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Multivariate Evalutaion of Physicochemical Properties of Functional Vegetable Powders

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Abstract

This study focuses on the development and characterization of functional vegetable powders obtained from freeze-dried red and purple vegetables. Due to their high content of bioactive compounds such as phenolics, flavonoids, and anthocyanins, vegetables like black carrot, red cabbage, red beetroot, and waste from fermented black carrot have attracted increasing attention as potential functional food ingredients. In this research, selected vegetables were freeze-dried, ground into powder form, and analyzed for their bioactive properties. Total phenolic content ranged from 16,012.02 to 44,001.09 mg GAE/kg, with the highest values observed in red cabbage (44,001.09 mg GAE/kg) and black carrot (40,460.11 mg GAE/kg). Antioxidant activity, determined by the DPPH assay, ranged from 22.88% to 51.84% inhibition, with black carrot (51.84%) and red cabbage (51.20%) showing the strongest activity. Total monomeric anthocyanin content ranged from 54.27 to 1,873.20 mg Cy3G/100 g, with the highest level detected in red cabbage samples. Principal Component Analysis (PCA) was used to evaluate differences and establish relationships between chemical composition and functional properties. Overall, the findings demonstrate that freeze-dried vegetable powders are promising natural sources of bioactive compounds and can be used to develop functional food formulations. The study also highlights the potential of valorizing vegetable-based materials, including waste-derived sources, to enhance sustainability and nutritional quality.

Key Words: *Antioxidant activity, Anthocyanins, PCA, Total Phenolic Content, Black carrot, Red cabbage, Red Beetroot*

Introduction

Consumer demand for natural, pigment-rich, and health-promoting food ingredients has increased interest in vegetable powders obtained from anthocyanin- and betalain-rich raw materials such as red cabbage, black carrot, and beetroot. These vegetables are valued not only for their intense coloring properties but also for their phenolic compounds and antioxidant capacity, which are associated with protective effects against oxidative stress-related diseases (Todorovic et al., 2026). Black carrots get their color from the high amount of pigments called anthocyanins (45.4–17.4 g/kg dry matter) (Dereli et al., 2015). The distinctive red color of beetroots comes from betalain pigments such as betanin and betacyanin (Clifford et al., 2015). In the anthocyanin profiles of red cabbage, acylated structures of cyanidin-3,5-diglucoside and cyanidin-3-sophoroside-5-glucoside with sinapic acid, ferulic acid, caffeic acid, p-coumaric acid, and malonic acid are commonly found (Ghareaghajlou et al., 2021).

Freeze-drying is generally regarded as one of the most suitable dehydration methods for heat-sensitive pigments and bioactive compounds, since the sublimation of ice at low temperature largely preserves the structure, color, and phytochemical content of the raw material compared with conventional hot-air drying. Red cabbage is a particularly rich source of acylated anthocyanins and phenolic compounds, and the processing method has repeatedly been shown to strongly influence its anthocyanin retention and antioxidant activity (Tan et al., 2023). Encapsulation and drying method significantly affected the physicochemical properties, antioxidant capacity, anthocyanin content, and stability of red cabbage powder colorants, with freeze drying and encapsulation providing the best overall preservation (Baltacıoğlu et al., 2024). Black carrot (*Daucus carota* ssp. sativus) is similarly recognized as a major natural source of cyanidin-based anthocyanins, and fermentation of black carrot materials with lactic acid bacteria has been reported to alter titratable acidity, phenolic acid composition, and antioxidant capacity, reflecting substantial biochemical transformation of the matrix during fermentation (Uzun et al., 2024). In recent years, turnip juice production and consumption have increased in Türkiye, and fermented black carrots, which are leftovers from turnip juice production, have been utilized in many different food products such as Turkish noodles, tarhana, and biscuits due to their high bioactive compounds (Baltacıoğlu et al., 2019; Tanguler and Tatlısoy, 2022; Ozer et al., 2024). The drying method significantly affects the antioxidant activity of black carrot powder. In a study that used different methods for producing black carrot powder, freeze-dried black carrot powder was reported to have the highest antioxidant activity (Murali et al., 2015). Beetroot (*Beta vulgaris* L.), in contrast, owes its characteristic color to betalain pigments rather than anthocyanins, and its phenolic content, color parameters, and mineral (ash) content are strongly influenced by both cultivar and processing conditions (Tarasevičienė et al., 2024).

