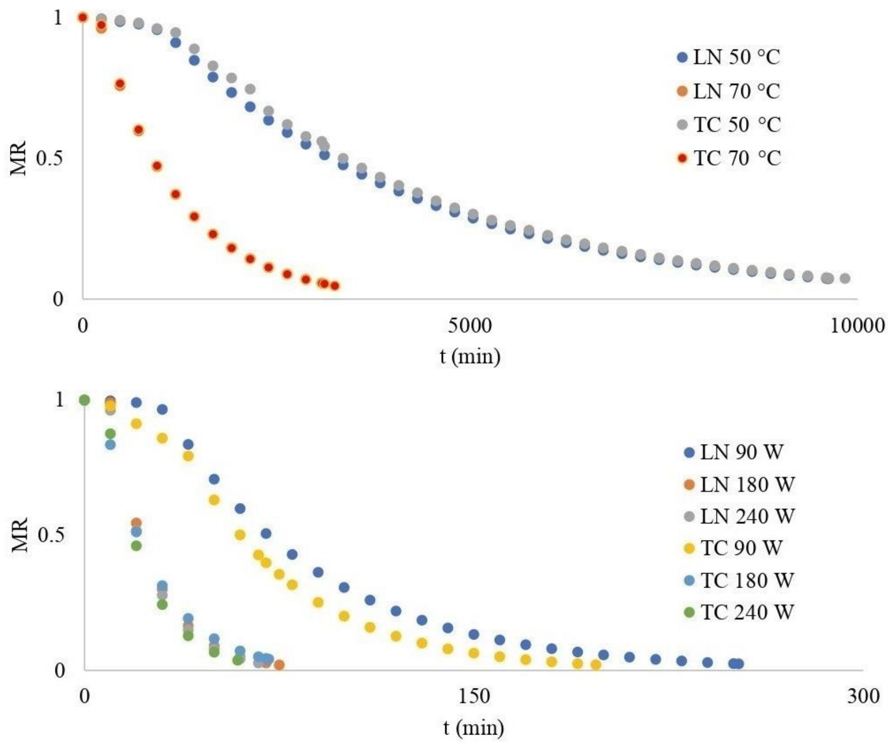

Figure 1. *MR* curves of convective drying (upper figure) and microwave drying (lower figure). LN and TC stand for Loch Ness and Triple Crown varieties.

Drying rate (*DR*) represents the total mass loss of dehydrated materials ($M_{i-1} - M_i$) between two consecutive measurements ($t_{i-1} - t_i$) on a defined tray [$DR = (M_{i-1} - M_i)/(t_{i-1} - t_i)$]. With an increase in temperature and power, *DR* was grown. The maximum *DR* was achieved on the same dehydration time for both analyzed blackberries fruits, for the same dehydration model (Figure 2). The maximum value of *DR* for convective drying is achieved after 960 minutes of drying at a temperature of 50 degrees (DR_{max} = 0.019 gmin^{-1} for LN and DR_{max} = 0.017 gmin^{-1} for TC), 480 minutes of drying at a temperature of 70 °C (DR_{max} = 0.053 gmin^{-1} for LN and DR_{max} = 0.048 gmin^{-1} for TC), 30 minutes of drying at a microwave power of 90 W (DR_{max} = 0.651 gmin^{-1} for LN and DR_{max} = 0.891 gmin^{-1} for TC), and 20 minutes of drying at a microwave power of 180 W (DR_{max} = 2.049 gmin^{-1} for LN and DR_{max} = 1.916 gmin^{-1} for TC) and 240 W (DR_{max} = 2.261 gmin^{-1} for LN and DR_{max} = 2.456 gmin^{-1} for TC).With an increase in temperature and microwave power, the DR_{max} also increases. It can be concluded that the drying time, as well as the values of *MR* and *DR*, will depend statistically more ($p < 0.05$) significantly on the chosen drying method (convective or microwave) and its parameters (temperature, power range), regardless the cultivars. Similar finding were found in Lackowicz's results [14]. The minimum *DR* ratio of blackberries dehydration was increased 12 – 119 times with microwave dehydration. Such an effective influence of microwave energy was found in the work of Pantelić, where the DR_{max} was increased up to 19 times [17].