Despite extensive individual studies on these vegetables, comparative data evaluating freeze-dried red cabbage, beetroot, black carrot, and fermented black carrot powders together, using the same analytical framework, are limited. Multivariate chemometric tools such as principal component analysis (PCA) have proven useful for discriminating plant-derived powders according to their physicochemical and bioactive markers, reducing complex multidimensional data into a smaller number of interpretable components (Gergen & Harmanescu, 2012).

The aim of the present study was therefore to determine and compare the physicochemical properties and bioactive compound contents of four freeze-dried vegetable powders, red cabbage, beetroot, black carrot, and fermented black carrot, and to apply PCA as a chemometric approach to evaluate the relationships among the measured variables and to discriminate the powders according to their physicochemical and bioactive identity.

Materials and Methods

Materials

Red cabbage (*Brassica Oleracea* var. capitata f. rubra), beetroot (*Beta vulgaris* L.), and black carrot (*Daucus carota* ssp. sativus) were obtained from local markets, washed, and cut into uniform pieces. The fermented black carrots (*Daucus carota ssp. sativus* var. *atrorubens Alef.*) used in this study were obtained from fermented carrot residues remaining after the removal of the şalgam samples produced at the Department of Food Engineering, Niğde Ömer Halisdemir University. All four vegetable materials were frozen (VWR Symphony, USA) and subsequently dried using a laboratory-scale freeze-dryer (Scanvac Coolsafe 95-15 Pro, Denmark) until the water was completely removed. The dried materials were ground into fine powders, sieved, and stored in airtight containers protected from light at low temperature until analysis. All analyses were performed in triplicate (n = 3) for each powder sample.

Methods

pH was measured directly in aqueous suspensions of the powders using a calibrated digital pH meter (Hanna Edge, USA). Dry matter content was determined gravimetrically by drying samples to constant weight in a hot-air oven and was calculated as the complement of the moisture loss. Soluble solids content was determined as °Brix using a digital refractometer (HI96801 - Hanna Instruments Canada). Titratable acidity was determined by titration with standardized sodium hydroxide solution and expressed as g citric acid equivalents per 100 g of powder. Ash content was determined by incineration of the samples in a muffle furnace at high temperature until a constant, whitish-gray residue was obtained, and expressed as a percentage of the initial sample weight. Total sugar content was determined spectrophotometrically and expressed as a percentage of the powder.

Color was measured directly on the powders using a colorimeter, and the CIE L* (lightness), a* (redness–greenness), and b* (yellowness–blueness) coordinates were recorded. The total color difference (ΔE) was calculated from the L*, a*, and b* values relative to a fixed reference point.

Total phenolic content (TPC) was determined using the Folin–Ciocalteu method, with absorbance measured spectrophotometrically and results expressed as mg gallic acid equivalents (GAE) per kg of dry powder, based on a gallic acid calibration curve (Baltacıoğlu et al., 2026). Total monomeric anthocyanin (TMA) content was determined by the pH-differential method using absorbance measurements at 525 nm and 700 nm in buffers at pH 1.0 and pH 4.5, and results were expressed as mg cyanidin-3-glucoside equivalents per 100 g of powder (Baltacıoğlu et al., 2024). Antioxidant activity (AA) was determined using the DPPH radical scavenging assay and expressed as percentage inhibition relative to a control solution (Baltacıoğlu et al., 2024).

Statistical Analysis

All results are expressed as mean ± standard deviation (SD) of triplicate determinations. Principal component analysis (PCA) was performed on the correlation matrix of the eleven measured physicochemical and bioactive variables (pH, dry matter, Brix, titratable acidity, ash content, L*, a*, b*, ΔE, total sugar, TPC, AA, and TMA) to reduce data dimensionality and to evaluate the relationships among variables and the discrimination of the four vegetable powders based on their physicochemical and bioactive profiles.

Results

The physicochemical characteristics of the four freeze-dried vegetable powders are summarized in Table 1. Fermented black carrot showed the lowest pH (3.77 ± 0.01) and the highest titratable acidity (0.241 ± 0.016 g citric acid/100 g) among the samples, consistent with acid production during fermentation, while beetroot showed the highest pH (6.36 ± 0.02) and the lowest titratable acidity (0.060 ± 0.004 g citric acid/100 g). Beetroot also had the highest dry matter content (14.23 ± 0.43%) and ash content (10.18 ± 0.16%), whereas fermented black carrot had the highest ash content among all samples (21.94 ± 0.08%). Total sugar content was highest in black carrot (7.17 ± 0.42%) and could not be determined in the fermented black carrot powder.

Table 1. Physicochemical properties of freeze-dried vegetable powders.

Parameter	*Black carrot*	*Beetroot*	*Red cabbage*	*Fermented black carrot*
pH	5.60 ± 0.14^{b}	6.36 ± 0.02^{a}	5.65 ± 0.15^{b}	3.77 ± 0.01^{c}
Dry matter (%)	10.90 ± 0.07^{b}	14.23 ± 0.43^{a}	11.00 ± 0.05^{b}	13.64 ± 0.21^{a}
Soluble solids (°Brix)	3.63 ± 0.32^{a}	4.13 ± 0.31^{a}	4.13 ± 0.06^{a}	1.60 ± 0.44^{b}
Titratable acidity (g citric acid/100 g)	0.090 ± 0.006^{c}	0.060 ± 0.004^{d}	0.139 ± 0.004^{b}	0.241 ± 0.016^{a}
Ash (%)	8.55 ± 0.07^{bc}	10.18 ± 0.16^{b}	8.21 ± 2.06^{bc}	21.94 ± 0.08^{a}
Total sugar (%)	7.17 ± 0.42^{a}	4.37 ± 0.15^{b}	4.77 ± 1.05^{b}	n.d.

*Different superscript letters within the same row indicate significant differences (*p* < 0.05); n.d.: not determined*

Table 2. CIE color coordinates (L*, a*, b*) and total color difference (ΔE) of freeze-dried vegetable powders.

Sample	*L**	*a**	*b**	*ΔE*
Black carrot	39.97 ± 0.65^{b}	15.75 ± 0.36^{d}	−2.52 ± 0.09^{c}	53.18 ± 0.54^{c}
Beetroot	21.45 ± 1.41^{c}	37.90 ± 2.74^{a}	8.93 ± 1.49^{d}	76.72 ± 2.34^{a}
Red cabbage	45.50 ± 0.88^{a}	20.79 ± 0.22^{c}	−12.86 ± 0.05^{d}	56.58 ± 0.68^{b}
Fermented black carrot	44.07 ± 0.53^{a}	28.52 ± 0.74^{b}	4.11 ± 0.14^{b}	54.70 ± 0.57^{bc}

*Different superscript letters within the same column indicate significant differences (*p* < 0.05)*

Table 3. Total phenolic content (TPC), total monomeric anthocyanin content (TMA), and antioxidant activity (AA) of freeze-dried vegetable powders.

Sample	*TPC (mg GAE/kg)*	*TMA (mg Cy-3-glu E/100 g)*	*AA (% inhibition)*
Black carrot	40460.1 ± 1013.9^{a}	538.96 ± 12.11^{c}	51.84 ± 2.15^{a}
Beetroot	21203.3 ± 1291.7^{b}	1141.09 ± 45.99^{b}	22.91 ± 1.20^{b}
Red cabbage	44001.1 ± 2549.0^{a}	1873.20 ± 1.25^{a}	51.20 ± 2.02^{a}
Fermented black carrot	16012.0 ± 341.3^{c}	54.27 ± 7.51^{d}	22.88 ± 2.92^{b}

*GAE: gallic acid equivalents; Cy-3-glu E: cyanidin-3-glucoside equivalents. Different superscript letters within the same column indicate significant differences (*p* < 0.05)*

Color parameters of the powders are presented in Table 2. Beetroot powder displayed the lowest lightness (L* = 21.45 ± 1.41) and the highest redness (a* = 37.90 ± 2.74) and overall color difference (ΔE = 76.72 ± 2.34), consistent with its intense betalain pigmentation. Red cabbage powder was the lightest sample (L* = 45.50 ± 0.88) and showed the most negative b* value (−12.86 ± 0.05), reflecting its blue-violet anthocyanin hue, whereas fermented black carrot exhibited a shift toward positive b* values (4.11 ± 0.14) compared with unfermented black carrot, indicating a fermentation-induced change in hue.