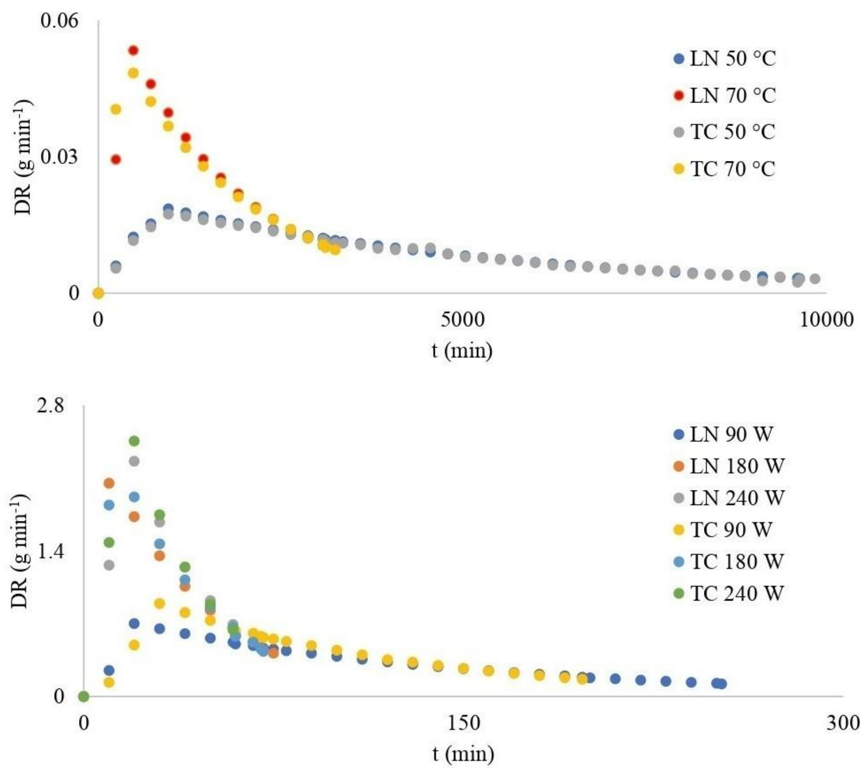

Figure 2. *DR* curves of convective drying (upper figure) and microwave drying (lower figure).

3.3. Determination of Effective Moisture Diffusivity and Energy of Activation

The effective moisture diffusivity D_{eff} can be determined through the application of Fick's second law of diffusion, considering the fruit's spherical shape (Eq. 1) [15]:

$$MR = \frac{6}{\pi^2} \times \sum_{i=1}^{\infty} \frac{1}{J_0^2} \times e^{-\frac{J_0^2 \times D_{eff}}{4 \times r^2}} \quad (1)$$

D_{eff} is the effective moisture diffusivity (m^2s^{-1}), t is time (s), J_0 is the roots of the Bessel function, and r is the blackberries radius (sphere is the appropriate model for the berries). If the D_{eff} was constant in a relatively long drying period, Eq. 1 could be transformed in $\ln(MR) = \ln(a) - k \times t$. The linear relation $\ln(MR)$ and t gives the possibility to calculate the equation slope which is equal to the drying constant (k, Eq. 2):

$$k = -\frac{\pi^2 \times D_{eff}}{4 \times r^2} \quad (2)$$

An Arrhenius equation, Eq. 3 for convective drying, and Eq. 4 for microwave drying, could be used for the energy of activation calculation, E_a [19]:

$$D_{eff} = D_0 \times e^{-\frac{E_a}{RT}} \quad (3)$$

$$D_{eff} = D_0 \times e^{-\frac{E_a \times m}{P}} \quad (4)$$

E_a (kJ mol^{-1}) is the energy of activation, R (8.3143 J $mol^{-1}K^{-1}$) is the universal gas constant, T (K) is the absolute air temperature, and D_0 (m^2 s^{-1}) is the pre-exponential factor of the Arrhenius equation. The Eq. 3 and Eq. 4 could be transformed into the linear equations:

$$\ln(D_{eff}) = \ln(D_0) - k \times (T + 273.15)^{-1} \quad (5)$$

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$$\ln(D_{eff}) = \ln(D_0) - k \times m\ P^{-1} \quad (6)$$

The linear relation $\ln(D_{eff})$ and T gives the possibility to calculate the equation slope which is equal to the drying constant $k = Ea \times R^{-1}$. The natural logarithm of D_{eff} versus mass load m (g)/P (W) was used to calculate the E_a (W g^{-1}) of microwave drying.

Elevated air-drying temperatures and higher microwave power statistically significantly ($p < 0.05$) resulted in higher D_{eff} values due to enhanced moisture diffusion at elevated temperatures (Table 3). The highest D_{eff} values were calculated for the experimental microwave drying on 240 W ($1.48\times10^{-8} \pm 1.10\times10^{-9}$ m^2s^{-1} for Loch Ness and $1.66\times10^{-8} \pm 9.48\times10^{-10}$ m^2s^{-1} for Triple Crown). The presented D_{eff} values were within the specific ranges ($10^{-8} - 10^{-11}$ m^2s^{-1}), according to the previous published data [15–17,21]. The moisture diffusion and D_{eff} were not depended of the blackberry diameter, since the diameter of Loch Ness was 23.76 ± 0.75 mm and 24.66 ± 0.81mm for Triple Crown.

The energy of activation E_a reflects the sensitivity of diffusivity to temperature and power range, indicating the energy required to initiate water diffusion. A higher E_a signifies increased sensitivity of D_{eff} to changes in temperature and power. E_a, for the convective drying, was calculated to be 54.45 kJ mol^{-1} for both varieties, while for microwave drying was 16.66 ± 1.63 W g^{-1} for Loch Ness and 12.06 ± 0.71 W g^{-1} for Triple Crown. As could be concluded for D_{eff}, E_a was not depended on the blackberry diameter, but on the type of drying and its parameters. A reduced E_a implies enhanced effective moisture diffusivity (higher D_{eff}) and increased moisture diffusion with the radius (thickness) of the sphere. This suggests that lower energy consumption leads to the breaking of bonds between water molecules in the sample [21] and was correlated with the results presented in the work of Pantelić [17], where the diameter of raspberries was about 25 mm ($E_a = 65.22$ kJ mol^{-1}). The calculated E_a were within the specific ranges (12.7 to 110 $kJmol^{-1}$), according to the previous research by *Eminoğlu*`s at all. in which the energy of activation was calculated as 42.25 $kJmol^{-1}$ [16].

3.4. Determination of Energy Consumption

Evaluating the energy usage (E), as well as the emission of CO_2, in dehydration procedures is crucial for gauging process efficiency and pinpointing potential energy–saving avenues. One approach to this assessment involves direct measurement, wherein the energy consumption analysis of the dehydration process entails directly measuring the energy input into the system. The experimental findings in Table 3 revealed a significant influence of the dehydration process on energy consumption (E), directly correlating with the duration of the drying process. It was evident that there was a statistically significantly reduction in energy input ($p < 0.05$) as the microwave energy for drying increased, accompanied by a subsequent decrease in drying time. The microwave drying on 180 and 240 W was the least energetically demanding (E = 0.19 – 0.23 kWh), while the convective drying was about 25 – 35 energetically demanding drying process. Additionally, the experimental findings indicated that convective drying of Loch Ness blackberries demanded a higher energy input compared to Triple Crown drying, whereas the opposite trend was observed for microwave drying. Microwave drying at power inputs of 180 and 240 W exhibited the shortest drying time and the highest D_{eff}, influenced by the lowest energy demand in the drying process. The previous results for drying organic blackberries showed that by increasing the microwave power decreased quadratically the amount of energy consumption [22]. Also, the use of pretreatment (e.g. ultrasound assistance) can significantly reduce the energy required for convective drying of blackberries [23,24].