The bioactive compound contents of the powders are shown in Table 3. Red cabbage and black carrot exhibited markedly higher total phenolic content, total monomeric anthocyanin content, and antioxidant activity than beetroot and fermented black carrot. Antioxidant activity closely paralleled total phenolic content across all samples, being highest in red cabbage (51.20 ± 2.02%) and black carrot (51.84 ± 2.15%) and lowest in beetroot (22.91 ± 1.20%) and fermented black carrot (22.88 ± 2.92%). Fermentation markedly reduced the total monomeric anthocyanin content of black carrot, from 538.96 ± 12.11 mg cyanidin-3-glucoside equivalents (Cy-3-glu E)/100 g in the unfermented sample to 54.27 ± 7.51 mg Cy-3-glu E/100 g in the fermented sample.

Principal Component Analysis

PCA was applied to the eleven physicochemical and bioactive variables measured for the four freeze-dried vegetable powders. The first two principal components explained 91.1% of the total variance, with PC1 accounting for 54.3% and PC2 accounting for 36.8%, indicating that the resulting score plot adequately represented the variability among the samples (Figure 1).

The score plot revealed a clear separation of the four powders into distinct groups. Red cabbage and black carrot were positioned on the positive side of PC1, associated with higher dry matter, total sugar, TPC, AA, and TMA values, and their close clustering indicated similar physicochemical and bioactive characteristics. Fermented black carrot was located in the upper-left quadrant (negative PC1, positive PC2), characterized by higher titratable acidity and lighter color values, illustrating the substantial effect of fermentation on the chemical composition of black carrot. Beetroot was clearly separated in the lower-left quadrant (negative PC1 and PC2), associated mainly with ash content and the color coordinates a* and b*, reflecting its distinct pigment and mineral composition.

The PCA biplot (Figure 2) showed that the vectors for TPC, AA, dry matter, total sugar, and TMA were oriented in similar directions on the positive side of PC1, indicating strong positive correlations among these variables; the proximity of red cabbage and black carrot to these vectors confirmed their richness in bioactive compounds. The vectors for titratable acidity and L* were associated with positive PC2 values and were oriented toward the fermented black carrot sample, reflecting the acidification and lightening of color associated with fermentation. Ash content and the color coordinates a*, b*, and ΔE were positioned on the negative side of PC1 and were associated with beetroot, consistent with its mineral-rich, intensely colored profile.

Table 4 presents the loading values of each variable on PC1 and PC2. PC1 was positively correlated with TPC, AA, dry matter, total sugar, and TMA, and negatively correlated with ash content, titratable acidity, and the color coordinates a* and b*, indicating that PC1 primarily represented the bioactive and nutritional quality of the powders. PC2 was positively correlated with L* and titratable acidity and negatively correlated with pH, ΔE, a*, b*, Brix, and TMA, indicating that PC2 mainly reflected differences related to acidity and color characteristics among the samples.

Table 4. Loading values of the principal components (PC1 and PC2) for the physicochemical and bioactive variables of freeze-dried vegetable powders.

Variable	*PC1*	*PC2*
pH	0.243	−0.345
Dry matter	0.331	0.210
Brix	0.296	−0.259
Titratable acidity	−0.223	0.341
Ash	−0.348	0.166
L*	0.053	0.444
a*	−0.255	−0.306
b*	−0.283	−0.238
ΔE	−0.069	−0.442
Total sugar	0.328	−0.119
TPC	0.361	0.115
AA	0.341	0.180
TMA	0.258	−0.151

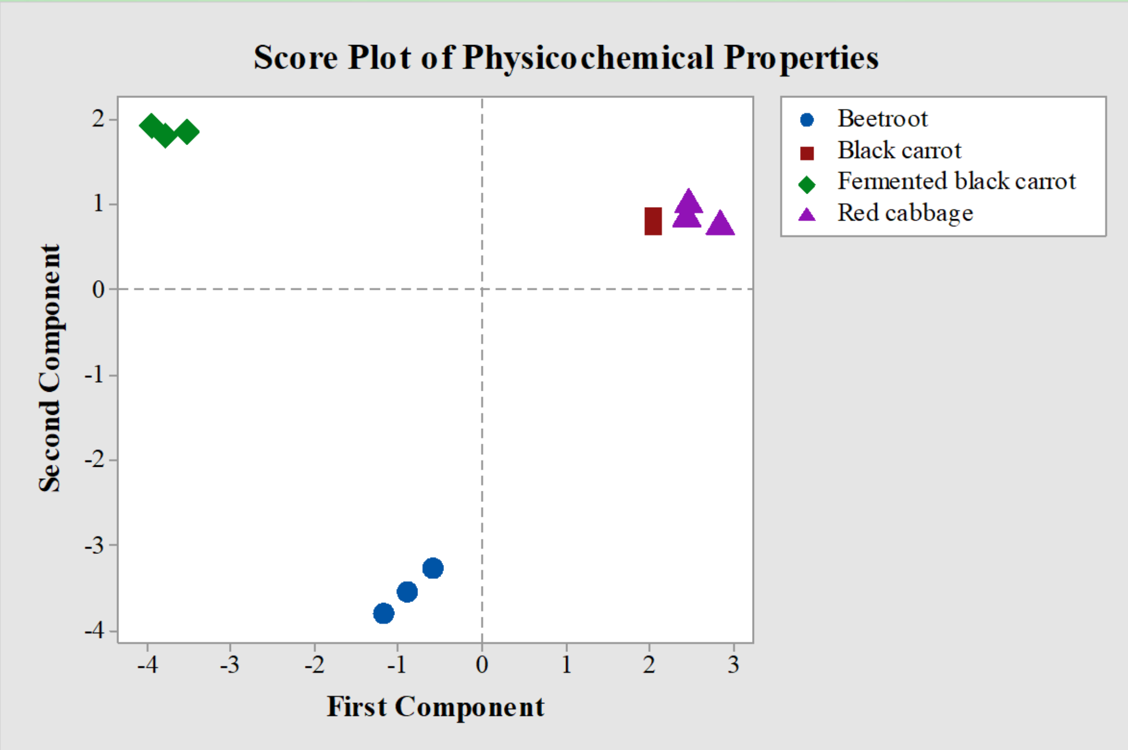

Figure 1. PCA score plot based on the physicochemical and bioactive properties of the freeze-dried vegetable powders.

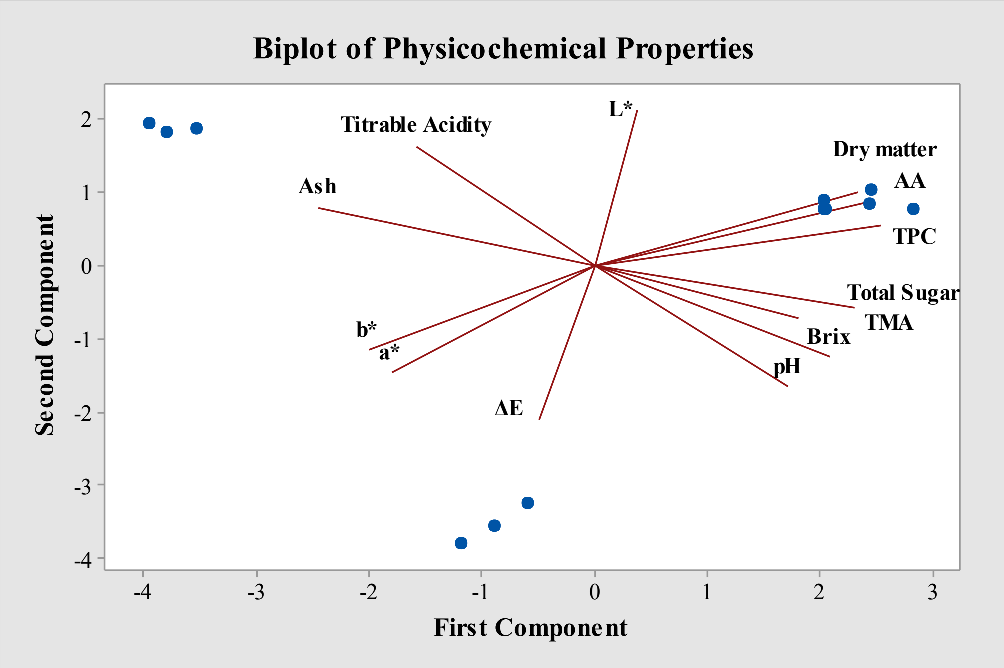

Figure 2. PCA biplot showing the relationships between the physicochemical variables and the freeze-dried vegetable powders.