3.4. Statistical analysis

The drying method (convective and microwave drying) and their parameters (temperature and microwave power) were used as independent variables, and PCA was applied to identify the structure in the correlation between these parameters and dependent variables, the drying time, effective moisture diffusivity, energy consumption / emission of CO_2, total anthocyanins and phenolics, antioxidant activity. The results of the PCA are shown in Figure 3. A scatter plot was generated using the initial two principal components derived from the PCA of the data matrix. The first principal component was assigned to the x-axis, while the second principal component was assigned to the y-axis. The purpose was to illustrate patterns within the presented data and showcase the efficacy of the descriptors employed in distinguishing between different data points. The angles between corresponding variables reflect the extent of their correlations, with smaller angles indicating stronger correlations [25]. A scatter plot was designed with the first two principal components (F1, F2) from the PCA data matrix. The first two components demonstrated 87.12% of the total variance in the experimental data. The contribution of the variables (%) showed that all variables except the effective moisture diffusivity (drying time, energy consumption / emission of CO_2, total anthocyanins and phenolics, antioxidant activity) equal participated in F1 (13.06 – 16.19 %). The drying time and energy consumption / emission of CO_2 most participated in F2 (22.60% and 16.07%, respectively). The position of the samples in Figure *3* was primarily more influenced by the type of drying, than the drying parameters and blackberry species. Similar correlations were previously published [13,26]. Blackberries, regardless of their species, dried by microwave power were characterized by higher values of all analyzed parameters except energy consumption / emission of CO_2 (oriented on the positive side of the x-axis by the positive value of the F1 component), while the convective dried blackberries were oriented on the negative side of x-axis (by the negative value of the F1 component). Therefore, the Triple Crown dried by microwave power 180 W were characterized by the high values of the following parameters: effective moisture diffusivity, total anthocyanins, total phenols and antioxidant activity. The blackberries dried by convective method were characterized by energy consumption / emission of CO_2.The high concentrations of anthocyanins and phenols contributed to the higher antioxidant activity of dried blackberries as well.

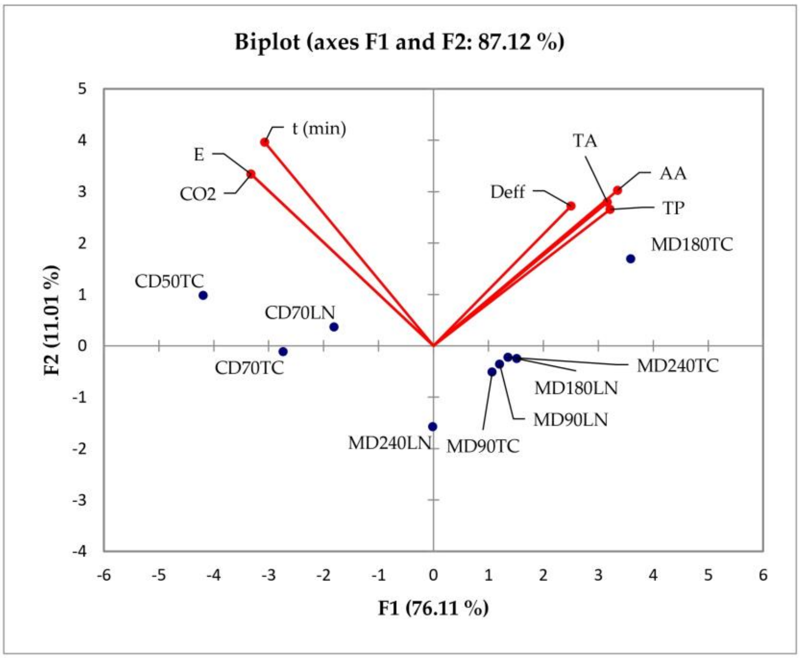

Figure 3. PCA of independent variables and responses of the convective and microwave drying.

The microwave drying proved to be more effective in terms of drying time, with a statistically significant shorter time of drying process. The D_{eff} generally rises as temperature and energy input increase. This is attributed to the heightened mobility of moisture molecules at higher temperatures and energy input, leading to a faster diffusion rate. The findings presented in the paper affirm this observation, as the D_{eff} values were found to be highest in the microwave drying associated with the highest microwave power range. As energy input escalates, there is a notable increase in the D_{eff}. The experimental findings reveal a notable influence of drying process duration on energy consumption. In particular, the results indicate a statistically significant decrease in energy input with an input of microwave energy and a subsequent reduction in drying time. This implies that substantial energy savings can be achieved by shortening the drying process duration. It is crucial to acknowledge that various drying processes may exhibit diverse energy requirements. Additionally, the discussion underscores that microwave drying proved to be less energetically demanding for the drying of blackberries. This suggests that selecting an appropriate drying method tailored to a specific product can contribute to reducing overall energy consumption.

A visual representation in the form of a color correlation diagram (Figure 4) was generated to illustrate the statistical significance of correlation coefficients between various variables and their corresponding responses (total anthocyanins and phenolics, antioxidative activity, drying time, effective moisture diffusivity, energy of activation and energy consumption/emission of CO_2). The graphical display employs circle size and color (blue indicating positive correlation and red indicating negative correlation) to represent the values of the correlation coefficients among the tested parameters (Figure 5) [27]. A high level of positive correlation was shown between drying time and energy consumption / emission of CO_2 (r = 0.8908, statistically significant at $p < 0.05$), and total anthocyanins – total phenolics – antioxidative activity (r = 0.9040 – 0.9167, statistically significant at $p <$ 0.05). These results are expected since there is a direct dependence between the drying model (convective, microwave), drying time, and total energy input. Also, antioxidative activity is directly dependent on the total anthocyanins and total phenolics content, as bioactive components.

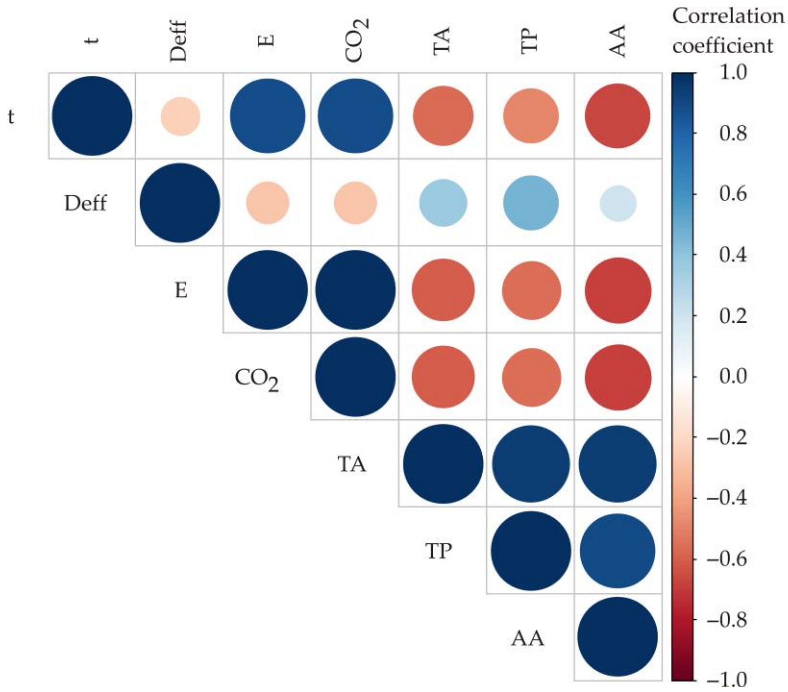

Figure 4. A color correlation diagram depicting the relationship between the independent variable parameters and the responses of the convective and microwave drying.

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A high level of negative correlation was shown between drying time /energy consumption (emission of CO_2) and antioxidant activity (r = – 0.7452 to –0.7597, statistically significant at $p < 0.05$). A lower level of negative correlationwas found between drying time time / energy consumption (emission of CO_2) and total anthocyanins and total phenolics content (r = – 0.6307 to –0.7290, statistically significant at $p < 0.05$).The bioactive components (anthocyanins, phenolics) are thermolabile, and their antioxidative activity will be decreased on a higher temperature or microwave power input, or longer dehydration time. The experimental results of this work are in a correaltion with the previously presented [23,28]. The results have implications for enhancing the drying process, particularly in sectors such as the food industry, where dehydration plays a crucial role in fruit processing and preservation.

4. Conclusions

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