Discussion

The results of this study confirmed that freeze-drying preserved distinct physicochemical and bioactive identities in red cabbage, beetroot, black carrot, and fermented black carrot powders, and that these identities could be effectively discriminated through PCA. Red cabbage and black carrot powders showed comparably high total phenolic content, total monomeric anthocyanin content, and antioxidant activity, consistent with reports that freeze-drying retains a higher proportion of anthocyanins and phenolic compounds than thermal drying methods, since red cabbage anthocyanin and phenolic retention has been shown to be strongly dependent on processing method, with freeze-drying generally outperforming hot-air drying in pigment preservation (Tan et al., 2023).

The strong positive correlation observed between TPC and AA on PC1 supports the well-established relationship between phenolic content and antioxidant capacity, in which phenolic compounds act as the principal contributors to free-radical scavenging activity in plant-derived powders. The clustering of red cabbage and black carrot along this component suggests that, despite differing in pigment chemistry, anthocyanins in red cabbage and black carrot, both vegetables share comparably high overall phenolic and antioxidant potential when processed by freeze-drying.

Fermented black carrot was clearly separated from the unfermented sample along PC2, mainly through the combined effect of increased titratable acidity and altered lightness. This is consistent with previous findings that fermentation of carrot matrices with lactic acid bacteria substantially increases titratable acidity through organic acid production while modifying the phenolic acid profile of the substrate (Uzun et al., 2024). In the present study, fermentation was further associated with a pronounced decrease in total monomeric anthocyanin content relative to unfermented black carrot, suggesting that the acidic, microbially active fermentation environment promoted degradation or structural transformation of anthocyanin pigments, consistent with the marked shift toward less negative b* values observed in the fermented sample.

Beetroot powder occupied a distinct position in the PCA space, mainly associated with ash content and the color coordinates a* and b*, reflecting its characteristic mineral richness and betalain-based pigmentation rather than the anthocyanin- and phenolic-driven profile of red cabbage and black carrot. This is in line with reports that beetroot powder color and phenolic content are strongly influenced by drying method and cultivar, with betalains representing a chemically distinct pigment class from anthocyanins despite producing a comparably intense coloring effect (Tarasevičienė et al., 2024). The comparatively lower antioxidant activity of beetroot relative to red cabbage and black carrot in this study may be attributed to the generally lower molar antioxidant efficiency of betalains compared with the highly conjugated, acylated anthocyanins typical of red cabbage and black carrot.

Overall, the PCA results demonstrate that combining physicochemical and bioactive markers within a single multivariate framework provides an efficient means of distinguishing vegetable powders according to their processing-related and compositional characteristics, in agreement with previous applications of PCA as a chemometric discrimination tool in plant-derived food matrices (Gergen & Harmanescu, 2012).

Conclusion

Freeze-dried red cabbage and black carrot powders were characterized by high dry matter, total sugar, phenolic, anthocyanin, and antioxidant capacity, whereas fermented black carrot displayed a distinct acidic and anthocyanin-reduced profile resulting from fermentation, and beetroot was distinguished by its ash content and betalain-related color attributes. PCA effectively discriminated the four vegetable powders based on these physicochemical and bioactive characteristics, confirming its usefulness as a chemometric tool for evaluating and classifying functional vegetable powders. These findings support the potential use of freeze-dried red cabbage and black carrot powders as concentrated sources of natural phenolic and anthocyanin compounds for functional food applications.

Declarations

Author Contribution Statement

İkbal Abdullah Şahin: Data collection, investigation, formal analysis, and writing the original draft

Hande Baltacıoğlu and Hasan Tangüler: Project administration, supervision, conceptualization, methodology, review and editing

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Conflict of Interest

The authors declare no conflict of interest.

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